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ABSTRACT

In Pursuit of the Green Transition — Electricity at Any Cost?*

We examine EU and UK plans for achieving a fossil-free energy system by 2050, centered on massive electrification and large-scale deployment of wind and solar power. Using empirical trends, cost analyses, and system-function assessments, we argue that current strategies underestimate real economic, technical, and social challenges. Three scenarios for meeting 2050 electricity demand are compared: full reliance on renewables; a 50/50 split between wind-solar and nuclear; predominantly nuclear. Evidence shows that higher shares of weather-dependent generation correlate with higher electricity prices, greater volatility, and increased system integration costs. High renewable shares require extensive backup, storage, and grid reinforcement, raising complexity and environmental impacts. Overlooked costs are highlighted: reduced capacity value, transmission expansion, balancing services, and so-cial externalities. Sustainability must encompass environmental, economic, and social dimensions. A technologically diverse, dispatchable-power-based strategy—especially with expanded nuclear power— offers a more robust, cost-effective, and socially acceptable pathway to climate neutrality than a predominant reliance on intermittent renewables.

JEL Classification: L26, L52, L70, O38, P11, Q48, Q58

Keywords: climate change, cispatchable electricity, green transition, mission-oriented policy, renewable electricity, rent-seeking

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Introduction

The European Union and several of its key institutions, and by implication its 27 member countries, have explicitly identified wind and solar power as essential for transitioning to a fossil-free economy.

The European Green Deal sets a binding target to reduce net greenhouse gas emissions by at least 55% by 2030. It underscores the need for higher shares of renewable energy and greater energy efficiency, aiming to make Europe the first climate-neutral continent by 2050 (European Commission, 2019).

The amended Renewable Energy Directive (RED III) sets binding national and EU targets for the share of renewable energy sources; to meet these targets the share of renewable energy in gross final consumption of energy needs to increase to 40% by 2030 (European Parliament, 2023). The energy transition mandate has been accelerated through the REPowerEU Plan (European Commission, 2022a) in response to a perceived need to reduce the EU's dependence on Russian fossil fuels following Russia's war on Ukraine.

Achieving net-zero emissions will require a dramatic shift in the electricity generation mix towards fossil-free sources. Renewables, particularly wind and solar,[1] are expected to dominate, with 2020 projections indicating that renewables could provide 75% to 100% of electricity, with at least 60% coming from wind and solar (European Commission, 2020).

Until February 2022, nuclear power was not included in the EU Green Taxonomy, and it was thus not expected to be part of the EU's long-term energy mix despite being fossil free. This was changed with the adoption of the Complementary Climate Delegated Act (European Commission, 2022b). Hence, the EU no longer considers that nuclear energy causes more harm to human health or the environment than other electricity production technologies already considered sustainable.

The European Union's stance on nuclear power has evolved over the past few years, particularly in the context of its green transition strategy. While nuclear energy has long been a component of the EU's energy mix, its role in achieving climate neutrality has been subject to extensive debate and policy shifts.

Although no longer a member of the EU, the United Kingdom has adopted similarly stringent goals having committed to fully decarbonizing the electricity system by 2035 (GOV UK, 2021) and having a legally binding target to achieve net-zero greenhouse gas emissions by 2050 (GOV UK, 2019). The Biden

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[1] Photovoltaic (PV) is the precise technical term for the technology that converts sunlight directly into electricity using semiconductor cells is photovoltaic (PV) power. Since our essay has a clear policy orientation, we have chosen to use the broader and more accessible term solar throughout.

administration in the United States adopted exactly the same goals (White House, 2024), goals that were instantly revoked by the Trump administration in early 2025.

The challenge is greatly enhanced by the fact that the generated electricity is not only required to be fossil free; a sharp increase in electricity consumption is key to achieving the transition. Total electricity consumption in the EU is expected to increase from some 2,700 TWh in 2024 to close to 7,000 TWh by 2050 (Dickson, 2021).[2] While EU bodies acknowledge that short-term price volatility is a concern, they suggest that, with appropriate measures, the long-term average electricity prices may not necessarily increase (European Commission, 2024).

