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# Beyond LCOE: Techno-Economic and Life-Cycle Assessment of Electricity Generation from Coal, Nuclear, Gas, Wind and PV

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## Abstract

Comparisons of electricity-generation technologies based solely on the plant-level levelized cost of electricity (LCOE) or direct emissions may obscure important system-level and life-cycle trade-offs. This study compares coal, natural gas, large-scale nuclear power, onshore wind and photovoltaic (PV) generation using a combined techno-economic and life-cycle framework comprising the LCOE, system LCOE (SLCOE), value-adjusted LCOE (VALCOE), screening-level levelized full system cost of electricity (LFSCOE), and life-cycle assessment (LCA). With EU ETS costs included, the calculated LCOE values were 141.00 EUR/MWh for coal, 103.84 EUR/MWh for gas, 73.07 EUR/MWh for nuclear, 57.20 EUR/MWh for PV and 46.35 EUR/MWh for wind. System integration increased the SLCOE particularly for PV (124.37 EUR/MWh) and wind (90.96 EUR/MWh), whereas the increases for dispatchable technologies were comparatively small. The screening LFSCOE comparison further highlighted the cost implications of requiring a single technology to provide firm supply, with substantially higher values for PV and wind than for dispatchable generation. The LCA results showed the lowest life-cycle global-warming impact for nuclear and wind, while coal and natural gas remained dominated by fossil-fuel emissions. Incorporating battery storage increased several environmental burdens of variable renewable generation, particularly water consumption, resource use and selected toxicity indicators. The results demonstrate that technology rankings depend strongly on whether plant-level cost, system integration, system value, firm-supply requirements or life-cycle environmental impacts are considered.

**Keywords:** levelized cost of electricity (LCOE); system LCOE (SLCOE); value-adjusted levelized cost of electricity (VALCOE); levelized full system cost of electricity (LFSCOE); life-cycle assessment (LCA); renewable energy; EU ETS

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## 1. Introduction

The increasing deployment of renewable energy sources (RESs) constitutes one of the principal components of the ongoing global energy transition. The expansion of renewable generation capacity is driven by climate-policy objectives, the need to reduce greenhouse gas emissions from the power sector, concerns regarding energy security, and the progressive electrification of transport, buildings and industry. The scale of this transformation has accelerated considerably in recent years. In 2025, global renewable power capacity increased by 692 GW, bringing the total installed renewable capacity to 5149 GW. Solar photovoltaic

(PV) technology accounted for approximately 510 GW of new capacity, while wind power added approximately 159 GW. Together, solar and wind represented nearly 97% of all net renewable-capacity additions in 2025. By the end of the year, renewable sources accounted for approximately 49% of global installed electricity-generation capacity [1–3].

The rapid expansion of renewable capacity occurs simultaneously with continued growth in electricity consumption. Global electricity demand reached approximately 28,600 TWh in 2025 and increased by around 3% compared with the previous year. The increase amounted to approximately 800 TWh in a single year and was driven by, among other factors, electrification, industrial activity, increasing use of air conditioning, electric vehicles and rapidly growing electricity consumption by data centres. At the same time, renewables accounted for approximately 34% of global electricity generation in 2025, while wind and solar PV together provided approximately 17% [4–6].

Poland provides a particularly relevant example of this transition. At the end of 2025, total installed renewable power capacity reached approximately 37.8 GW, corresponding to slightly more than 50% of the country's installed generation capacity. Solar PV represented approximately 24.8 GW and wind power approximately 10.5 GW, meaning that these two variable renewable technologies accounted for the vast majority of installed renewable capacity. Renewable electricity generation reached almost 55 TWh in 2025 and accounted for 31.41% of total domestic electricity generation. In comparison, total domestic electricity consumption amounted to 167.5 TWh in the same year [7–9].

The increasing share of installed renewable capacity does not translate directly into an equivalent share of electricity supplied to the power system. This difference is partly attributable to technology-specific capacity factors, but it is also increasingly related to the ability of the electricity system to accommodate variable generation. Solar and wind generation depend on weather conditions and their production profiles do not necessarily coincide with the temporal profile of electricity demand. Consequently, increasing penetration of variable renewable energy creates additional requirements for system flexibility, balancing resources, electricity storage, dispatchable generation, interconnection capacity, demand-side response and grid development [10].

The significance of this issue is already evident in the Polish power system. In 2025, approximately 1.4 TWh of potential renewable electricity generation was curtailed and therefore not delivered to the electricity system, approximately twice the volume recorded in 2024. Importantly, around 97.8% of this curtailment resulted from balancing constraints rather than physical-grid congestion. Curtailment occurred particularly during periods of high renewable generation and relatively low electricity demand, demonstrating that additional renewable generation capacity alone is insufficient to ensure its effective utilization. Instead, further decarbonization requires simultaneous development of system flexibility, storage, transmission infrastructure and other measures capable of matching electricity supply with demand [11].

These developments indicate that electricity-generation technologies should not be compared solely on the basis of installed capacity, direct emissions or plant-level generation costs. Technologies differ substantially in dispatchability, temporal availability, balancing requirements, storage needs, system integration and environmental burdens throughout their life cycles. Therefore, a more comprehensive comparison requires the consideration of both economic and environmental dimensions, as well as the ability of individual technologies to provide electricity in accordance with power-system requirements.

The present study compares coal-fired power generation, natural-gas-fired combined-cycle generation, large-scale nuclear power, onshore wind power and photovoltaic generation using an integrated techno-economic and life-cycle framework. The economic assessment combines the levelized cost of electricity (LCOE), system levelized cost of elec-

tricity (SLCOE), value-adjusted levelized cost of electricity (VALCOE), and a screening-level levelized full system cost of electricity (LFSCOE). In parallel, the environmental assessment applies life-cycle assessment (LCA) to quantify environmental burdens throughout the entire life cycle of each technology.

The objective of the study is therefore to evaluate how the comparative performance of electricity-generation technologies changes when the assessment progresses from conventional plant-level costs toward system-integration requirements, electricity-system value, firm-supply considerations and life-cycle environmental impacts. The theoretical background and previous research related to these assessment approaches are discussed in Section 2.

## 2. Literature Review

### *2.1. Economic Assessment of Electricity-Generation Technologies*

A substantial body of research compares electricity-generation technologies using the levelized cost of electricity. The LCOE is one of the most widely used indicators for evaluating and comparing power-generation technologies because it expresses the average discounted lifetime cost of producing a unit of electricity. The indicator typically incorporates capital expenditure, operation and maintenance costs, fuel costs, carbon costs and, where relevant, decommissioning and waste-management costs [12,13].

The principal advantage of the LCOE is that it enables technologies with different investment structures, operating costs, capacity factors and lifetimes to be compared using a common monetary unit. However, the LCOE remains a plant-level metric and does not directly account for transmission, distribution, balancing, electricity storage or other system-integration costs. Consequently, technologies with similar or even lower LCOE values may differ substantially in the total cost imposed on the electricity system once their variability, dispatchability, flexibility requirements and network needs are considered [14–18].

This limitation is particularly important when dispatchable technologies are compared with variable renewable energy sources. Coal-fired, natural-gas-fired and nuclear generation can provide electricity according to system requirements within their technical operating constraints, whereas wind and photovoltaic generation depend on weather conditions. Their electricity production may therefore occur at times when system demand is relatively low or may be insufficient during periods of high demand. As a result, plant-level generation cost does not necessarily represent the full economic consequence of integrating a technology into the electricity system.

An additional element affecting the economic performance of fossil-fuel technologies in the European Union is carbon pricing. Under the European Union Emissions Trading System, electricity generators are required to surrender allowances corresponding to their verified direct greenhouse-gas emissions, with one allowance representing the right to emit one tonne of $CO_2$-equivalent [19,20]. The EU ETS therefore increases the cost of electricity generation from carbon-intensive technologies and changes their relative competitiveness compared with low-carbon generation.

However, the EU ETS component is conceptually different from physical production-cost components, such as fuel consumption, capital expenditure, or operation and maintenance. It represents a policy-induced carbon-pricing mechanism intended to internalize part of the climate-related externality associated with direct emissions. For this reason, carbon pricing should be considered separately when interpreting the economic performance of electricity-generation technologies.

### *2.2. System-Level Cost and Value Assessment*

The limitations of the conventional LCOE have led to the development of broader system-level assessment approaches. These methods distinguish between the cost of producing electricity at the plant level and the additional costs or benefits associated with delivering electricity with the reliability and temporal availability required by the power system.

One such approach is the system levelized cost of electricity. The SLCOE extends the conventional LCOE by incorporating additional system-integration costs associated with the temporal profile of electricity generation, short-term balancing and network infrastructure. These costs are commonly classified as profile costs, balancing costs and grid-related costs [21–24].

Profile costs arise from differences between the temporal pattern of electricity generation and electricity demand. Balancing costs are associated with short-term deviations between forecast and actual generation, while grid-related costs include network connection, reinforcement and transmission requirements. The magnitude of these costs depends on several factors, including the characteristics of the electricity system, the penetration level of a given technology, the geographical distribution of generation capacity and the availability of flexibility resources [21–24].

The importance of these effects is particularly evident for variable renewable energy sources. As the penetration of wind and photovoltaic generation increases, their output may increasingly coincide with periods of high renewable availability but relatively low demand. This can reduce the market value of generated electricity and increase the need for flexibility, electricity storage, demand response, interconnection or dispatchable back-up capacity.

A complementary perspective is provided by the value-adjusted levelized cost of electricity. The VALCOE extends conventional generation-cost analysis by considering the value that electricity from a given technology provides to the power system. The approach accounts for energy value, capacity value and flexibility value. Energy value reflects the temporal coincidence between electricity generation and market prices, capacity value represents the contribution of a technology to system adequacy, and flexibility value describes the ability of a technology to respond to changing system conditions [25].

The VALCOE therefore addresses a different analytical question from the SLCOE. Whereas the SLCOE focuses on additional costs associated with integrating a technology into the electricity system, the VALCOE incorporates the system value of the electricity generated. These indicators should therefore be interpreted as complementary rather than additive.

A further extension of the system-level perspective is the levelized full system cost of electricity. The LFSCOE framework considers the cost of supplying electricity demand when a single generation technology is assigned responsibility for satisfying the temporal demand profile and is complemented by electricity storage or additional generation capacity where required [14].

Unlike the conventional LCOE, which evaluates the cost of electricity generated, the LFSCOE incorporates the effects of generation overcapacity, storage requirements, storage losses and curtailment associated with providing firm electricity supply. This distinction is particularly important for variable renewable technologies, since electricity generation from wind and PV is not fully controllable and may not coincide with the temporal profile of electricity demand.

At the same time, the LFSCOE represents a highly specific system boundary and should not be interpreted as the direct cost of an actual diversified electricity system. Real power systems combine multiple generation technologies, storage options, interconnections, flexible demand and dispatchable capacity. Nevertheless, the framework provides an

additional perspective on the consequences of requiring individual technologies to provide firm electricity supply.

### *2.3. Life-Cycle Assessment and Integrated Evaluation of Electricity Technologies*

Economic performance represents only one dimension of electricity-system sustainability. Electricity-generation technologies are also associated with environmental burdens occurring throughout their entire life cycles. These impacts may arise from raw-material extraction, fuel production, infrastructure manufacturing, construction, operation, maintenance, component replacement, decommissioning, waste treatment and end-of-life processes [15].

