System Levelized Cost of Electricity of Nuclear Power Plants and Other Energy Sources

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ABSTRACT

Within energy system analysis, there is discourse regarding the role and economic benefits of nuclear energy in terms of overall system costs. The reported findings range from considerable drawbacks to substantial benefits, depending on the chosen models, scenarios, and underlying assumptions.

Levelized Costs of Electricity (LCOE) are a common metric of comparing various power generating technologies. However, the mass introduction of variable renewable energy sources, including wind and solar photovoltaic, leads to additional costs caused by intermittency, the so-called integration costs. This paper will try to investigate and re-define the concept of system LCOE and proposes concrete methods to estimate it for each technology.

This system LCOE will try to allow for the economic comparison of various generating technologies and derive appropriate metrics. Integrating low-carbon nuclear-based power generation technologies to balance the fluctuating supply from renewable sources is becoming increasingly important in the future energy mix, as well as that integration costs increase with growing renewables shares and become an economic barrier to deploying renewable energy sources at high shares.

The goal of system LCOE is to help understand and resolve the challenge of integrating hybrid energy systems and can guide research and policy makers in realizing a cost-efficient transformation towards an energy system with a mix of nuclear power and a high share of variable renewables.

Keywords: *LCOE, integration costs, hybrid energy systems, System LCOE, energy mix*

1 INTRODUCTION

One of the most burning issues in electricity policy making today are the costs of a transformation towards an energy system with a high share of variable renewable energy sources. These crucial questions are often responded using a common metric for estimating and comparing the costs of generating technologies, namely LCOE.

Traditionally, the LCOE method allows power plants with different generation and cost structures to be compared with each other. The LCOE is calculated by comparing all costs incurred over the lifetime of the power plant for the construction and operation and the total amount of energy generated. [1]

The calculation can be conducted either based on the net present value method (NPV) or the so-called annuity method. When applying the net present value method, the expenses for the investment, as well as the payment flows of revenues and expenditures during the power plant's lifetime, are calculated by discounting related to a shared reference date. For this purpose, the present values of all expenses are divided by the present value of electricity generation. A discounting of power generation initially seems incomprehensible from a physical point of view but is a consequence of financial mathematical transformations. The underlying idea is that the generated electricity implicitly corresponds to the revenue from the sale of this energy. Thus, the further this income is in the future, the lower the associated present value. The total annual expenditure throughout the entire operating period consists of the investment expenditure and the operating costs, which arise during the lifetime. [1]

The total annual costs are composed of fixed and variable costs for the operation of the power plant, maintenance, servicing, repairs and insurance payments. The share of debt and equity can be explicitly included in the analysis by the weighted average cost of capital (WACC) over the discount factor (interest rate). The discount factor depends on the amount of the equity, the return on equity over the lifetime, the borrowing costs and the share of the contributed debt. [1]

Through discounting all expenditures and the quantity of electricity generated over the lifetime to the same reference date, the comparability of LCOE is assured. LCOE represents a comparative calculation on a cost basis and not a calculation of feed-in tariffs. These can only be calculated by adding further influencing parameters. Self-consumption regulations, tax legislation, and realized operator revenues make it difficult to calculate a feed-in tariff from the results for the LCOE. A further restriction arises from the fact that a calculation of LCOE does not take into account the value of the electricity produced within an energy system in a given hour of the year. At this point, it is to be emphasized that this method is an abstraction of reality aiming at making different power plants comparable. The method is not suitable for determining the profitability of a specific power plant. For this purpose, a financial calculation, which takes into account all income and expenditure with a cash flow model must be carried out. [1]

However, there is qualified criticism towards the metric of LCOE. Some studies show that LCOE are a flawed metric for comparing the economic attractiveness of VRE (variable renewable energy sources) with conventional dispatchable generating technologies such as fossil, nuclear, or hydro plants. LCOE alone do not say anything about competitiveness or economic efficiency. The main reason is that electricity is not a homogenous good in time, because demand is varying and electricity storage is costly. This is reflected by electricity prices, which fluctuate widely on time scales of minutes and hours up to seasons, depending on the current demand and supply situation. Hence, the value of VRE depends on the time when their output is produced. Since the output of wind and solar PV is driven by natural processes, the value of VRE is an intrinsic property associated with their variability patterns that determines their generation profile. An LCOE comparison ignores the temporal heterogeneity of electricity and in particular the variability of VRE. [2]