The purpose of this essay is to critically review the current plans by the EU and the UK to achieve a full green energy transition by 2050 where a key component is a huge expansion of the consumption of fossil-free electricity.

Our analysis shows that key system functions are largely ignored,[3] that the cost models underestimate real economic consequences, and conclusions are not supported by empirical evidence or theory.

The essay is organized as follows. In the next section, we present the empirical trends in electricity consumption and production in the EU, the UK and the United States, illustrating the divergence between political ambition and actual development. We then turn to the economic consequences of different technology mixes, focusing first on electricity prices and their correlation with weather-dependent power, and then on neglected but crucial system functions. This is followed by an analysis of system-level costs, demonstrating that levelized cost comparisons conceal major integration and balancing costs. After that, we discuss the economics at the power-plant level, showing that actual costs are higher than often reported and that profitability is undermined by market design and intermittency. In the subsequent sections, we review broader societal consequences, including external costs related to land use, biodiversity, and property values. We also stress that the concept of sustainability should not be narrowly defined but encompass system-level analysis and a broader understanding of sustainability that includes environmental, social, and economic dimensions.[4] The final section contains our main conclusions.

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[2] For the UK, an approximate doubling is expected in order to achieve net zero by 2050 (NESO, 2025).

[3] Concerning the system function and system-related costs we will to a great extent rely on studies and experiences from our native country, Sweden. Considering that the share of weather-dependent electricity production is significantly greater in large countries such as Germany, the UK, and Spain, Swedish experiences are highly likely to be applicable in most other European countries.

[4] For a more thorough elaboration on this point, the reader is referred to Fahlén (2023a) and Harjanne and Korhonen (2019).

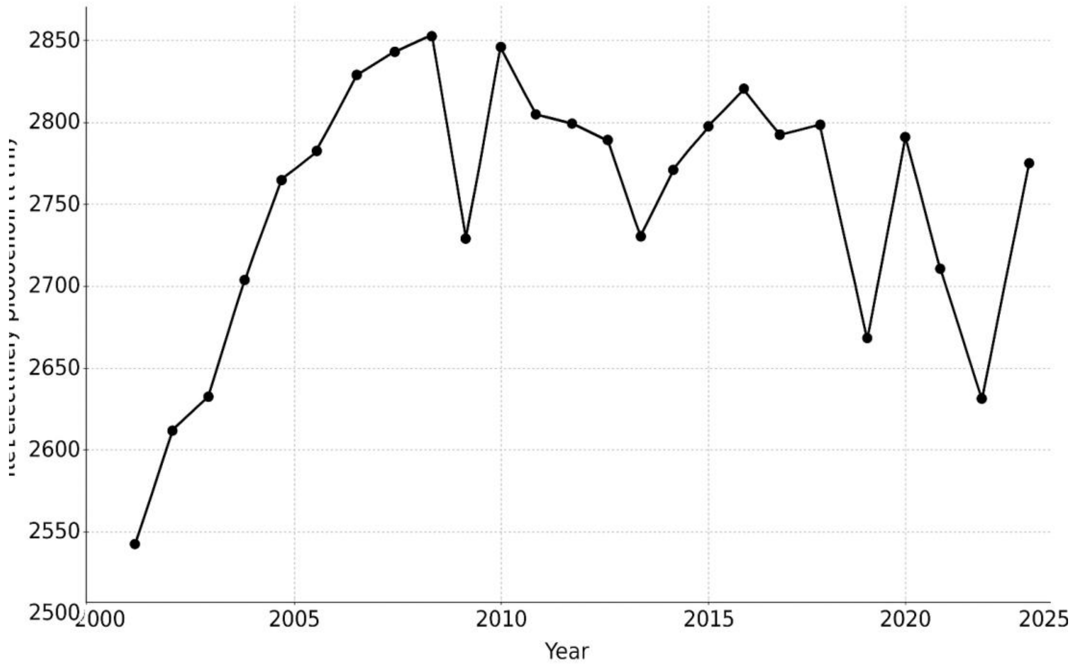
Our objective is *not* to dispute the goal of climate neutrality. Rather, we argue that the transition must be pursued in a manner that is technologically robust, economically viable, and socially acceptable. This requires a sober analysis of how different electricity generation technologies contribute—or fail to contribute—to the functionality, resilience, and cost-effectiveness of the power system as a whole.