Life-cycle assessment provides a structured methodological framework for quantifying these environmental impacts per unit of electricity generated or delivered. Comparative LCA studies demonstrate substantial differences between electricity-generation technologies. Fossil-fuel technologies are generally dominated by environmental burdens associated with fuel extraction and combustion, particularly in the global-warming and fossil-resource categories. By contrast, renewable and nuclear technologies transfer a larger proportion of their environmental impacts to upstream and infrastructure-related processes [15–17].

This distinction is important because low direct or operational greenhouse-gas emissions do not necessarily imply uniformly low environmental impacts throughout the entire life cycle. Renewable technologies may generate relevant burdens associated with material demand, mineral-resource use, toxicity, land occupation and infrastructure manufacturing, while nuclear generation is associated with specific impacts related to the nuclear-fuel cycle and ionizing radiation.

The environmental performance of variable renewable generation may also change when additional system infrastructure is required. Electricity storage is particularly relevant in this context. Battery systems require additional materials and manufacturing processes, and storage losses increase the amount of electricity that must be generated to deliver a given quantity of usable electricity. Therefore, the environmental consequences of providing electricity may differ from those associated with electricity generation considered only at the plant boundary.

Recent research increasingly emphasizes the need to integrate life-cycle assessment with broader energy-system modelling and techno-economic analysis. Such integration enables environmental performance to be evaluated alongside system-level economic and technical requirements and can reveal trade-offs that remain hidden when cost or environmental indicators are considered separately [16,17].

A structured review published in 2025 analysed 448 life-cycle studies of electricity-production technologies and found that approximately 80% focused primarily on environmental impacts, while many studies lacked a broader system-wide perspective and considered individual technologies in isolation rather than their interactions within the electricity system. The authors therefore highlighted the need for more integrated sustainability-assessment frameworks capable of capturing environmental, economic and system-level trade-offs [19].

Accordingly, an important research gap concerns the simultaneous consideration of plant-level generation costs, system-integration costs, electricity-system value, firm-supply requirements and life-cycle environmental performance. While LCOE, SLCOE, VALCOE, LFSCOE and LCA are individually established approaches, they address different analytical questions and are rarely interpreted jointly within a harmonized comparative framework covering both dispatchable and variable electricity-generation technologies.

The present study addresses this gap by combining LCOE, SLCOE, VALCOE, screening-level LFSCOE and LCA in a comparative assessment of coal, natural gas, large-scale nuclear

power, onshore wind and photovoltaic generation. The purpose is not to combine these indicators into a single composite score, but rather to determine how the comparative position of each technology changes depending on whether the assessment focuses on plant-level cost, system integration, electricity-system value, firm-supply requirements or life-cycle environmental impacts.

Figure 1 shows the conceptual frameworks for LCOE, SLCOE, VALCOE and LFSCOE [14,21].

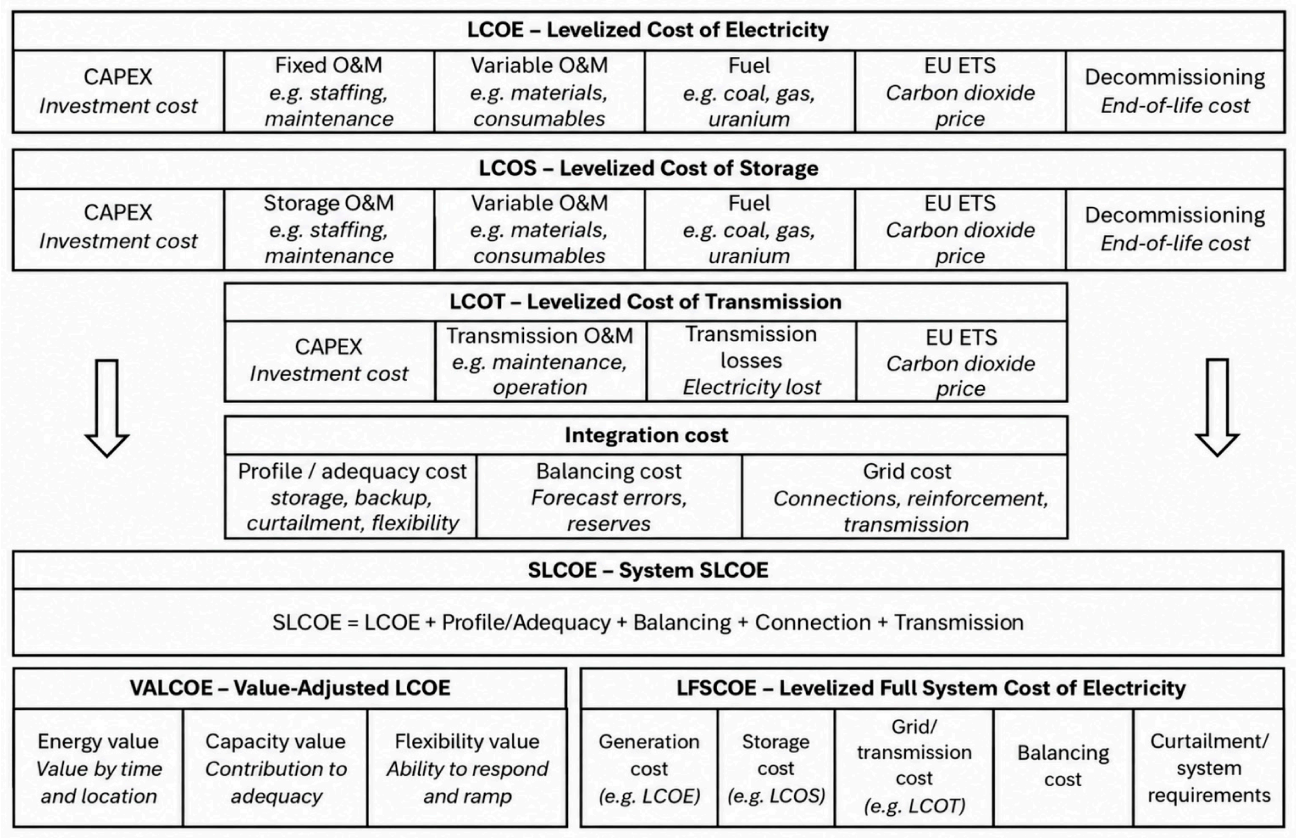



**Figure 1.** Conceptual frameworks for LCOE, SLCOE, VALCOE and LFSCOE.

### *2.4. Novelty*

The central research question addressed in this study is: how does the comparative performance of major electricity-generation technologies change when plant-level cost, system-integration effects, electricity-system value, firm-supply requirements and life-cycle environmental impacts are evaluated jointly rather than separately?

The novelty of the study lies not only in demonstrating that technology rankings vary across individual indicators, but in identifying how technological advantages and disadvantages shift between assessment dimensions. In particular, the integrated framework makes it possible to distinguish whether an apparent advantage at the plant level is retained, reduced or transferred into system-level costs, firm-supply requirements or environmental burdens. This provides a more complete interpretation of technology trade-offs than approaches based on a single economic or environmental metric. The geographical context of the analysis is primarily European, with particular relevance to Poland. Economic assumptions were harmonized to European market conditions, while selected system-level parameters were derived from the international literature and OECD/NEA frameworks. The analysis does not constitute a full optimization of the Polish electricity system. In particular, the LFSCOE assessment is screening-level rather than a Poland-specific 8760 h optimization,

and the SLCOE results are conditional on the adopted penetration assumptions. These limitations define the scope within which the results should be interpreted.

## 3. Materials and Methods

The levelized cost of electricity (LCOE) was used as the baseline economic indicator for comparing the electricity generation costs of the five technologies considered in this study: coal-fired power generation, natural-gas-fired combined-cycle generation, large-scale nuclear power, wind power, and photovoltaic (PV). The LCOE represents the discounted lifetime cost of an electricity-generating technology per unit of electricity generated over its economic lifetime [18].

The calculation was based on the discounted cash-flow approach adopted by the International Energy Agency (IEA) and the OECD Nuclear Energy Agency (NEA) in Projected Costs of Generating Electricity 2020 (NEA and IEA, 2020) [22,23].

The original IEA/NEA formulation accounts for capital expenditure, operation and maintenance costs, fuel costs, carbon costs, and decommissioning and waste-management costs. In the present study, operation and maintenance costs were further separated into fixed and variable components to allow a more transparent comparison of technologies with different cost structures [23].

For each technology (i), the LCOE was calculated according to

$$\mathrm{LCOE_i} = \frac{\sum_{t=0}^{n_i} \frac{I_{i,t} + FOM_{i,t} + VOM_{i,t} + F_{i,t} + C_{CO_2,i,t} + D_{i,t}}{(1+r_i)^t}}{\sum_{t=0}^{n_i} \frac{E_{i,t}}{(1+r_i)^t}} \quad (1)$$

where

$I_{i,t}$—capital expenditure (CAPEX) incurred for technology (i) in year (t) [EUR];
$FOM_{i,t}$—fixed operation and maintenance costs in year (t) [EUR/year];
$VOM_{i,t}$—variable operation and maintenance costs in year (t) [EUR/year];
$F_{i,t}$—fuel costs in year (t) [EUR/year];
$C_{CO_2,i,t}$—cost associated with direct $CO_2$ emissions in year (t) [EUR/year];
$D_{i,t}$—decommissioning and, where applicable, waste-management costs [EUR];
$E_{i,t}$—net electricity generated by technology (i) in year (t) [MWh];
$r_i$—real discount rate, represented in this study by the weighted average cost of capital (WACC) [-];
$n_i$—economic lifetime of technology (i) [years];
t—year of the analysis.

The LCOE indicates only the cost of producing a unit of electricity using a given technology. It does not include grid-related or system-integration costs. The IEA defines the LCOE as a plant-level generation-cost metric that excludes network integration and other indirect system costs. Therefore, an additional assessment is required to determine the cost of stabilization and system integration.

The system levelized cost of electricity (SLCOE) was used to extend the conventional LCOE by including the additional costs associated with the integration of a given generation technology into the electricity system. While the LCOE reflects the plant-level cost of electricity generation, the SLCOE accounts for system-level effects related to the temporal profile of generation, short-term balancing requirements and grid infrastructure.

For each technology *i*, the SLCOE was calculated as

$$\mathrm{SLCOE_i} = \mathrm{LCOE_i} + C_{INT,i} \quad (2)$$

where

$C_{INT,i}$—total system-integration cost associated with technology *i* [EUR/MWh].

The total integration cost was further decomposed into profile, balancing and grid-related components [24]:

$$C_{INT,i} = C_{PROFILE,i} + C_{BAL,i} + C_{GRID,i} \quad (3)$$

Therefore,

$$SLCOE_i = LCOE_i + C_{PROFILE,i} + C_{BAL,i} + C_{GRID,i} \quad (4)$$

where

$C_{PROFILE,i}$—profile cost associated with the mismatch between the temporal pattern of electricity generation and electricity demand [EUR/MWh];

$C_{BAL,i}$—balancing cost associated with short-term deviations between forecast and actual generation [EUR/MWh];

$C_{GRID,i}$—grid-related cost associated with network connection, reinforcement and transmission requirements [EUR/MWh].