To overcome the deficits of an LCOE comparison, we will emphasize the basic economic principle that often seems forgotten: the economic evaluation of any power generating technology should consider both costs and value of that technology. VRE are economically efficient if their LCOE (marginal costs) equal their marginal economic value. Moreover, they are competitive if LCOE are equal or below their market value, which is the revenue per unit generated by a technology. Assuming perfect and complete markets, the marginal economic value equals the market value and consequently economic effectiveness and competitiveness become congruent. [2]

The limitations of an LCOE analysis become even more severe in the future, because market values of VRE are decreasing with increasing VRE shares due to their variability. This is why a new concept, System LCOE, will seek to comprise all economic costs of VRE in a simple cost metric instead of comparing costs and values. The metric should not only contain standard LCOE but also reflect the costs of variability that occur on a system level. However, standard definitions of integration costs are motivated from a bottom-up engineering perspective and not linked to economic theory. That is why it is not clear how integration cost estimates relate to the economic efficiency or competitiveness of VRE. [2]

The main objective of System LCOE is that in contrast to standard LCOE their comparison should allow to economically evaluate VRE and other technologies. The new concept should be equivalent to the market value perspective that might alternatively be used to correct the caveats of an LCOE comparison. The task and context would then decide which perspective is more suitable. [2]

2 INTEGRATION COSTS

The integration of wind and solar generators into power systems causes "integration costs" - for grids, balancing services, more flexible operation of thermal plants, and reduced utilization of the capital stock embodied in infrastructure, among other things. [3]

As with any other investment, wind turbines and solar cells incur direct costs in the form of capital and operational expenses. These costs can be aggregated to average discounted life-time costs, called LCOE. In addition, integrating wind and solar power or other VRE into power systems causes costs elsewhere in the system. Examples include distribution and transmission networks, short-term balancing services, provision of firm reserve capacity, a different temporal structure of net electricity demand, and more cycling and ramping of conventional plants. These costs have been called "hidden costs", "system-level costs", or "integration costs". [3]

This definition of integration costs aims to be economically rigorous and comprehensive. Integration costs should be defined such that they can be used in economic assessments, e.g. on the welfare-optimal deployment of VRE. Moreover, the definition should include all economic impacts of variability to make sure that an economic evaluation of VRE is complete. [3]

The definition of integration costs is derived from the marginal economic value of electricity from VRE in terms of €/MWh. The marginal economic value (or benefit) is the increase in welfare when increasing wind generation by one MWh. If demand is perfectly price-inelastic, this equals the incremental cost savings when adding one MWh to a power system. This value is impacted by the properties of VRE mentioned in the introduction: variability, uncertainty, and location. Here we assume perfect and complete markets so that the marginal value of VRE equals the market value. The market value is the specific (€/MWh) revenue that an investor earns from selling the output on power markets excluding subsidies such as green certificates or feed-in premiums. This reduction in market value is caused by the interaction of VRE variability and the inflexibilities of the rest of the power system. We interpret this reduction as integration costs. Already at this point it becomes clear that integration costs are not "caused by VRE", but by the interactions of VRE and power system properties. [3]

Therefore we can define integration costs of wind Δ_{wind} as the market value of wind p_{wind} compared to the load-weighted average electricity price $p_{electricity}$.