The Empirical Picture

In its "Fit-for-55" package the European Commission envisages that Europe's electricity will be almost completely zero carbon-based by 2050. They project that electricity will be 57% of the EU's energy mix and that a further 18% will be electrified indirectly via renewable hydrogen and its derivatives (Dickson, 2021).

At the time of writing, four years have elapsed since these plans were launched but as shown in Fig. 1, net electricity production has fallen in the EU since the 2008 peak. In 2024 it was 5% lower than in 2008 and in 2023 consumption was the lowest in two decades. Despite an increase in 2024, total EU power demand remained almost 5% below the level just before the onset of the pandemic. The development in Germany is particularly noteworthy: From the peak in 2008 to 2023 German electricity consumption fell by 17% from 618 to 514 TWh.[5]

Fig. 1. Net Electricity Production in the EU, 2001–2024 (TWh).



Source: Eurostat.

Although the EU's net electricity generation has remained relatively stable, fluctuating between 2,700 and 2,800 TWh, Table 1 shows that there has been a

[5] The development is even more dramatic in the UK: From the peak in 2007 to 2023, UK electricity consumption fell by 24% from 373 to 283 TWh.

significant change in the composition of production. In EU-27, the shares of coal, natural gas, oil and nuclear power have fallen substantially, while the share of wind, solar and biomass have increased sharply to almost 32% in 2023. The change in the UK is even more dramatic, where coal has been almost totally phased out and replaced by wind power; wind, solar, and biomass were close to 40% in 2023. The fossil fuel share has fallen by 44 percentage points in the UK since 2008 compared to 34 percentage points in EU-27. The fossil fuel share has fallen far less in the United States since coal has been largely replaced by natural gas.

Table 1. The Electricity Generation Mix in EU-27, the UK and the US, 2008 and 2023 (%).

	EU-27		**United Kingdom**		**United States**	
Source	**2008**	**2023**	**2008**	**2023**	**2008**	**2023**
Coal	29.0	11.7	31.0	1.0	48.0	16.2
Natural Gas	20.0	17.0	45.0	31.2	21.0	43.1
Nuclear	28.0	22.8	13.0	14.8	19.0	18.6
Wind	1.3	18.5	1.5	28.8	1.3	10.2
Solar	0.1	9.1	0.0	4.6	0.1	3.9
Biomass	2.0	4.1	1.0	4.9	1.0	1.1
Hydro	11.0	13.5	1.0	1.2	6.1	5.7
Geothermal	0.2	0.2	–	–	0.4	0.4
Oil	5.0	1.4	–	–	1.1	
Other	1.7	1.6	7.5	13.4*	2.0	0.8
Fossil share	54.0	30.1	76	32.2	70.1	59.3

*The bulk of this share consists of net imports (12.4%).
Source: Eurostat, National Energy System Operator (NESO), and the U.S. Energy Information Administration.

If we take the EU projection of a need for 7,000 TWh in 2050, let us see what that requires in terms of electricity generation from different sources in the case of 100% renewable electricity and in two alternatives where it is sufficient that the electricity is fossil free. This exercise is presented in Table 2 based on the following three scenarios:

2050: I. The entire (except for some increase in hydro and biomass) increase in electricity is renewable, which was EU policy until early 2022. This means that all nuclear energy will be phased out.