In the present study, grid-related costs were further separated into connection and transmission components:

$$C_{GRID,i} = C_{CONN,i} + LCOT_i \quad (5)$$

Thus, the final formulation applied in the analysis was

$$SLCOE_i = LCOE_i + C_{PROFILE,i} + C_{BAL,i} + C_{CONN,i} + LCOT_i \quad (6)$$

where

$C_{CONN,i}$—levelized grid-connection cost [EUR/MWh];

$LCOT_i$—levelized cost of transmission [EUR/MWh].

The SLCOE framework enables a more comprehensive comparison of electricity generation technologies than the conventional LCOE because it accounts for differences in variability, dispatchability, balancing requirements and network needs. These additional costs are particularly relevant for variable renewable energy sources, such as wind and photovoltaic generation, for which the electricity output is weather-dependent and may not coincide with the temporal profile of electricity demand.

In this study, the system-integration cost components were based on the OECD/NEA system-cost framework, which distinguishes profile costs, balancing costs and grid-related costs as the principal categories of system costs associated with electricity generation technologies. The resulting SLCOE therefore represents the plant-level generation cost augmented by the additional costs required for the integration of each technology into the electricity system.

The value-adjusted levelized cost of electricity (VALCOE) was used to extend the conventional LCOE assessment by incorporating the value that each generation technology provides to the electricity system. The methodology follows the approach developed by the International Energy Agency (IEA), in which the LCOE is adjusted according to three system-value components: energy value, capacity value and flexibility value.

The energy value reflects the temporal coincidence between electricity generation and wholesale electricity prices. Technologies generating electricity predominantly during high-price periods receive a higher energy value, whereas generation concentrated during periods of low electricity prices receives a lower value. The capacity value represents the contribution of a technology to system adequacy and its ability to provide reliable capacity during periods of high demand. The flexibility value reflects the ability of a technology to respond to changes in electricity demand and system conditions [25].

In the present study, technology-specific LCOE values calculated within the economic model were combined with value adjustments derived from the IEA framework. The

adjustments were converted to EUR/MWh using the same exchange-rate assumption as in the LCOE assessment. The VALCOE was treated as an alternative measure of technology competitiveness and was not added to the system LCOE, since the two indicators represent different perspectives on power-system performance.

The levelized full system cost of electricity (LFSCOE) was used to assess the cost of supplying electricity demand when a single generation technology assumes full responsibility for meeting the temporal demand profile.

Unlike the conventional LCOE, which considers only the cost of electricity generated, the LFSCOE incorporates the additional generation capacity, storage capacity, storage losses and curtailment required to ensure that electricity demand is satisfied continuously.

In the full LFSCOE framework, electricity generation and demand are evaluated on an hourly basis over 8760 h. Hourly generation is determined from installed capacity and the corresponding hourly capacity factor. For dispatchable technologies, generation is constrained by available plant capacity, whereas solar PV and wind generation follow technology-specific hourly availability profiles.

For variable renewable technologies, surplus electricity may be directed to storage, while stored electricity is discharged during periods in which generation is insufficient to meet demand. Storage operation therefore accounts for charging and discharging efficiency, storage-energy capacity, storage-power capacity and the evolution of the state of charge. Electricity that can neither be directly consumed nor stored is classified as curtailed generation.

Within the full LFSCOE framework, generation and storage capacities are selected so that the complete electricity-demand profile can be supplied. The resulting LFSCOE is defined as the discounted lifetime cost of the complete generation and storage system divided by the discounted amount of electricity demand served.

The full-system cost numerator includes generation investment costs, fixed and variable operation and maintenance costs, fuel costs where applicable, carbon costs for fossil-fuel technologies, decommissioning costs, storage investment and operating costs, storage replacement where required and relevant transmission and system-related costs. Storage losses and renewable-energy curtailment are reflected through the additional generation and storage capacity required to satisfy electricity demand.

The LFSCOE therefore represents the cost of providing firm electricity rather than merely producing electricity. This distinction is particularly important for variable renewable technologies because the conventional LCOE does not account for the additional infrastructure required to match electricity generation with demand.

However, a Poland-specific 8760 h optimization was not performed in the present study. For the numerical comparison reported here, the LFSCOE was implemented as a screening-level estimate using the German benchmark reported within the Idel framework. For each technology, the full-system premium, defined as the difference between the benchmark LFSCOE and benchmark LCOE, was transferred to the technology-specific LCOE calculated in the present study after currency conversion. Negative benchmark premiums were not transferred.

Accordingly, the reported LFSCOE values should be interpreted as screening-level indicators illustrating the potential effect of firm-supply requirements rather than as results of an hourly simulation or optimization of the Polish electricity system.

### *3.1. Life-Cycle Assessment (LCA)*

The environmental assessment was performed using the life-cycle assessment (LCA) methodology in accordance with ISO 14040 and ISO 14044 [26,27]. The models were

developed in SimaPro desktop version 10.5 using the ecoinvent 3.12 database and the allocation cut-off by classification system model [28,29].

The analysed technologies included coal-fired power generation, natural-gas-fired combined-cycle generation, large-scale nuclear power, onshore wind power and photovoltaic. Where available, geographically representative datasets for European were selected [30].

A cradle-to-grave system boundary was applied, including raw-material extraction, fuel-cycle processes where applicable, manufacturing and construction of generation infrastructure, operation and maintenance, direct emissions, component replacement, decommissioning, waste treatment and end-of-life processes.

Life-cycle impact assessment was performed using the ReCiPe 2016 Midpoint method with the Hierarchist perspective—ReCiPe 2016 Midpoint (H). All 18 midpoint-impact categories were evaluated, including global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, fine particulate matter formation, terrestrial acidification, freshwater and marine eutrophication, terrestrial, freshwater and marine ecotoxicity, human toxicity, land use, mineral and fossil resource scarcity, and water consumption. The functional unit (FU) is 1 MWh [31,32].

The primary results are reported separately for each impact category. Technology-specific lifetime, capacity factor and electricity-output assumptions were harmonized with those used in the economic analysis to ensure consistency between the LCOE and LCA.

EU ETS costs were treated exclusively as an economic parameter and were not included as environmental flows in the LCA. Instead, physical greenhouse-gas emissions from the entire life cycle of each technology were quantified directly within the inventory and assessed in the global-warming impact category [33].

In addition to the conventional generation-only LCA, a storage-adjusted sensitivity scenario was evaluated for PV and wind. A lithium iron phosphate ($LiFePO_4$) battery energy storage system (BESS) with an energy capacity of 1 MWh was assumed per 1 MWh of electricity delivered. The BESS was assumed to operate at one full equivalent cycle per day over a 15-year lifetime, corresponding to a total lifetime energy throughput of 5475 MWh per 1 MWh of installed battery capacity. A round-trip efficiency of 85% was assumed. Consequently, 1.176 MWh of electricity generation was required to deliver 1 MWh after storage losses. The environmental burden associated with battery production was amortized over the total lifetime energy throughput of the BESS and allocated to the functional unit of 1 MWh of electricity delivered. This scenario is intended to illustrate the direction and magnitude of environmental burden shifting caused by storage and should be interpreted as a storage-adjusted sensitivity case rather than as an optimized 8760 h BESS-sizing model [34–36].

A distinction was made between the functional basis of the generation-only and storage-adjusted scenarios. For coal, natural gas, nuclear, onshore wind and PV without storage, the environmental results are expressed per 1 MWh of electricity generated. In the storage-adjusted PV + BESS and wind + BESS sensitivity scenarios, the results are expressed per 1 MWh of electricity delivered after storage, including the additional electricity generation required to compensate for round-trip storage losses.

Accordingly, the generation-only and storage-adjusted results do not represent strictly identical electricity services. The former characterize the environmental burdens of electricity generation at the technology level, whereas the latter additionally include the storage function and associated conversion losses. Comparisons involving the BESS scenarios should therefore be interpreted as sensitivity analyses illustrating the additional life-cycle burden associated with storage rather than as direct like-for-like comparisons of functionally equivalent electricity supply.

### *3.2. Operational and Technology-Specific Assumptions*

For all the analysed scenarios, a weighted average cost of capital (WACC) of 7% was assumed. All monetary values originally expressed in US dollars were converted to euros using an exchange rate of 1 USD = 0.8592 EUR. The EU Emissions Trading System (EU ETS) allowance price was assumed to be 75.99 EUR/$tCO_2$ [37].

The cost parameters were harmonized to represent average European market conditions. Where technology-specific values were not available for Poland, European-average assumptions were applied, including labour, materials, operation and maintenance, and other relevant cost components. This approach was adopted to ensure consistency and comparability across the analysed electricity-generation technologies [38].

For the assessment of profile and adequacy costs, literature-based values reported by the OECD Nuclear Energy Agency were adopted. The analysis considered a 30% penetration level, defined as the share of electricity generated by a given technology in the total electricity system. Under this scenario, the profile/adequacy cost amounted to 0.33 USD/MWh for coal-fired generation, while no additional profile/adequacy costs were reported for nuclear and gas-fired generation. In contrast, substantially higher values were observed for variable renewable energy sources, reaching 36.48 USD/MWh for onshore wind and 48.16 USD/MWh for solar PV. These higher costs reflect the temporal mismatch between weather-dependent electricity generation and electricity demand and the resulting requirement for dispatchable back-up capacity or other flexibility resources during periods of insufficient renewable generation. The values are system- and penetration-dependent and should therefore not be interpreted as intrinsic characteristics of individual technologies (OECD/NEA, 2024, Table 1; adapted from NEA, 2012) [39].

To improve the transparency of the technology-specific assumptions applied in the analysis, Table 1 summarizes the principal operational, economic and LCA characteristics of the five electricity-generation technologies considered in this study. The table distinguishes between technology-specific assumptions and methodological parameters applied consistently across all technologies.

The parameters common to all technologies included a WACC of 7%, an exchange rate of 1 USD = 0.8592 EUR and an EU ETS allowance price of 75.99 EUR/$tCO_2$. The cost parameters were harmonized to represent average European market conditions. Where Poland-specific technology data were unavailable, European-average assumptions were applied to maintain methodological consistency across the analysed technologies.

The 30% penetration case derived from the OECD/NEA French-system analysis was adopted as a common reference scenario because it provides a technology-consistent set of system-cost estimates under the same methodological framework. The purpose of using this benchmark was not to reproduce the Polish electricity system, but to provide a harmonized comparative basis for evaluating the relative magnitude of profile, balancing and grid-related effects across the analysed technologies. The 30% penetration level represents an intermediate system-integration case and was therefore used as a standardized reference point rather than as a country-specific forecast.

Because these values originate from the French electricity system, they should be interpreted as scenario-dependent reference parameters. Their absolute magnitude may differ under Polish conditions owing to differences in generation mix, demand patterns, interconnection, grid topology and available flexibility. Accordingly, the resulting SLCOE values are used for comparative purposes and should not be interpreted as intrinsic or geographically universal technology costs.