$$\Delta_{wind}(q) = p_{electricity}(q) - p_{wind}(q) \tag{1}$$

This definition of integration costs is comprehensive as it captures the economic impact of all characteristic properties of a technology that reduce (or increase) its market value. It implies that all generating technologies have integration costs, not just VRE. As prices reflect marginal costs, this definition specifies integration costs in marginal, not average, terms. A key strength of this definition is that it reconciles the concept of integration costs with standard economic theory: it is a basic economic principle that the welfare-optimal deployment q* of a technology is given by the point where market value $p_{wind}(q)$ and marginal costs coincide. The long-term marginal costs of a technology can be expressed as LCOE (€/MWh). Hence, VRE like any technology, are optimally deployed when their market value equals their LCOE. [3]

$$\begin{gathered} p_{wind}(q^*) = LCOE_{wind}(q^*) \\ p_{electricity}(q^*) - \Delta_{wind}(q^*) = LCOE_{wind}(q^*) \end{gathered} \tag{2}$$

As defined here, integration costs can be used for the economic evaluation of VRE and have a welfare-economic interpretation. Integration costs reduce the market value of VRE and consequently reduce their optimal deployment q*. We refer to this way of accounting for integration costs and evaluating VRE as the value perspective (Fig. 1, left).

There is an alternative but equivalent perspective of understanding integration costs. From a cost perspective, integration costs can be added to the LCOE of wind, resulting in the metric "system levelized costs of electricity" (system LCOE). This metric comprises the total economic costs of a technology (Fig. 1, right). [3]

$$sLCOE_{wind}(q) = LCOE_{wind}(q) + \Delta_{wind}(q) \tag{3}$$

In the cost perspective the above optimality condition (equation (2)) can be analogously formulated: VRE, like any technology, are welfare-efficient when their system LCOE equals the average electricity price. [3]

$$p_{electricity}(q^*) = sLCOE(q^*) \tag{4}$$

Consequently, the sum of generation and integration cost (system LCOE) of each generation technology is identical in the long-term optimum. This shows that there are two ways of accounting for integration costs. First, from a value perspective they reduce the market value of a technology, and second, from a cost perspective they can be added to the marginal costs (LCOE) of a technology. Fig. 2 illustrates this duality. Integration costs of VRE tend to increase with VRE penetration. At low penetration VRE typically have negative integration costs because their output is often positively correlated with demand. The welfare-optimal deployment q* is equivalently given either at the intersection of market value and LCOE, or where system LCOE intersect with the average electricity price. A cost perspective has at least three merits: LCOE is commonly used in industry, policy, and academia as a metric to compare technologies - apparently there is demand for cost comparisons. System LCOE can correct the flawed metric while retaining its intuitive and familiar touch. Secondly, a cost perspective is often applied by the integration cost literature. System LCOE can help to connect this literature with the economic literature on market value. Finally, a cost metric that comprises generation and integration costs can help parameterize VRE variability in multi-sector models. [3]