2050: II. Wind and solar will make up 50% of the total in 2050 and the remainder (except for some increase in hydro and biomass) will be picked up by nuclear energy.

2050: III. Wind and solar will make up 20% of the total in 2050 and the remainder (except for some increase in hydro and biomass) will be picked up by nuclear energy.

In all scenarios fossil-fuel sources are set to zero and we assume that hydro and biomass can increase by approximately 50% from current levels. The item "Others" is set to 1%. We also assume that the share of wind will be double that of solar (which was roughly the case in 2023).

Table 2. Rough Electricity Mix Share (%) in EU-27 in 2022 and Potential Mixes Totaling 7,000 TWh in 2050.

	2022		**2050: I**		**2050: II**		**2050: III**	
Source	**Share**	**TWh**	**Share**	**TWh**	**Share**	**TWh**	**Share**	**TWh**
Wind	~15	~420	59.1	4,150	33.3	2,333	13.3	933
Solar	~8	~210	29.5	2,050	16.7	1,167	6.7	467
Nuclear	~22	~610	0	0	38.6	2,700	68.6	4,800
Natural gas	~19	~540	0	0	0	0	0	0
Coal	~17	~475	0	0	0	0	0	0
Hydro	~11	~305	6.4	450	6.4	450	6.4	450
Bioenergy/ Waste	~7	~185	4.0	280	4.0	280	4.0	280
Others	~2	~55	1.0	70	1.0	70	1.0	70
Total	100	~2,800	100	7,000	100	7,000	100	7,000

Source: Eurostat.

The table clearly shows that the demand for wind and solar is very large in the first two scenarios, requiring expansion of roughly 900 and 450 percent, respectively. In scenario III, where wind plus solar is restricted to 20 percent of the total, the required expansion is roughly 120 percent from the 2022 level. Instead, a huge expansion of nuclear electricity is needed; by roughly 2,100 and 4,200 TWh, respectively, in scenarios II and III.

To achieve the projected expansion of electricity production, the required expansion of installed power will differ greatly across scenarios. This will have substantial effects on system costs and stability. Assuming a capacity factor[6] of 0.3 for wind, 0.1 for solar, 0.85 for nuclear and 0.45 for hydro, scenario III, heavy on nuclear power, requires 2.4 times the installed capacity in 2022 to achieve the projected 2.5-fold increase in electricity output. Scenario II, with a greater reliance on renewables, requires 3.5 times the 2022 capacity, and scenario I, where renewables predominates, requires 5.2 times the 2022 installed capacity. In addition to the larger capacity, the greater number of generators being spread over a much

[6] The capacity factor is the ratio of the actual electricity generated over a given period to the electricity it could have generated if it operated at its full capacity the entire time.

wider area will require an oversized transmission, stabilizing and balancing system and this simple comparison does not even include the larger required gross supply of energy to cover the given net demand due to the increasing system losses resulting from a greater share of renewable production (Fahlén, 2023b). The assumed capacity factors are based on current data. Thus, they do not consider that these factors will decline as the share of renewables goes up. This is especially so for wind and solar generators, as the need for curtailment rises due to the installed overcapacity.

If we translate this into a need for new reactors, let us use the recently built reactor in Olkiluoto in northern Finland, OL3, as a benchmark. In 2024, the OL3 power plant unit produced 9.69 TWh. Hence, 217 and 433 reactors of that size would be needed in scenarios II and III, respectively. There are many proponents for covering most of the need using small modular reactors (SMRs) instead. SMRs are projected to produce somewhere in the range 0.4 to 2.4 TWh per year. Assuming an average size of half the maximum, we are talking about several thousand SMRs in both scenarios.