**Table 1.** Summary of technology-specific operational, economic and LCA assumptions used in the analysis [36].

| Parameter | Coal | Natural Gas | Nuclear | Onshore Wind | PV |
|---|---|---|---|---|---|
| Generation type | Dispatchable | Dispatchable | Dispatchable | Variable renewable | Variable renewable |
| Fuel requirement | Coal | Natural gas | Nuclear fuel | None during operation | None during operation |
| Direct operational $CO_2$ emissions subject to EU ETS | Yes | Yes | No | No | No |
| EU ETS cost included in economic assessment | Yes | Yes | No | No | No |
| Profile/adequacy cost at 30% penetration | 0.33 USD/MWh | 0 USD/MWh | 0 USD/MWh | 36.48 USD/MWh | 48.16 USD/MWh |
| LCA system boundary | Cradle-to-grave | Cradle-to-grave | Cradle-to-grave | Cradle-to-grave | Cradle-to-grave |
| Functional unit | 1 MWh | 1 MWh | 1 MWh | 1 MWh | 1 MWh |
| LCIA method | ReCiPe 2016 Midpoint (H) | ReCiPe 2016 Midpoint (H) | ReCiPe 2016 Midpoint (H) | ReCiPe 2016 Midpoint (H) | ReCiPe 2016 Midpoint (H) |
| LCA database | ecoinvent 3.12 | ecoinvent 3.12 | ecoinvent 3.12 | ecoinvent 3.12 | ecoinvent 3.12 |
| Direct combustion emissions included in LCA | Yes | Yes | No combustion emissions | No | No |
| Fuel-cycle processes included | Yes | Yes | Yes | Not applicable | Not applicable |
| Generation infrastructure included | Yes | Yes | Yes | Yes | Yes |
| Decommissioning/end-of-life included | Yes | Yes | Yes | Yes | Yes |
| BESS sensitivity scenario | No | No | No | Yes | Yes |
| BESS technology | – | – | – | $LiFePO_4$ | $LiFePO_4$ |
| BESS lifetime | – | – | – | 15 years | 15 years |
| BESS round-trip efficiency | – | – | – | 85% | 85% |

To enhance the transparency and reproducibility of the system-level economic assessment, Table 2 summarizes the technology-specific integration costs applied in the SLCOE calculations, together with the German benchmark values and corresponding premiums used to estimate the LFSCOE. The table provides a consolidated overview of the assumptions underlying both indicators and facilitates the interpretation of the differences between plant-level generation costs and system-level costs.

Table 2 summarizes the system-integration costs and full-system premiums applied in the economic assessment. The SLCOE calculations were based on the OECD/NEA framework, using a common 30% technology penetration scenario. The total integration cost comprises profile/adequacy, balancing, connection and transmission costs. Profile costs were derived from the OECD/NEA benchmark and converted into EUR/MWh, while the remaining integration costs are presented in aggregate form.

The LFSCOE assessment was implemented as a screening-level approach based on the German benchmark reported by Idel (2022) [14]. Technology-specific full-system premiums were defined as the difference between the German benchmark LFSCOE and LCOE and subsequently converted into EUR/MWh before being added to the LCOE calculated in this study.

Negative benchmark premiums were excluded by applying a zero lower bound. This assumption was adopted because the screening approach was intended to illustrate potential additional costs associated with firm electricity supply, rather than to transfer technology-specific cost advantages from a different electricity system. Consequently, negative premiums were set to zero to avoid introducing cost reductions that could not be independently verified under the adopted system conditions. This simplification should be considered when interpreting the resulting LFSCOE values.

**Table 2.** System-integration costs and screening-level full-system premiums applied in the SLCOE and LFSCOE calculations.

| Technology | Profile Cost | Other Integration Costs * | Total Integration Cost | SLCOE | LFSCOE Premium | LFSCOE |
|---|---|---|---|---|---|---|
| Coal | 0.28 | 0.81 | 1.09 | 142.09 | 1.72 | 142.72 |
| Natural gas | 0 | 0.46 | 0.46 | 104.3 | 0 | 103.84 |
| Nuclear | 0 | 1.76 | 1.76 | 74.83 | 19.76 | 92.83 |
| Onshore wind | 31.34 | 13.27 | 44.61 | 90.96 | 380.63 | 426.98 |
| PV | 41.38 | 25.79 | 67.17 | 124.37 | 1154.78 | 1211.98 |

All values in EUR/MWh. * Other integration costs represent the combined balancing, connection and transmission costs, reconstructed as SLCOE–LCOE−profile cost. Profile costs are converted from USD using 1 USD = 0.8592 EUR.

To further improve the reproducibility of the economic assessment, the principal technology-specific input assumptions used in the LCOE calculations are summarized in Table 3. These parameters represent the direct model inputs rather than the resulting levelized cost contributions reported later in Section 4.

**Table 3.** Main economic and operational input assumptions used in the LCOE calculations.

| Parameter | Coal | Natural Gas CCGT | Large Nuclear | Onshore Wind | PV |
|---|---|---|---|---|---|
| Plant capacity [MW] | 650 | 1227 | 1000 | 200 | 75.8 |
| Economic lifetime [years] | 40 | 30 | 60 | 30 | 30 |
| Capacity factor [-] | 0.85 | 0.85 | 0.93 | 0.43 | 0.25 |
| Investment cost [EUR/kW] | 3525.34 | 745.79 | 4940.46 | 1690.93 | 1280.22 |
| Fixed O&M [EUR/kW-year] | 52.93 | 10.41 | 150.36 | 36.95 | 21.19 |
| Variable O&M [EUR/MWh] | 5.5 | 2.93 | 2.41 | 0 | 0 |
| Fuel cost [EUR/MWh] | 31.48 | 66.11 | 8.85 | 0 | 0 |
| Direct operational $CO_2$ emission factor [t $CO_2$/MWh] | 0.807 | 0.333 | 0 | 0 | 0 |
| Decommissioning cost basis [EUR/kW] | 106 | 43 | 1074.01 | 128.88 | 85.92 |

The values in Table 3 were used directly in the discounted cash-flow model described above. The direct $CO_2$ emission factors reported for coal and natural gas refer exclusively to operational emissions used to calculate the EU ETS component of the LCOE and should not be confused with the life-cycle greenhouse-gas emission factors used in the LCA. A common real WACC of 7%, the exchange rate of 1 USD = 0.8592 EUR and the EU ETS allowance price of 75.99 EUR/t$CO_2$ were applied consistently as described above.

For the VALCOE assessment, technology-specific value adjustments were derived from the European Union benchmark reported within the IEA framework. The benchmark combines the effects of energy value, capacity value and flexibility value into an aggregate

technology-specific adjustment. The values applied in the present study are summarized in Table 4.

**Table 4.** Technology-specific value adjustments used in the VALCOE calculation.

| Technology | IEA Benchmark LCOE 2040 [USD/MWh] | IEA Benchmark VALCOE 2040 [USD/MWh] | Value Adjustment [USD/MWh] | Value Adjustment [EUR/MWh] | Study LCOE [EUR/MWh] | Calculated VALCOE [EUR/MWh] |
|---|---|---|---|---|---|---|
| Coal | 150 | 125 | −25 | −21.48 | 141 | 119.52 |
| Natural gas | 110 | 75 | −35 | −30.07 | 103.84 | 73.77 |
| Large nuclear | 110 | 115 | 5 | 4.3 | 73.07 | 77.37 |
| Onshore wind | 65 | 80 | 15 | 12.89 | 46.35 | 59.23 |
| PV | 50 | 80 | 30 | 25.78 | 57.2 | 82.98 |

The VALCOE adjustment was calculated as the difference between the technology-specific benchmark VALCOE and LCOE values:

$$\text{Value adjustment} = \text{IEA VALCOE} - \text{IEA LCOE}$$

The resulting adjustment was converted from USD/MWh to EUR/MWh using the same exchange-rate assumption applied throughout the economic analysis and was subsequently added to the LCOE calculated in the present study. The IEA benchmark reports the aggregate technology-specific value adjustment but does not provide a separate numerical decomposition into energy, capacity and flexibility components for each technology. Therefore, no additional numerical decomposition of these three components was introduced in the present analysis.

The assumptions summarized in this section constitute the input dataset used for the subsequent LCOE, SLCOE and VALCOE calculations presented in Section 4.

A methodological limitation of the present study concerns the reproducibility of the original LCA inventory at the individual database-process level. The LCA calculations were performed some time ago using a licensed SimaPro environment, and the original software access is no longer available. Consequently, the complete list of individual ecoinvent processes used in the original model cannot be reconstructed with sufficient certainty from the retained manuscript outputs alone.

A further limitation concerns the storage-adjusted sensitivity scenario. Although the analysis retained the main battery assumptions, including $LiFePO_4$ chemistry, a 15-year lifetime and an 85% round-trip efficiency, the battery representation was based on simplified assumptions and does not constitute a fully parameterized storage model with complete process-level documentation. Accordingly, the BESS results should be interpreted as indicative sensitivity results illustrating the direction of life-cycle burden shifting rather than as a fully reproducible stand-alone battery-system LCA.

## 4. Results

The results are presented in two complementary dimensions. First, the life-cycle assessment compares the environmental burdens of the technologies per 1 MWh, including a storage-adjusted sensitivity case for PV and wind. Second, the techno-economic results show how the ranking of technologies changes when the assessment progresses from plant-level LCOE to system integration, value adjustment and firm-supply screening.

Table 5 presents the life-cycle environmental impacts of the analysed technologies using two explicitly distinguished functional bases: 1 MWh of electricity generated for the

generation-only scenarios and 1 MWh of electricity delivered after storage for the PV + BESS and wind + BESS sensitivity scenarios.

**Table 5.** Life-cycle environmental impacts for the analysed electricity-generation technologies. Generation-only results are expressed per 1 MWh of electricity generated, whereas the PV + BESS and wind + BESS sensitivity scenarios are expressed per 1 MWh of electricity delivered after storage.

| Impact Category | 1 MWh | Coal | PV + BESS | Wind + BESS | PV | Wind | Nuclear | Gas |
|---|---|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | 1140 | 90.02 | 43.08 | 65.7 | 25.8 | 16.2 | 684 |
| Fine particulate matter formation | kg $PM_{2.5}$ eq | 1.81 | 0.195 | 0.0735 | 0.159 | 0.0553 | 0.0477 | 0.561 |
| Fossil resource scarcity | kg oil eq | 226 | 22.47 | 10.41 | 16.7 | 6.45 | 4.04 | 260 |
| Freshwater ecotoxicity | kg 1,4-DCB | 12.9 | 20.59 | 22.94 | 17.5 | 19.5 | 1.17 | 1.93 |
| Freshwater eutrophication | kg P eq | 0.416 | 0.0651 | 0.0189 | 0.0548 | 0.0155 | 0.00611 | 0.0286 |
| Human carcinogenic toxicity | kg 1,4-DCB | 26 | 7.13 | 9.97 | 6.06 | 8.47 | 2.22 | 3.94 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 391 | 291.45 | 102.39 | 247 | 86.3 | 31 | 52 |
| Ionizing radiation | kBq Co-60 eq | 8.25 | 12.04 | 2.24 | 10.2 | 1.87 | 1170 | 12.3 |
| Land use | $m^2$a crop eq | 5.79 | 1.42 | 2.04 | 0.39 | 0.912 | 0.147 | 0.268 |
| Marine ecotoxicity | kg 1,4-DCB | 18 | 27.06 | 28.12 | 23 | 23.9 | 1.72 | 2.86 |
| Marine eutrophication | kg N eq | 0.0445 | 0.0631 | 0.0127 | 0.0534 | 0.0106 | 0.00814 | 0.0176 |
| Mineral resource scarcity | kg Cu eq | 0.375 | 1.99 | 2.12 | 1.37 | 1.48 | 0.884 | 0.444 |
| Ozone formation–Human health | kg $NO_x$ eq | 2.2 | 0.246 | 0.13 | 0.174 | 0.0758 | 0.0505 | 1.03 |
| Ozone formation–Terrestrial ecosystems | kg $NO_x$ eq | 2.2 | 0.254 | 0.134 | 0.181 | 0.0788 | 0.0515 | 1.08 |
| Stratospheric ozone depletion | kg CFC-11 eq | $2.77 \times 10^{-4}$ | $4.57 \times 10^{-5}$ | $1.57 \times 10^{-5}$ | $3.63 \times 10^{-5}$ | $1.08 \times 10^{-5}$ | $4.13 \times 10^{-5}$ | $3.26 \times 10^{-5}$ |
| Terrestrial acidification | kg $SO_2$ eq | 5.29 | 0.538 | 0.203 | 0.404 | 0.119 | 0.0808 | 1.67 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 325 | 1683.31 | 288.01 | 1430 | 244 | 324 | 113 |
| Water consumption | $m^3$ | 1.88 | 20.29 | 18.51 | 1.84 | 0.329 | 3.13 | 1.05 |