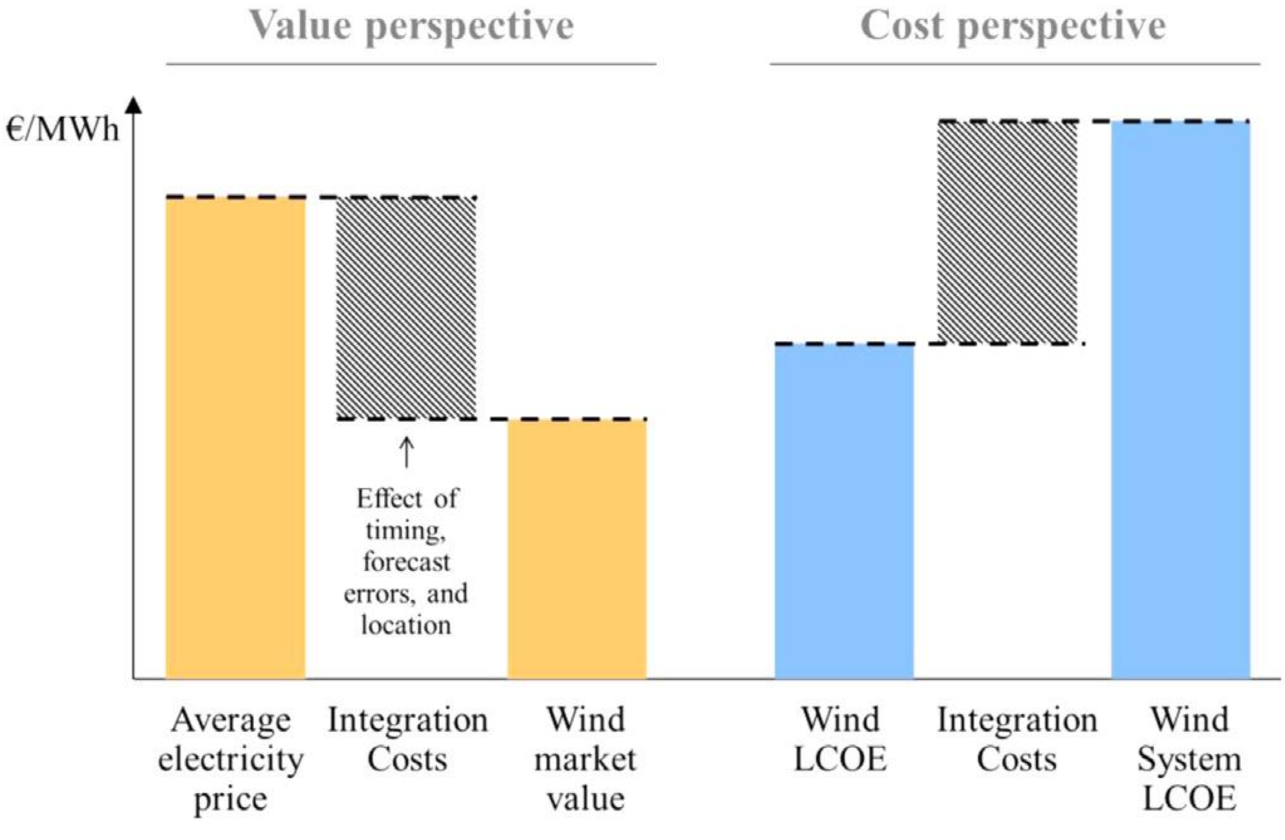

Figure 1: Wind integration costs are defined as the gap between its market value and the average electricity price. The value perspective (left) is equivalent to the cost perspective (right).

Integration costs not only depend on the characteristics of VRE technologies but also on the power system into which they are integrated, and the power system's flexibility to adapt. Published studies typically estimate integration costs by analyzing the impact of VRE on currently existing power systems with a fixed capacity mix and transmission grid. This is a short-term perspective. Integration costs depend on the properties of the legacy system: short-term integration costs are increased by a large stock of inflexible and capital-intensive base-load power plants, a scarce grid connection to regions with high renewable potentials and an inflexible electricity demand profile that hardly matches VRE supply. [3]