The remainder of this essay will be devoted to discussing the consequences of each of the three 2050 scenarios outlined above, focusing on their implications for electricity prices, and system functionality. We begin by examining the current relationship between electricity prices and the share of weather-dependent electricity production, using cross-country data to highlight the economic consequences of large-scale wind and solar deployment. We then turn to core system functions—such as capacity adequacy, grid stability, and system inertia—and assess how these are affected by an increasing reliance on intermittent power. Particular attention is given to the growing complexity and cost of securing a stable electricity supply when dispatchable generation is replaced by variable renewables.

A central challenge in scenarios with high shares of wind and solar is the need for vast amounts of storage, such as hydrogen or batteries, to compensate for periods with little or no wind and sun. We show that storage needs, and associated costs, differ dramatically between scenarios: a system dominated by intermittent sources may require orders of magnitude more storage than one based on dispatchable, fossil-free baseload. Finally, we discuss the broader system-level and economic implications of each pathway, arguing that any viable strategy must consider the full set of system requirements, not just nominal production targets or power plant-level cost estimates.

The Price of Electricity

European Union institutions acknowledge that the rapid integration of intermittent renewable energy sources, such as wind and solar, introduces challenges related to electricity price volatility and grid stability. Flexibility solutions are said to be essential to address these challenges (ACER, 2023). However, they do not assert that this transition will necessarily lead to increased average electricity prices over the long term. Instead, they emphasize the need for strategic investments and market reforms to mitigate potential cost impacts.

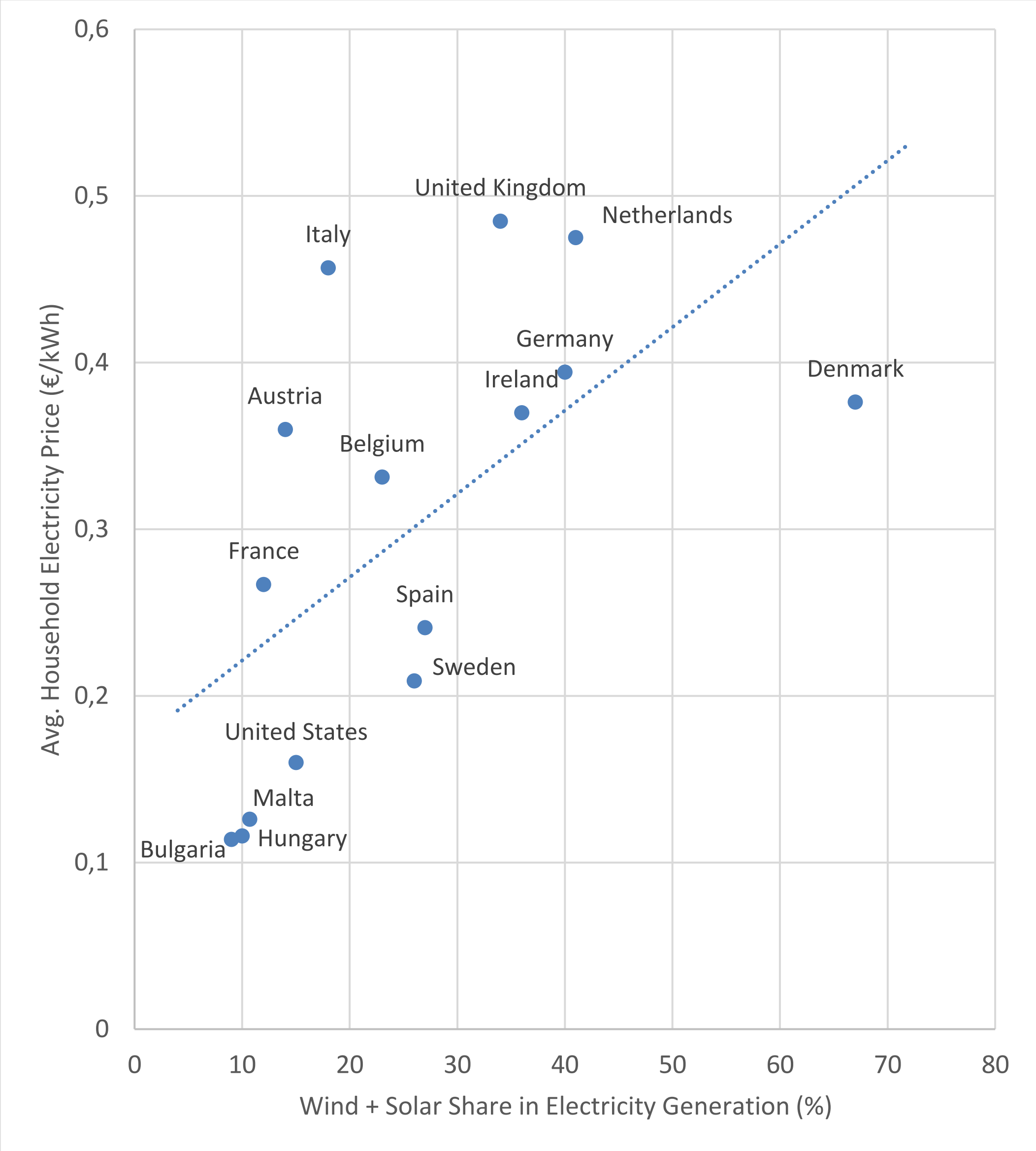
The European Union Agency for the Cooperation of Energy Regulators (ACER) has highlighted that the expansion of renewable energy sources contributes to increased price volatility in electricity markets. One suggestion is to use enhanced forecasting methods to support the EU's energy policies by stabilizing electricity markets and reducing financial risks associated with price fluctuations (Cerasa and Zani, 2025).