Table 5 shows marked differences in both the magnitude and structure of life-cycle impacts. For global warming, coal exhibited the highest impact (1140 kg $CO_2$-eq/MWh), followed by natural gas (684 kg $CO_2$-eq/MWh), while PV, wind and nuclear reached 65.7, 25.8 and 16.2 kg $CO_2$-eq/MWh, respectively. When a BESS was included, the global-warming impact increased to 90.02 kg $CO_2$-eq/MWh for PV and 43.08 kg $CO_2$-eq/MWh for wind. Storage also increased several non-climate impacts: PV + BESS reached 20.29 m3/MWh of water consumption and 1683.31 kg 1,4-DCB/MWh for terrestrial ecotoxicity. Nuclear power showed a distinctive profile, with the lowest or near-lowest results in many categories but a substantially higher ionizing-radiation indicator (1170 kBq Co-60 eq/MWh). The results therefore demonstrate that a low carbon footprint does not imply uniformly low impacts across all ReCiPe categories.

Figure 2 shows the relative contribution of the analysed technologies to ReCiPe 2016 midpoint impacts for the conventional generation-only LCA scenario (1 MWh generated).

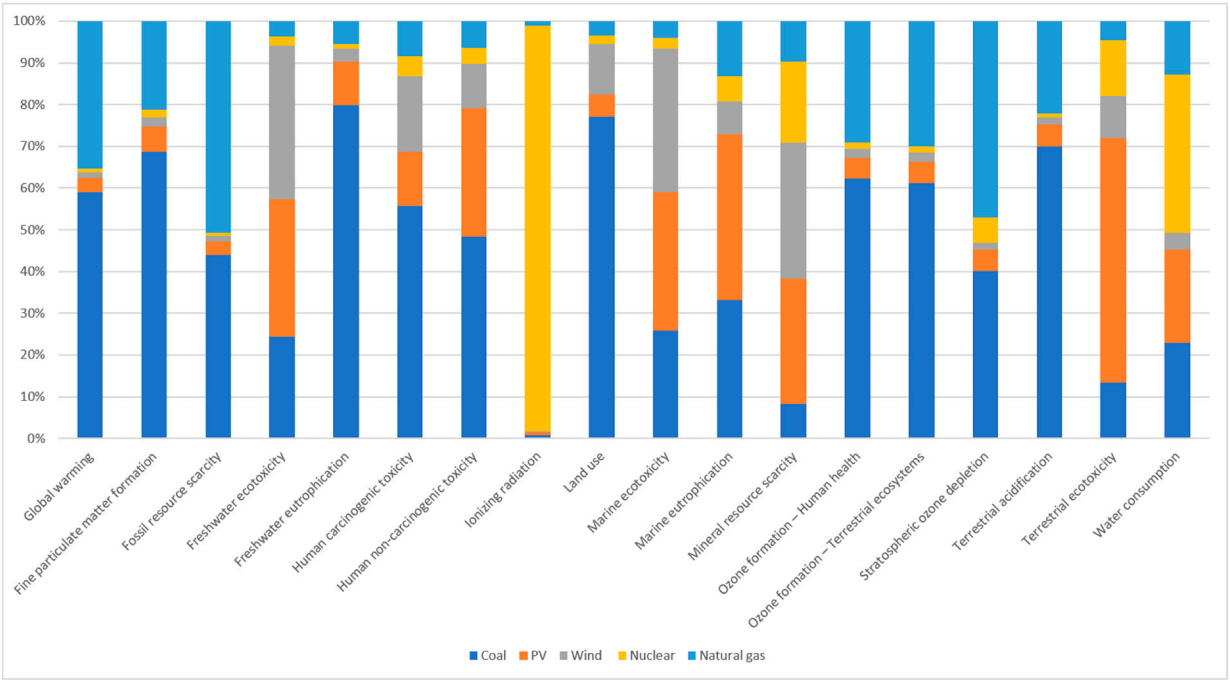



**Figure 2.** Relative contribution of the analysed technologies to ReCiPe 2016 midpoint impacts for the conventional generation-only LCA scenario (1 MWh generated).

The percentage contribution of each technology was calculated by dividing its environmental impact score in a given ReCiPe midpoint category by the sum of the corresponding scores for all technologies included in the comparison and multiplying the result by 100. These percentages represent relative contributions within the analysed set of technologies and should not be interpreted as the actual electricity generation mix or the contribution of individual technologies to the environmental impacts of a real electricity system.

Figure 3 shows the relative contribution to ReCiPe 2016 midpoint impacts for the storage-adjusted scenario, including BESSs for PV and wind (1 MWh delivered in the storage-adjusted sensitivity case).

The percentage contributions were calculated using the same approach as in Figure 2, with the inclusion of the storage-adjusted PV + BESS and wind + BESS scenarios. Each percentage represents the relative contribution of a given technology or scenario to the sum of the environmental impact scores within a specific ReCiPe category. These values are intended exclusively for comparative visualization and do not represent an actual electricity generation mix or a modelled electricity supply system.

Figure 4 shows the LCOE cost-component breakdown including the EU ETS carbon cost for coal and natural gas.

Figure 4 shows that inclusion of the EU ETS materially changes the plant-level cost ranking of fossil-fuel technologies. The calculated LCOE reaches 141.00 EUR/MWh for coal and 103.84 EUR/MWh for natural gas, compared with 73.07 EUR/MWh for nuclear, 57.20 EUR/MWh for PV and 46.35 EUR/MWh for wind. The EU ETS component alone accounts for 61.33 EUR/MWh for coal and 25.27 EUR/MWh for gas, making carbon pricing one of the dominant cost components for fossil-fuel generation in the analysed European-market scenario.

Figure 5 shows the LCOE cost-component breakdown excluding the EU ETS carbon cost.

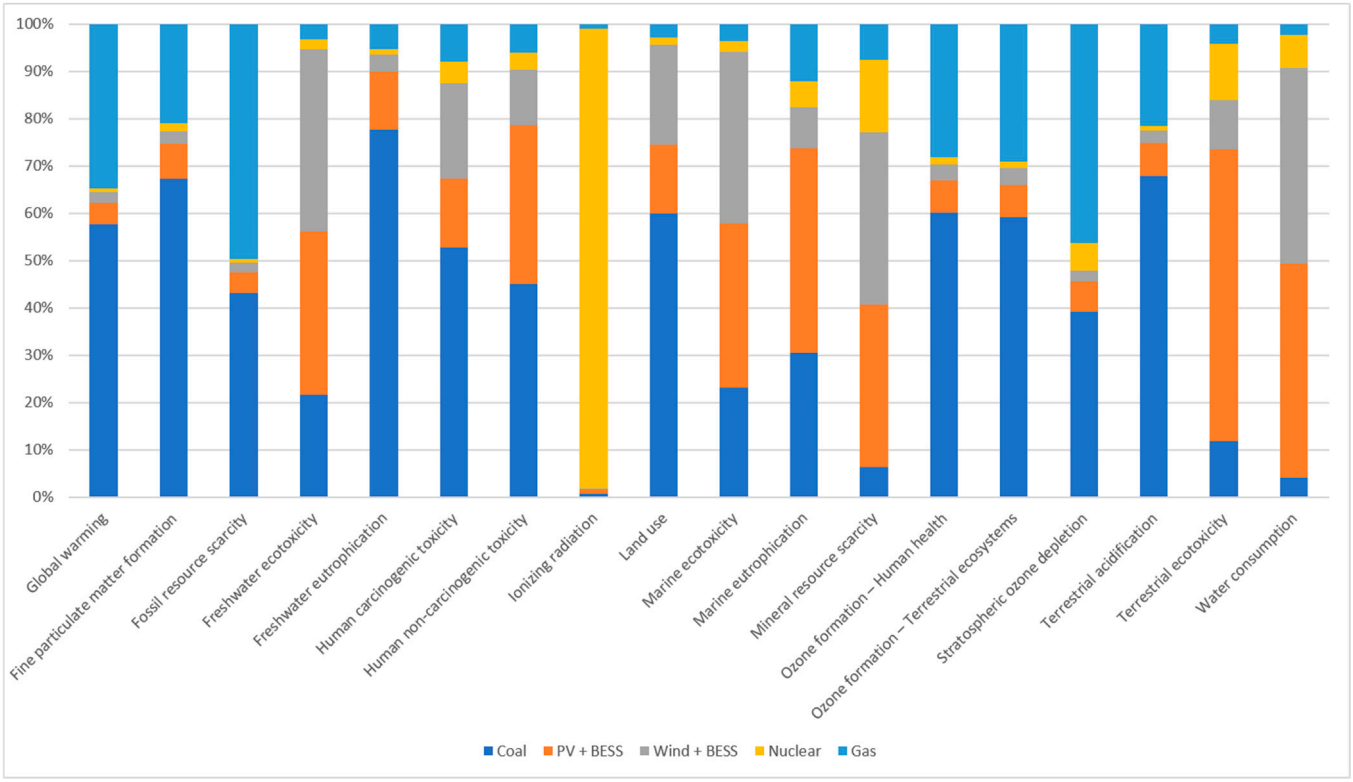



**Figure 3.** Relative contribution to ReCiPe 2016 midpoint impacts for the storage-adjusted scenario, including BESSs for PV and wind (1 MWh delivered in the storage-adjusted sensitivity case).