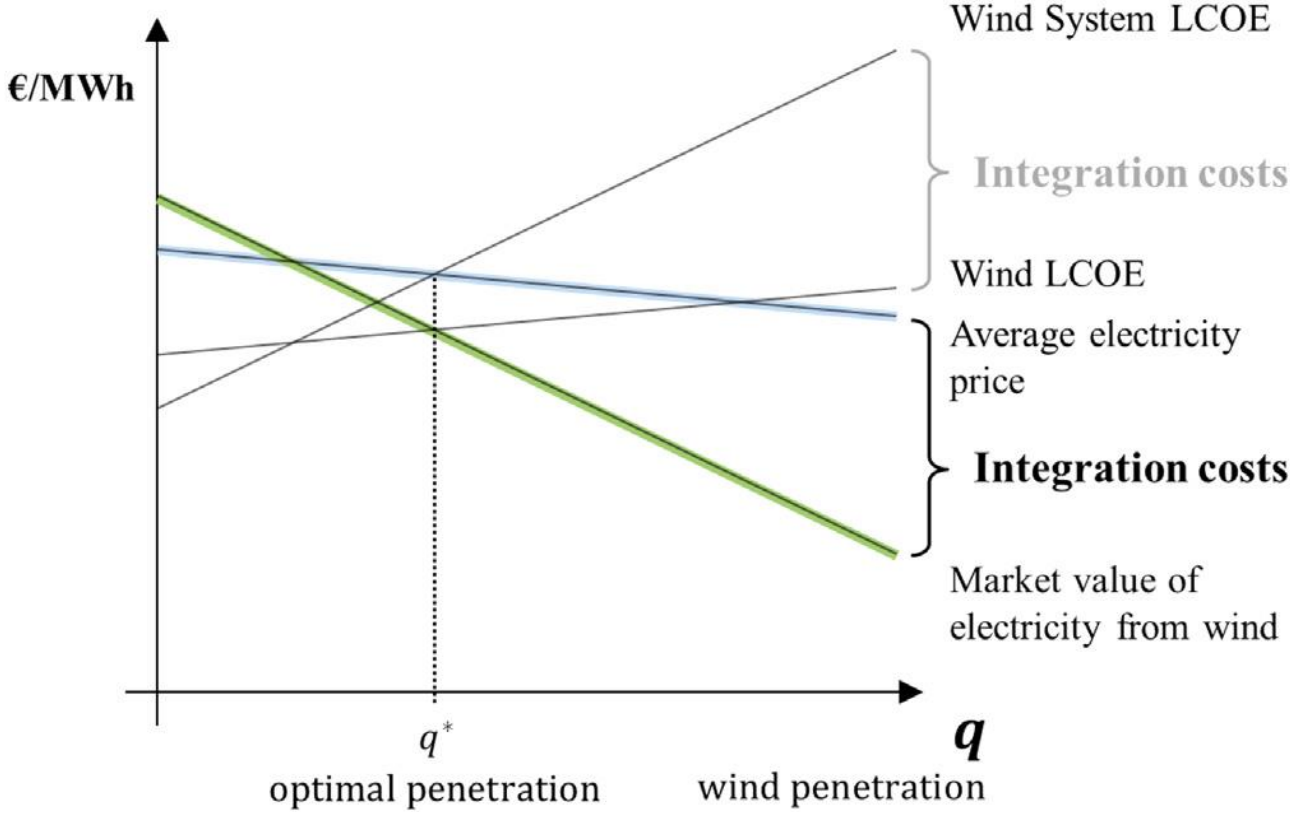

Figure 2: Integration costs can be accounted for by reducing the market value of VRE compared to the average electricity price (value perspective). Alternatively, they can be accounted for by adding them to the generation costs of VRE leading to system LCOE (cost perspective). The welfare-optimal deployment q* is defined by the intersection of market value and LCOE, and, equivalently, by the intersection of system LCOE with the average electricity price.

In contrast, over the long term, the power system can fully and optimally adapt to increased VRE volumes. These potential changes comprise operational routines and procedures, market design, increased flexibility of existing assets, a shift in the capacity mix, transmission grid extensions, a change in load patterns, demand-side management and technological innovations. Integration costs can be expected to be generally smaller in the long term than in the short term (Fig. 3). Hence, short-term costs should be carefully interpreted and should not be entirely attributed to VRE. Integration cost studies should be explicit about the assumed time horizon and considered system adaptations. [3]