However, while short-term price volatility is a concern, EU bodies suggest that, with appropriate measures, the long-term average electricity prices may not necessarily increase. Although most of the challenges are caused by the rapidly growing share of weather-dependent electricity sources, it is striking that the European Parliament and the Commission continue to focus primarily on reducing the influence of fossil fuels on electricity prices and on promoting investments in renewable energy projects. (European Commission, 2025). These changes are intended to enhance the EU's energy security and stabilize prices in the long term.

Is there any evidence that this will work? Since there are large cross-country variations in the share of electricity from weather-dependent sources, an indication can be made by studying the correlation between the share of wind + solar electricity and the average electricity price paid by households. This relationship is shown in Fig. 2 for EU countries plus the UK and the United States. A correlation coefficient of $r = 0.60$ shows a strong positive relationship, i.e., countries with higher shares of wind and solar tend to have higher electricity prices. The inserted trend line has a slope of 0.0050, indicating that each percentage point increase in wind + solar share is associated with an estimated increase of EUR 0.005/kWh in household electricity prices. A recent German study supports the view that the cost of electricity increases sharply as the share of renewables goes up (Begemann et al., 2025).

If Denmark is excluded from the dataset, the correlation coefficient increases to 0.71, indicating an even stronger positive relationship between wind + solar share and electricity price. The slope also increases to 0.0083. Denmark's extreme share of wind + solar of almost 70 percent would not have been possible without access to baseload power from Sweden and Germany.

Fig. 2. The share of wind + solar electricity and household electricity price (EUR/kWh) in 2023.



Source: Eurostat and https://ember-energy.org/data/electricity-data-explorer/.

Admittedly, Fig. 2 is based on a small number of countries due to data availability, and it can sometimes be difficult to compare prices between countries as prices vary due to different forms of support.[7] Despite these differences, the positive correlation remains robust. Hannesson (2025) finds a nearly identical relationship using averaged data from 2019–2021 for OECD countries. She reports a correlation similar to what we observe when Denmark is excluded from our dataset, with a slope coefficient of 0.65. This means that each percentage point

[7] Germany is an obvious case in point where the average electricity price for households was roughly EUR 0.40 per kWh in 2024 despite extensive direct subsidies to producers (Karlsson, 2025a).

increase in the share of wind and solar is associated with an estimated increase of USD 0.0065/kWh in household electricity prices.