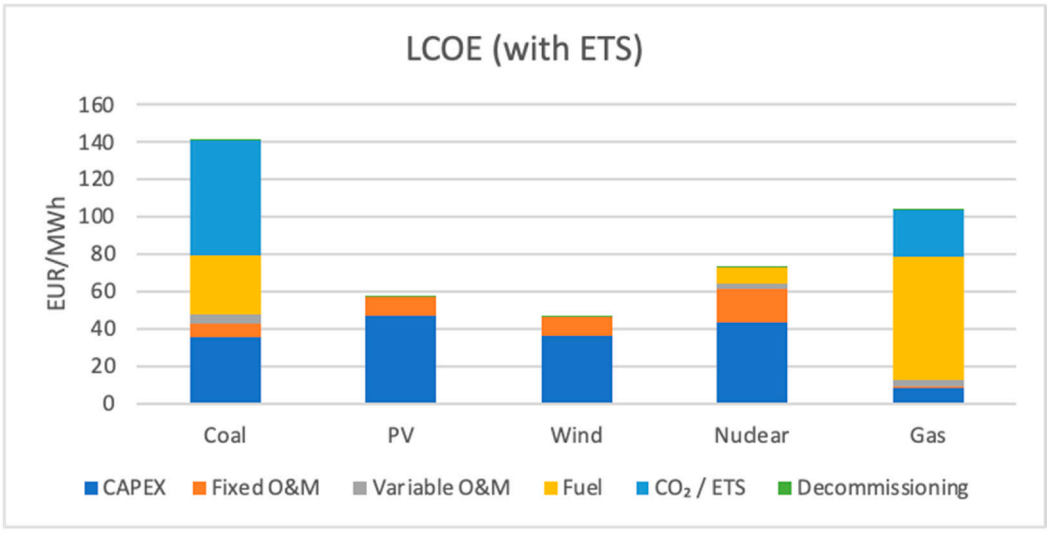



**Figure 4.** LCOE cost-component breakdown including the EU ETS carbon cost for coal and natural gas.

Figure 5 isolates the effect of carbon pricing by setting the EU ETS component to zero. The resulting LCOE falls to approximately 79.67 EUR/MWh for coal and 78.57 EUR/MWh for natural gas, while the LCOE of PV, wind and nuclear is unchanged because no direct operational EU ETS charge was assigned to these technologies. The comparison demonstrates that a substantial part of the cost disadvantage of coal and gas in the base case arises from the monetization of direct $CO_2$ emissions rather than from CAPEX and O&M alone.

Figure 6 shows a comparison of the LCOE, SLCOE and VALCOE with and without the EU ETS component.

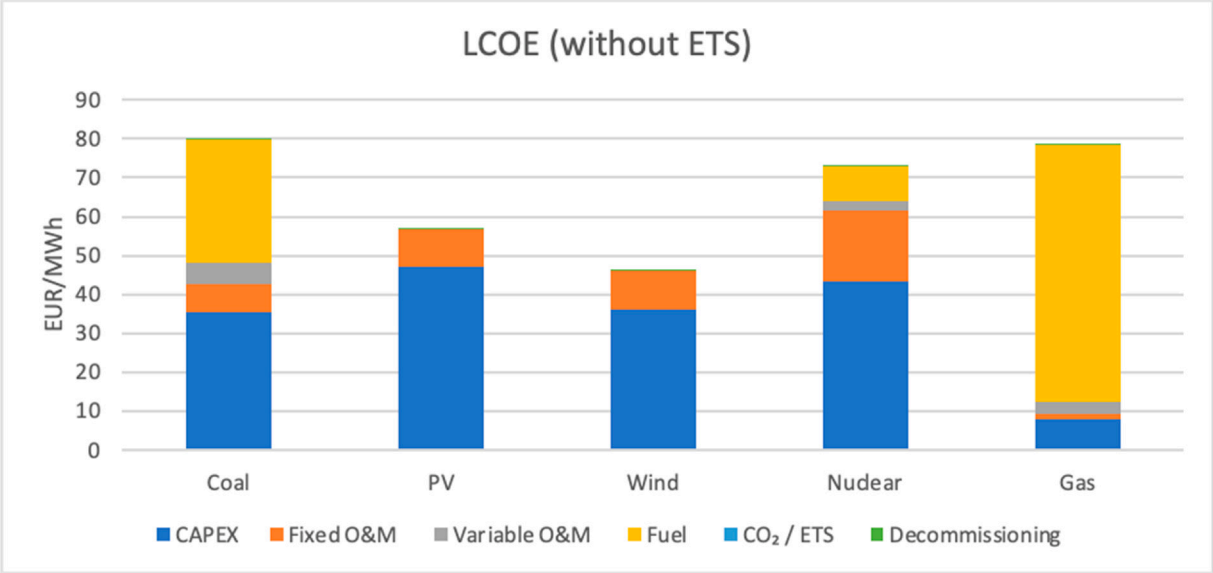



**Figure 5.** LCOE cost-component breakdown excluding the EU ETS carbon cost.

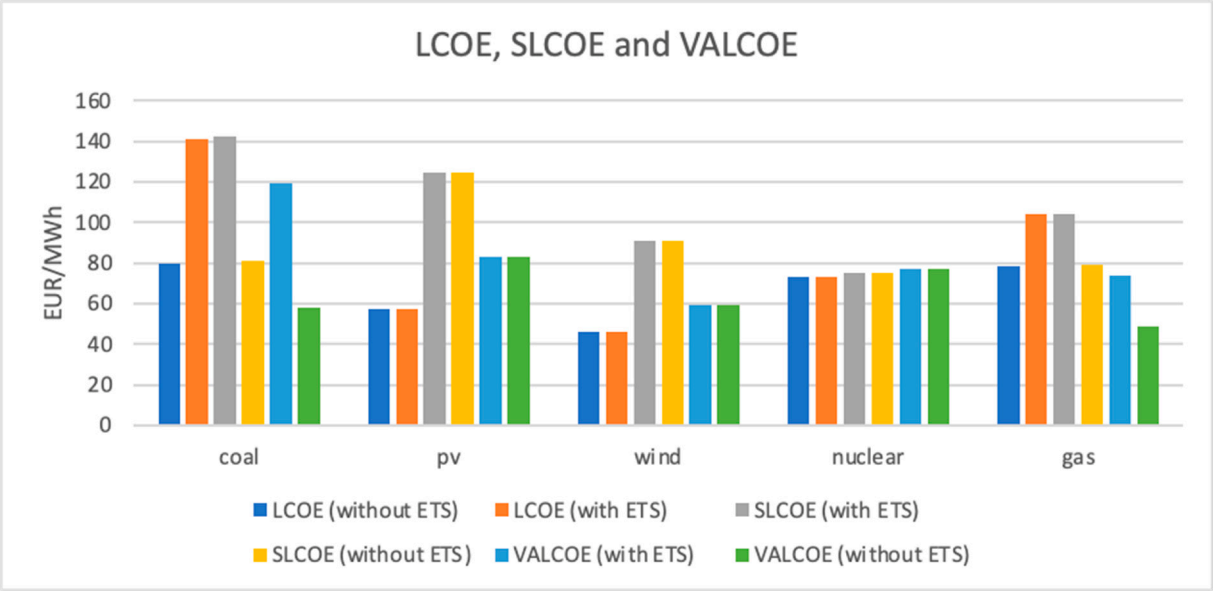



**Figure 6.** Comparison of LCOE, SLCOE and VALCOE with and without the EU ETS component.

Figure 6 demonstrates that the ranking of technologies depends on the metric used. With EU ETS included, wind has the lowest plant-level LCOE (46.35 EUR/MWh), followed by PV (57.20 EUR/MWh) and nuclear (73.07 EUR/MWh). After system-integration costs are added, SLCOE rises to 90.96 EUR/MWh for wind and 124.37 EUR/MWh for PV, whereas nuclear changes only slightly to 74.83 EUR/MWh. The VALCOE results provide a different perspective by adjusting the generation cost according to energy, capacity and flexibility value, and should therefore be interpreted as a competitiveness indicator rather than an additive system-cost component.

Figure 7 shows a screening-level LFSCOE comparison across the analysed electricity-generation technologies.

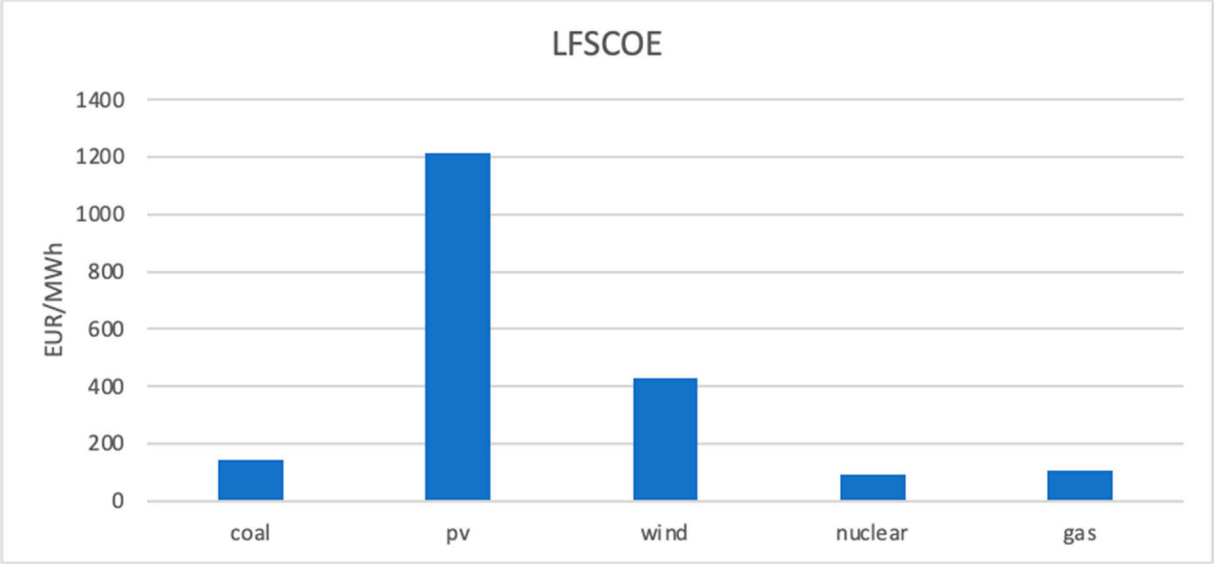



**Figure 7.** Screening-level LFSCOE comparison across the analysed electricity-generation technologies.

Figure 7 shows the screening-level LFSCOE results. The estimated values are 142.72 EUR/MWh for coal, 1211.98 EUR/MWh for PV, 426.98 EUR/MWh for wind, 92.83 EUR/MWh for nuclear and 103.84 EUR/MWh for natural gas. The very large values for PV and wind arise from the strict full-system interpretation of LFSCOE, under which a single technology is assumed to take responsibility for meeting the complete demand profile and must therefore be complemented by storage and/or substantial generation overcapacity. Because the present values are benchmark-adjusted screening estimates rather than an independently optimized Polish 8760 h model, they should be interpreted as an indication of full-system cost sensitivity rather than as a final forecast for the Polish electricity system.

Table 6 consolidates the plant-level, system-adjusted and life-cycle indicators reported separately in Figures 4–7, allowing the five technologies to be compared directly across the economic and environmental dimensions. Wind and PV are most competitive at the plant level (LCOE), nuclear becomes comparatively more favourable once system integration and firm-supply requirements are considered (SLCOE, LFSCOE), and nuclear and wind show the lowest life-cycle global-warming impact.

**Table 6.** Summary of key techno-economic and life-cycle indicators for the analysed technologies (values include the EU ETS components where applicable).

| Technology | LCOE (EUR/MWh) | SLCOE (EUR/MWh) | VALCOE (EUR/MWh) | LFSCOE (EUR/MWh) | Life-Cycle GWP (kg $CO_2$-eq/MWh) |
|---|---|---|---|---|---|
| Coal | 141.00 | 142.09 | 119.52 | 142.72 | 1140 |
| Natural gas | 103.84 | 104.30 | 73.77 | 103.84 | 684 |
| Nuclear | 73.07 | 74.83 | 77.37 | 92.83 | 16.2 |
| PV | 57.20 | 124.37 | 82.98 | 1211.98 | 65.7 |
| Wind | 46.35 | 90.96 | 59.23 | 426.98 | 25.8 |

Figure 8 combines the economic and environmental results into a single cost–carbon view. Nuclear and wind occupy the most favourable, lower-cost/lower-carbon quadrant, PV combines low carbon impact with intermediate cost, while coal and natural gas fall in the higher-cost/higher-carbon quadrant once the EU ETS cost is included. This figure therefore provides a plant-level cost–carbon comparison and should not be interpreted as a comparison of full-system electricity costs.