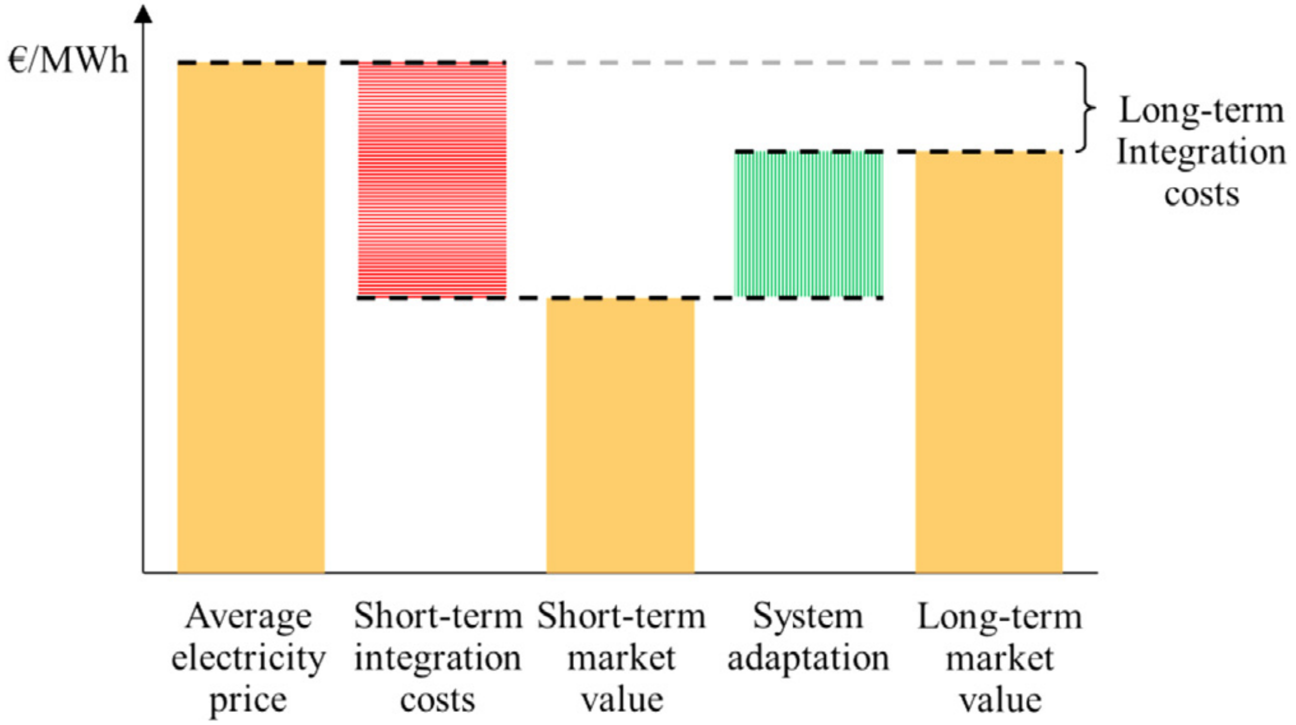

Figure 3: Integration costs depend on how the system adapts in response to VRE deployment. In the short term when the system does not adapt integration costs can be high (red area), while in the long term VRE can be better accommodated and thus long-term integration costs are smaller.

3 LCOE LIMITATIONS AND LEVERS FOR NUCLEAR POWER PLANTS

Levelized cost of electricity (LCOE) represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generation plant during an assumed cost recovery period and for a specific duty cycle. Costs include not just operation and maintenance, but also debt financing, equity returns, and tax effects. LCOE also accounts for the discounting of yearly cash flows. [4]

LCOE can be a useful metric for quantifying cost reduction progress, e.g., from FOAK (First of a Kind) to NOAK (N-th of a Kind), within a technology or for comparing different options that provide the same services, e.g., different clean firm resources. Cost reductions and predictability improvements will be critical for nuclear projects, and LCOE will be a useful metric for tracking progress. [4]

The LCOE of nuclear is driven primarily by construction costs, which can be broken into overnight capital costs and financing costs. Overnight capital cost is the cost to construct a nuclear plant without the impact of financing costs (as if it were constructed “overnight”). As a result, reducing overnight capital cost, construction time, and financing costs are all key levers for reducing LCOE. Construction costs can drive ~70– 80% of nuclear’s LCOE while operating costs are low and predictable. This contrasts with natural gas, where rather than construction costs, the LCOE is strongly influenced by fuel prices, which can create volatility in operating costs. [4]

Nuclear operating costs are in a predictable band and have decreased over time. In 2022, the average total generating cost for US nuclear was ~$31/MWh: ~60% operating costs, ~15-20% fuel costs, and ~20-25% capital costs. Generating costs declined from ~$51/MWh in 2012 to ~$31/MWh in 2022 with reductions in operating and fuel costs. [4]