The empirical evidence presented above shows a clear correlation between the share of intermittent renewables and higher average electricity prices. It is therefore relevant to revisit the three 2050 scenarios introduced above in order to assess their respective exposure to long-term price pressures.

Scenario I assumes that the entire increase in electricity demand is met with renewable sources, mainly wind and solar. This is the scenario with the highest share of intermittency; the resulting share exceeds 93%, which is far higher than any other country today. The strong positive correlation and steep slope documented in Fig. 2 strongly suggest that such a high share of intermittency would result in average prices far above levels experienced by the UK and Germany today. This observation is consistent with the documented correlation between the share of wind and solar power and household electricity prices. Scenario I is therefore likely to involve high costs for balancing, storage and system stabilization, which in turn would lead to higher electricity prices.

Scenario II reduces the share of wind and solar and replaces it with nuclear power, which is dispatchable and thus not weather-dependent. Although this configuration lowers the volatility and the need for balancing services compared to Scenario I, it still includes a substantial amount of intermittent generation. In fact, countries that already have similar shares of weather-dependent electricity, such as Denmark and Germany, tend to experience elevated average electricity prices and frequent price spikes. Thus, the associated integration costs are likely to be substantial also in Scenario II.

Scenario III reduces the share of wind + solar to 20% and relies primarily on nuclear power to meet the projected demand increase. This significantly lowers the need for large-scale storage and short-term balancing measures. The dependence on external stabilization mechanisms is also much smaller. If implemented, this scenario would resemble systems that rely on stable baseload production and therefore tend to show lower and more predictable electricity prices.

In conclusion, current empirical data suggest that scenarios with large shares of weather-dependent electricity, such as Scenario I, are more likely to result in high electricity prices unless large-scale and costly countermeasures are introduced. A system based on fossil-free but dispatchable baseload, such as Scenario III, offers a more robust foundation for price stability and long-term cost control. Scenario studies by Fahlén (2023b) and Begemann et al. (2025) support these findings.

In sum, there is little evidence to date that the EU will be able to find efficient measures that hinder a rise in long-term average electricity prices if the share of electricity from intermittent sources continues to increase.

System Functions

Ensuring proper system functionality is fundamental to a reliable electricity supply. A well-functioning electricity system requires four things: delivery of sufficient energy, sufficient instantaneous power, high power quality, and robust security of supply. These requirements must be met in real time and in concert.

Sweden provides a striking example. In 2023, the Swedish National Audit Office (2023) delivered scathing criticism of the Swedish energy policy's lack of impact assessment for these basic needs. Svenska kraftnät, the national grid operator responsible for the secure operation, development, and maintenance of Sweden's high-voltage electricity transmission system, has for many years warned of the rapidly increasing problems with the expansion of wind power. In its 2025 report, the operator estimated that in the winter of 2025/26, there may be a lack of planned capacity equivalent to seven nuclear power plants (Svenska kraftnät, 2025). However, increasing the share of wind power will not address the capacity adequacy issue. On the contrary, due to its weather dependency and limited dispatchability, it may exacerbate the challenge of ensuring firm capacity during peak demand periods.