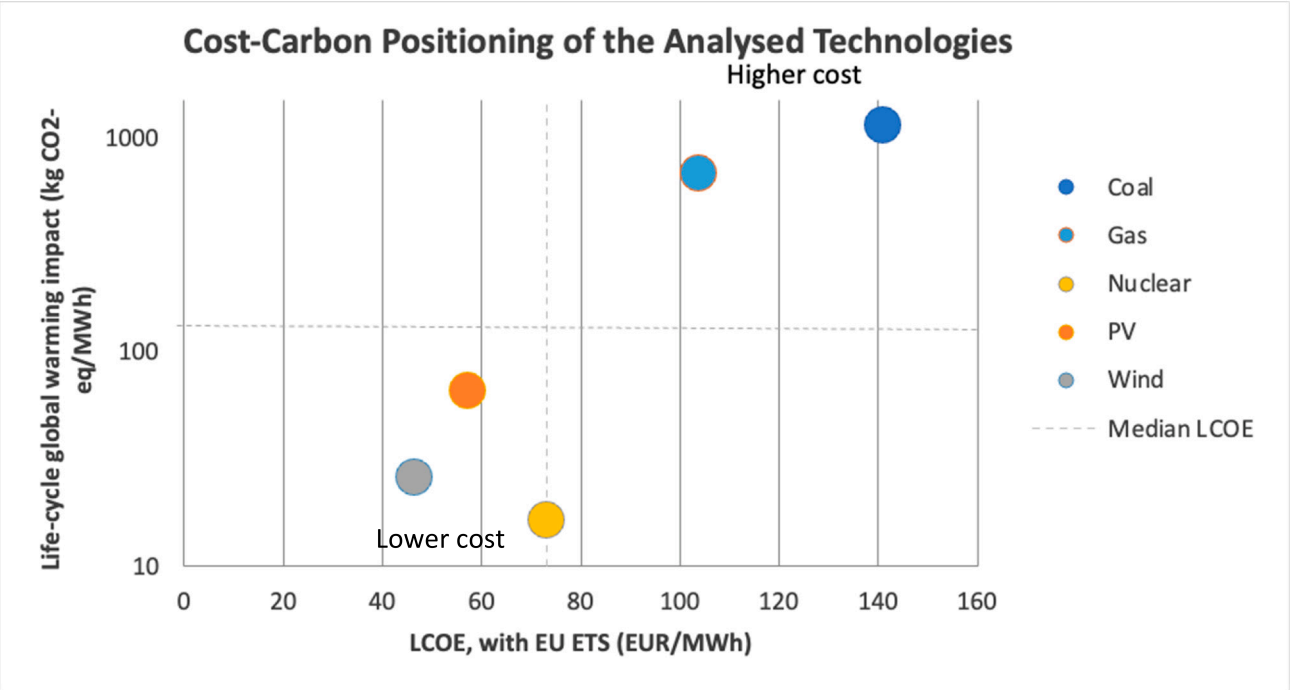



**Figure 8.** Cost–carbon positioning of the analysed technologies. LCOE (EUR/MWh, with EU ETS) is plotted against life-cycle global-warming impact (kg $CO_2$-eq/MWh, log scale). Dashed lines mark the median value on each axis.

Figure 9 restates the results of Table 6 on a common normalized scale. Coal ranks worst on LCOE, SLCOE, VALCOE and life-cycle global warming; PV ranks worst on LFSCOE due to the storage and overcapacity required for firm supply; and nuclear and wind combine consistently low or intermediate scores across all five indicators, supporting the conclusion that technology ranking is highly sensitive to the indicator selected.

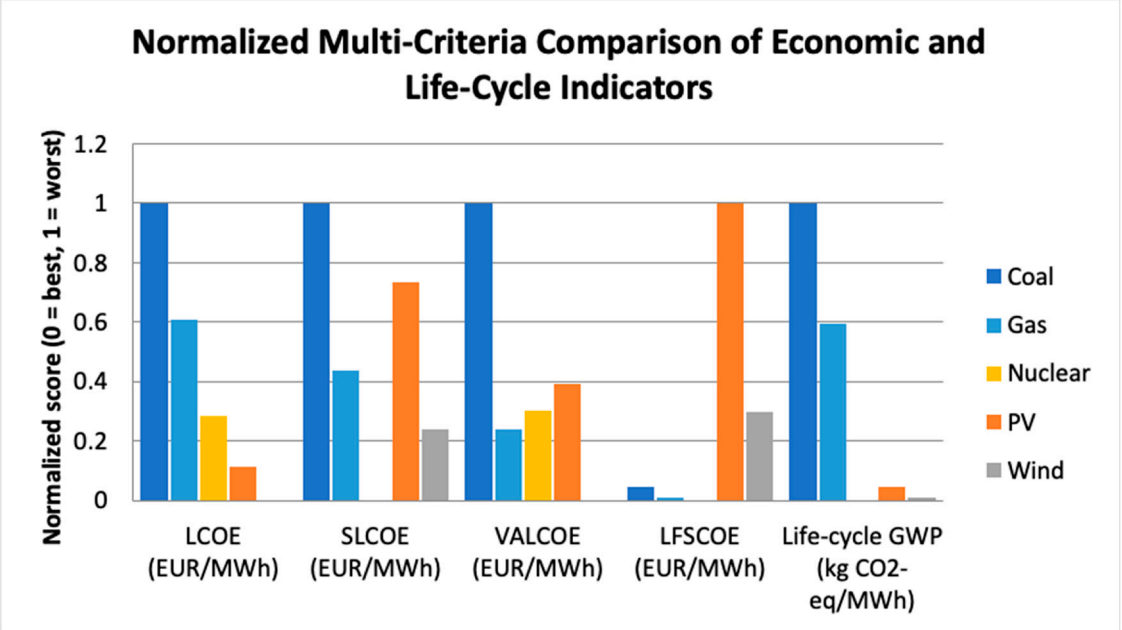



**Figure 9.** Normalized multi-criteria comparison of economic and life-cycle indicators. Each indicator is min–max normalized across the five technologies (0 = best, 1 = worst) to allow comparison across different units.

## 5. Discussion

### *5.1. Plant-Level Cost and Carbon Pricing: LCOE*

The plant-level results demonstrate substantial differences in the economic structure of the analysed electricity-generation technologies. Wind and photovoltaic generation exhibit the lowest LCOE values in the base-case comparison, whereas coal becomes the most expensive technology when the EU ETS component is included. Nuclear power occupies an intermediate position, while natural gas remains strongly influenced by fuel and carbon costs. This general pattern is consistent with comparative assessments showing that the relative economic performance of electricity-generation technologies depends strongly on technology-specific investment, and operational, fuel and environmental characteristics [40].

The comparison with and without the EU ETS component demonstrates the importance of carbon pricing for fossil-fuel generation. Removing the EU ETS component reduces the coal LCOE from 141.00 to 79.67 EUR/MWh and natural-gas LCOE from 103.84 to 78.57 EUR/MWh. This difference indicates that a substantial share of the economic disadvantage of fossil-fuel generation under the adopted European-market assumptions results from the monetization of direct $CO_2$ emissions rather than exclusively from capital, fuel, or operation and maintenance costs. The importance of this mechanism is supported by empirical evidence from European electricity markets demonstrating the pass-through of EU ETS allowance prices into power-sector costs and electricity prices [41].

These results confirm that the conventional LCOE provides an important first-level comparison of electricity-generation technologies but does not capture their complete economic interaction with the electricity system. This limitation becomes particularly relevant when technologies with substantially different temporal generation profiles and dispatchability characteristics are compared.

### *5.2. System Integration, System Value and Firm Supply: SLCOE, VALCOE and LFSCOE*

The comparison changes substantially when system-level considerations are introduced. The SLCOE results show that the integration of variable renewable technologies introduces additional costs associated with generation profiles, balancing, connection and transmission. PV increases from 57.20 EUR/MWh at the plant level to 124.37 EUR/MWh after the adopted integration-cost components are included, while wind increases from 46.35 to 90.96 EUR/MWh. By comparison, the corresponding increases for nuclear, coal and natural gas are considerably smaller.

The magnitude of these differences should not be interpreted as an intrinsic and constant characteristic of the technologies. System-integration costs depend on renewable penetration, the temporal relationship between electricity generation and demand, forecast accuracy, network conditions, storage availability, interconnection capacity and other flexibility resources. Accordingly, the SLCOE results should be interpreted within the system assumptions adopted in the present analysis. This interpretation is consistent with recent system-based LCOE research demonstrating that the comparative cost of electricity-generation technologies depends not only on plant-level characteristics but also on the configuration and flexibility of the surrounding electricity system [42].

VALCOE provides a complementary perspective because it evaluates not only the cost of electricity production but also the value that generated electricity provides to the power system. Energy value, capacity contribution and flexibility may therefore alter the relative position of technologies compared with the conventional LCOE. For this reason, the VALCOE should not be added mechanically to the SLCOE. The two indicators answer different analytical questions: the SLCOE focuses on the additional cost of integration, whereas the VALCOE reflects the value of electricity supplied at particular times and under particular system conditions.

The LFSCOE results extend the comparison further by examining a substantially more restrictive question: the cost of making an individual technology responsible for satisfying the full temporal electricity-demand profile. Under this assumption, PV and wind require considerable overcapacity and electricity storage to compensate for periods of insufficient generation. Consequently, their screening-level LFSCOE values increase much more strongly than those of dispatchable technologies.

These results should not be interpreted as evidence that electricity systems with high shares of renewable generation must necessarily exhibit costs equivalent to the single-technology LFSCOE estimates. Real electricity systems combine different generation technologies, storage technologies, interconnections, demand-side flexibility and dispatchable resources. The screening-level LFSCOE therefore illustrates the cost implications of firm-supply responsibility under a deliberately stringent system boundary rather than predicting the cost of an actual future electricity mix.

Taken together, the SLCOE, VALCOE and LFSCOE results demonstrate that the relative economic performance of electricity-generation technologies depends strongly on the system service being evaluated. A technology that performs favourably when assessed solely on plant-level generation cost may occupy a different position once system integration, temporal electricity value or firm-supply requirements are considered.

An important limitation of the present LFSCOE assessment is that the full-system premium was transferred from a German benchmark rather than derived from a Poland-specific hourly optimization. Consequently, the reported LFSCOE values are sensitive to differences between the German and Polish electricity systems, including hourly demand profiles, solar irradiation, wind availability, generation structure, interconnection capacity, grid topology and the availability of system-flexibility resources. These differences may affect the required generation overcapacity, storage capacity, curtailment and energy losses. Therefore, the reported LFSCOE values should be interpreted as screening-level indicators of the potential magnitude of full-system effects rather than as geographically specific estimates for the Polish power system.