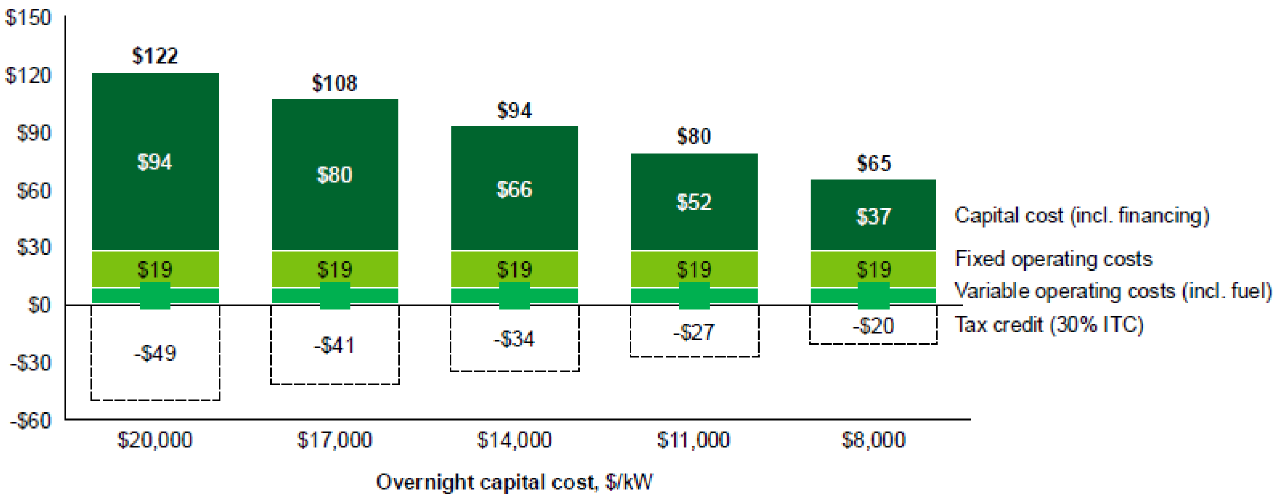

Figure 4: Impact of varying overnight capital costs on nuclear LCOE, 2024 $/MWh [4]

LCOE does not capture the full benefits of nuclear as a clean firm resource. LCOE is an imperfect metric with which to compare firm resources to variable resources because it does not reflect total system costs. LCOE measures only average generation irrespective of the time it is produced, which excludes two key categories of cost: delivery cost and firming cost. LCOE also does not capture the benefits of clean carbon-free generation, excluding the costs incurred by fossil fuels of carbon emissions on air pollution, human health. [4]

LCOE does not include delivery system costs such as interconnection and transmission. Firm resources tend to have lower overall delivery costs. With higher capacity factors, less delivery capacity is needed for a given amount of electricity generated (the transmission line capacity has a higher utilization). In addition, nuclear is more geographically concentrated; therefore, it can require less delivery buildout, including interconnection costs. [4]

LCOE does not include the cost to maintain additional generation to balance or “firm” the system during times when variable resources are not producing. For variable resources, this firming is provided by natural gas peaking plants, overbuilding with curtailment, or by batteries, which create costs for matching system load. It is challenging to capture system and firming costs to create clean firm comparisons even with modified LCOE, e.g., the Lazard LCOE+ analysis “firms” solar and wind with unabated natural gas (not clean) or four-hour battery storage (not firm). Modelling shows that this firming cost can increase as the penetration of variable renewables reaches high levels. [4]

Nuclear compares more favourably to other generation sources when accounting for full costs of provision and decarbonization. Renewable electricity sources can have higher system costs because of their variability, limited dispatchability, and forced curtailment. As a result, they require either overbuilding of both capacity and storage to meet load. A resilient grid includes a variety of generating assets, not just those with the lowest marginal LCOE. [4]

LCOE fails to capture the value of 80-year operating assets. Capital recovery periods, the time over which the project amortizes the initial construction costs, are likely capped at 30 years. Even if a nuclear plant’s LCOE ranges up to $150/MWh during that capital recovery period, once the asset is paid off, it could continue to operate for ~50 additional years, generating electricity within a predictable range of $30-35/MWh for (a range that could continue to decrease over time given efficiencies). Since LCOE doesn’t capture the post-capital repayment value, it underestimates the value of multi-decade investments that will provide future generations with affordable clean firm power. [4]

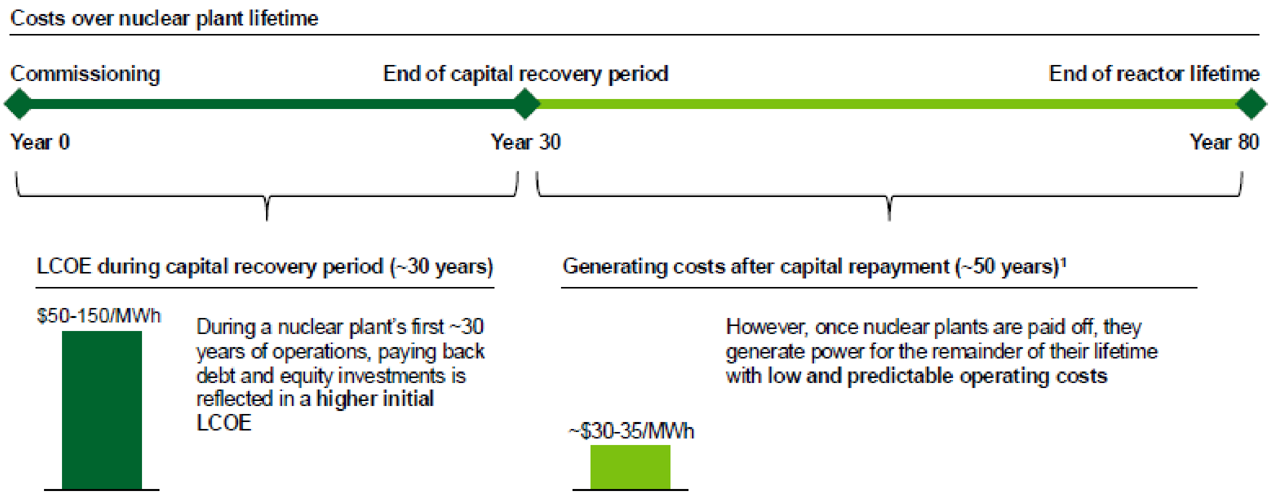

Figure 5: LCOE fails to capture the full benefit of 80-year clean firm operating assets [4]

4 CONCLUSION

For renewable energy sources, integration costs are those costs that do not occur at the level of the wind turbine or solar panel, but elsewhere in the power system. The preferred definition in this article is as the gap between the average electricity price and the market value of electricity from wind (or solar) power. This definition is rigorous, comprehensive, and has a straightforward welfare-economic interpretation: in the long-term optimum, the sum of generation and integration costs of all generation technologies coincide. The proposed decomposition of integration costs is along three inherent properties of VRE: uncertainty causing balancing costs, locational inflexibility causing grid-related costs, and temporal variability causing profile costs.

Despite the unavoidable considerable methodology and parameter uncertainty, the following synthesis can be presented:

- in thermal systems, wind integration costs are about 25-35 €/MWh at 30-40% penetration, assuming a base price of 70 €/MWh. Integration costs are 35-50% of generation costs.
- As integration costs can be large in size, ignoring them in cost-benefit analyses or system optimization can strongly bias results.
- The size of integration costs depends on the power system and VRE penetration: integration costs can be negative at low (<10%) penetration, they generally increase with penetration, and are typically smaller in hydro than in thermal systems.
- VRE-rich power systems require flexible thermal plants, but even more so they require plants that are low in capital costs.

LCOE does not capture the full benefits of nuclear as a clean firm resource, does not include delivery system costs such as interconnection and transmission, and does not include other system costs to balance or “firm” the system during times when variable resources are not producing. While system-level analyses show a more complete picture, it can be difficult for individual project decision makers to make comparisons on an asset-by-asset basis.

System modeling efforts consistently show the cost saving benefits of clean firm sources like nuclear in a low-carbon energy future. Including nuclear and other clean firm generation allows systems to build less variable renewable capacity, storage, and transmission. To better measure system costs and benefits, quantitative frameworks that capture the marginal impact of individual investments on the system could inform better decisions (versus LCOE).

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