The profile and adequacy costs applied in the present study were evaluated at a 30% penetration level in order to provide a consistent and comparable reference point across the analysed technologies. This intermediate penetration level was selected on the basis of the OECD/NEA system-cost framework and was intended to represent a meaningful system-integration case without introducing additional scenario-specific assumptions. However, these costs should not be interpreted as fixed technology-specific parameters. Their magnitude depends strongly on the penetration level of variable renewable generation, the temporal relationship between generation and demand, the available generation mix, storage capacity, interconnection and other sources of system flexibility. Consequently, the SLCOE results reported in this study represent the adopted 30% penetration scenario rather than a universal system cost applicable to all power systems or stages of renewable-energy deployment. A broader sensitivity analysis covering multiple penetration levels and system configurations therefore represents an important direction for future research and a natural extension of the present assessment.

An additional source of uncertainty arises from transferring the full-system premium derived from the German benchmark to the Polish context. Germany and Poland differ in several system characteristics that may materially affect full-system electricity costs, including hourly electricity-demand profiles, solar irradiation, wind regimes, installed generation structure, interconnection capacity, grid topology and the availability of system-flexibility resources. These differences may influence the amount of generation overcapacity, storage capacity, curtailment and energy losses required to provide firm electricity. Consequently, a numerical margin of error cannot be reliably quantified without conducting a dedicated

Poland-specific 8760 h optimization. The LFSCOE values reported in this study should therefore be interpreted as screening-level indicators of the direction and potential magnitude of full-system effects rather than as geographically transferable estimates with a defined statistical uncertainty. A Poland-specific hourly optimization using national demand and renewable-generation profiles is therefore identified as an important direction for future research.

### *5.3. Life-Cycle Environmental Performance: LCA and Storage Effects*

The life-cycle assessment complements the economic indicators by identifying environmental trade-offs that are not visible in cost-based comparisons. Coal and natural gas are characterized by the highest life-cycle global-warming impacts, whereas nuclear, wind and photovoltaic generation exhibit substantially lower greenhouse-gas burdens per MWh. This general pattern is consistent with recent comparative life-cycle assessments of electricity-generation technologies, which likewise report substantially higher climate-related environmental burdens for fossil-fuel-based generation than for renewable and nuclear alternatives [43].

However, the ReCiPe midpoint results demonstrate that low greenhouse-gas emissions do not imply uniformly low environmental impacts across all categories. The environmental profiles of the analysed low-carbon technologies differ considerably. Photovoltaic generation exhibits comparatively greater contributions in selected resource- and toxicity-related categories, while nuclear generation is distinguished by a substantially higher ionizing-radiation indicator. Wind also shows selected material-related environmental burdens despite its low life-cycle climate impact. Recent systematic evidence similarly demonstrates that the comparative environmental performance of electricity-generation technologies varies considerably across impact categories and depends on methodological assumptions, system boundaries and technology characteristics [44].

The storage-adjusted scenarios further demonstrate the possibility of environmental burden shifting. The addition of $LiFePO_4$ battery storage to PV and wind increases several environmental impacts because storage requires additional materials and manufacturing processes, while round-trip efficiency losses increase the amount of generation needed to deliver 1 MWh of electricity. The most visible increases occur in categories associated with water consumption, terrestrial ecotoxicity and mineral-resource use.

This finding is particularly relevant when renewable technologies are evaluated at the electricity-system level. Their environmental performance should not be characterized solely by operational emissions or even by generation-only life-cycle greenhouse-gas emissions. When additional infrastructure is required to provide electricity with greater temporal availability, part of the environmental burden is transferred from the generation technology to storage, additional generation capacity and associated material supply chains.

The LCA results therefore reinforce the need for a multi-category life-cycle perspective. Global-warming impacts remain central to electricity-sector decarbonization, but resource use, toxicity, water consumption, land use and technology-specific environmental effects should also be considered when comparing alternative generation pathways [43,44].

### *5.4. Integrated Interpretation of Economic and Environmental Performance*

The combined results demonstrate why no single indicator is sufficient to characterize the overall performance of electricity-generation technologies. Each metric used in this study represents a different analytical perspective.

The LCOE describes the plant-level cost of producing electricity. The SLCOE extends this perspective by incorporating selected system-integration costs. The VALCOE accounts for the value that electricity provides to the system depending on its temporal availability,

capacity contribution and flexibility. The LFSCOE examines the cost implications of requiring a technology to provide firm electricity under a stringent single-technology assumption. LCA, in turn, evaluates environmental burdens occurring throughout the complete life cycle.

The comparative position of the analysed technologies therefore changes depending on the assessment perspective. Wind and photovoltaic generation perform favourably in terms of plant-level generation costs and life-cycle greenhouse-gas emissions but are more strongly affected by system-integration and firm-supply requirements. Nuclear generation has a higher plant-level cost than wind and PV but shows relatively limited additional integration requirements and a low life-cycle global-warming impact. Coal and natural gas retain dispatchability advantages, but their economic performance is strongly affected by fuel and carbon costs, while their life-cycle climate impacts remain substantially higher than those of low-carbon technologies.

The principal methodological implication is therefore not that one indicator should replace another, but that they should be interpreted jointly. LCOE, SLCOE, VALCOE, LFSCOE and LCA describe complementary dimensions of electricity-generation performance and should not be mechanically combined into a single score. Their simultaneous interpretation enables the distinction between electricity-production cost, system-integration requirements, electricity-system value, firm-supply requirements and life-cycle environmental impacts. This type of multi-dimensional assessment is also consistent with recent approaches combining economic and life-cycle perspectives in comparative evaluations of power-generation technologies [40].

This integrated perspective provides a more complete representation of electricity-generation technologies than any individual metric considered separately. It also illustrates why technology comparisons may lead to different conclusions depending on whether the analysis focuses on plant-level economics, system operation, reliability or environmental performance.

The principal limitations of the present analysis include the use of harmonized European-average cost assumptions, literature-based system-integration parameters, a screening rather than Poland-specific optimized LFSCOE, and a simplified BESS-adjusted LCA scenario. Future research should therefore combine Poland-specific hourly demand and renewable-generation profiles with optimized generation and storage capacities, sensitivity analyses for WACC, fuel and EUA prices, and a fully harmonized life-cycle representation of both generation and storage infrastructure.

To provide a transparent synthesis of the comparative assessment, Table 7 summarizes the relative position of the analysed technologies across the principal operational, economic, system-level and environmental dimensions considered in this study. The ranking is indicator-specific and should not be interpreted as an overall ranking of electricity-generation technologies.

**Table 7.** Comparative positions of the analysed electricity-generation technologies across the assessment dimensions considered in this study.

| Assessment Dimension | 1st | 2nd | 3rd | 4th | 5th |
|---|---|---|---|---|---|
| Plant-level economic performance (LCOE) | Wind | PV | Nuclear | Natural gas | Coal |
| System-adjusted economic performance (SLCOE) | Nuclear | Wind | Natural gas | PV | Coal |
| Value-adjusted economic performance (VALCOE) | Wind | Natural gas | Nuclear | PV | Coal |
| Firm-supply economic performance (LFSCOE) | Nuclear | Natural gas | Coal | Wind | PV |
| Life-cycle climate performance (GWP) | Nuclear | Wind | PV | Natural gas | Coal |

From an operational perspective, coal, natural gas and nuclear generation provide dispatchable electricity and therefore require comparatively limited additional measures to

match generation with the temporal demand profile. Wind and PV have variable generation profiles and consequently show greater dependence on system flexibility, balancing, storage and complementary generation when firm electricity supply is required. Conversely, wind and PV show strong plant-level economic performance and low life-cycle greenhouse-gas impacts. Nuclear power combines low life-cycle greenhouse-gas emissions with comparatively limited system-integration and firm-supply requirements, whereas fossil-fuel technologies retain operational dispatchability but are disadvantaged by carbon costs and substantially higher life-cycle climate impacts.

The comparison therefore does not identify a universally superior technology. Instead, it demonstrates that the advantageous characteristics of each technology depend on the assessment criterion considered. Wind and PV perform particularly favourably in plant-level cost and climate-related terms, nuclear performs favourably when system integration and firm-supply requirements are considered, while coal and natural gas provide dispatchability but exhibit substantially less favourable carbon-related performance.

The principal finding emerging from the combined assessment is that the advantages of individual generation technologies are not eliminated when the analytical perspective is broadened, but are redistributed across different dimensions of system performance. Wind and PV retain favourable plant-level cost and climate characteristics, but part of this advantage is offset by greater system-integration and firm-supply requirements. Dispatchable technologies retain operational advantages, although fossil-fuel generation is penalized by carbon costs and life-cycle greenhouse-gas burdens. Nuclear generation exhibits a different trade-off structure, combining low life-cycle climate impact and limited system-integration requirements with higher plant-level capital-related costs. The integrated framework therefore reveals not simply a change in ranking, but the specific dimension in which each technology gains or loses comparative advantage.

A broader sensitivity analysis covering alternative discount rates, carbon-price assumptions and system-integration costs could further test the robustness of the technology rankings reported in this study. Such an extension would allow the stability of the comparative results to be evaluated under different financial and system-level conditions and is therefore identified as an important direction for future research.

## 6. Conclusions

The results demonstrate that the comparative performance of electricity-generation technologies depends strongly on the assessment perspective adopted. Plant-level generation cost alone does not fully reflect differences in dispatchability, system-integration requirements, temporal electricity value, firm-supply capability and life-cycle environmental performance.

Wind and photovoltaic generation are characterized by favourable plant-level economic performance and low life-cycle greenhouse-gas emissions, although their variable generation profiles increase the importance of balancing, flexibility, storage and complementary system infrastructure. Nuclear generation combines low life-cycle climate impacts with comparatively limited additional system-integration and firm-supply requirements, although its economic structure is strongly influenced by capital-related costs. Coal and natural gas retain operational advantages associated with dispatchability, but their comparative performance is adversely affected by fuel and carbon costs and by substantially higher life-cycle greenhouse-gas emissions.

The analysis also shows that environmental performance cannot be represented by greenhouse-gas emissions alone. Technologies with low climate impacts may exhibit different trade-offs related to resource consumption, toxicity, water use, land use or other

life-cycle impact categories, while the inclusion of electricity storage may shift part of the environmental burden from electricity generation to supporting infrastructure.

The LCOE, SLCOE, VALCOE, LFSCOE and LCA should be interpreted as complementary rather than competing indicators. Their joint application provides a more comprehensive basis for comparing electricity-generation technologies by distinguishing plant-level economics, system-level requirements, electricity-system value, firm-supply capability and life-cycle environmental consequences. This multi-dimensional perspective can support more transparent technology assessment in electricity systems undergoing decarbonization and increasing integration of variable renewable generation.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| LCOE | Levelized cost of electricity |
| SLCOE | System levelized cost of electricity |
| VALCOE | Value-adjusted levelized cost of electricity |
| LFSCOE | Levelized full system cost of electricity |
| LCOT | Levelized cost of transmission |
| CAPEX | Capital expenditure |
| O&M | Operation and maintenance |
| WACC | Weighted average cost of capital |
| EU ETS | European Union Emissions Trading System |
| EUA | European Union Allowance |
| LCA | Life-cycle assessment |
| ReCiPe | ReCiPe 2016 life cycle impact assessment method |
| FU | Functional unit |
| GWP | Global warming potential |
| BESS | Battery energy storage system |
| RES | Renewable energy source |
| VRE | Variable renewable energy |
| IEA | International Energy Agency |
| NEA | Nuclear Energy Agency |
| OECD | Organization for Economic Co-operation and Development |

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