Increasing the amount of wind power also means more transmission infrastructure. But the larger the transmission network and the more distributed the electricity generation, the more difficult it will be to maintain the stability of the system. This is clearly demonstrated by the Spanish blackout in April 2025. The more uneven production spread over larger areas requires transmission networks that are not only longer but also of higher capacity. This creates a high additional cost and is negative for the environment. To a large extent, these transmission costs are avoided with nuclear power. The operator's evaluation of the Spanish blackout (Red Eléctrica, 2025, p. 8) presents a number of important lessons such as

> [i]t is important to highlight the rate at which generation output can change within the system. New technologies based on power electronic inverters are capable of adjusting their output within a matter of seconds. While this capability is highly beneficial for the economic optimisation of individual generating plants, it is not necessarily ideal from a power system stability perspective in general.
>
> A clear example of this is the rapid schedule changes in photovoltaic generation driven by price fluctuations in electricity markets. From an electrical standpoint, such abrupt changes in inverter-based generation introduce significant imbalances into the system, because regulation mechanisms haven't operated yet. These imbalances must be compensated mainly through interconnections, particularly the one with France.
>
> Severe imbalances lead to drastic shifts in power flows across the network, which in turn alter the capacitive and inductive behavior of the grid. Consequently, system voltages can vary rapidly. This effect is further exacerbated when such generation operates under power factor control and does not provide dynamic voltage control, as it limits the dynamic reactive power support that could otherwise help stabilize voltage.

Fuel-based power, such as nuclear power, can act as baseload, balancing and regulating power and the fuel itself functions as storage. It can also be located close to high-consumption areas, whereas wind power is generally built far from users and requires additional external systems in the form of balancing power/storage, transmission networks and grid stabilization systems. Synchronous generators in hydro and nuclear power plants, due to their large rotating mass, are proactive, i.e., prevent disturbances from occurring. In contrast, "synthetic" inertia, which is often promoted as a solution for wind power, is reactive and must constantly correct disturbances that have already occurred. This adds both complexity and cost to the system. To assist wind power, large rotary converters are also installed to stabilize the grid and manage reactive power.[8] They basically act as synchronous generators but without producing any electricity; instead, they consume electricity and incur an additional cost.

A reliable electricity system must be able to deliver sufficient energy and power at the right time and place, maintain frequency and voltage within narrow margins, and uphold a high level of security of supply. These requirements must be met continuously and simultaneously. The three 2050 scenarios differ markedly in how well they support these fundamental system functions.

Scenario I, which relies almost entirely (93%) on wind and solar power, presents the greatest challenges. Weather-dependent production cannot be dispatched on demand and often requires extensive backup in the form of balancing power, synthetic inertia, frequency control systems, and large transmission networks. The expansion of transmission infrastructure becomes necessary because wind and solar installations are typically located far from consumption centers. These additions increase both cost and vulnerability, while also having environmental consequences. In this scenario, large investments would be needed in grid stabilization and reserve capacity to ensure system reliability, especially during periods of low wind and solar output.

Scenario II reduces the share of weather-dependent power and introduces a significant amount of nuclear energy. While still dependent on wind and solar for a substantial portion (50%) of production, this configuration allows for a greater degree of dispatchability and reduces the strain on ancillary systems. Nuclear power can provide both baseload and balancing services, and its contribution to system inertia improves frequency stability. However, the share of wind + solar in Scenario II

[8] Reactive power is the difference between active power—i.e., the useful power—and the total power consumed. In electric power systems with a high share of weather-dependent solar and wind generation, there are few synchronous generators, which traditionally provide intrinsic control of reactive power. As a result, active power is controlled but reactive power probably not. This may lead to severe problems in voltage control, which was the case in the Spanish blackout (Red Eléctrica, 2025). Additional, often costly, equipment may be required to manage reactive power. Excessive reactive power reduces system efficiency, limits transmission capacity, and increases losses.

is almost double the 2023 share in EU-27 (Table 1). Thus, the system will still require substantial investments in backup capacity and advanced control technologies to manage fluctuations in renewable output.

Scenario III, with its emphasis on nuclear power and a limited share of wind + solar (20%), offers the most favorable conditions for robust system operation. Dispatchable power is available in large quantities, and system inertia is inherently provided by synchronous generators. The need for additional stabilization mechanisms, fast-reacting reserves, and external balancing resources is much lower. This reduces both the technical complexity and the operating cost of the system, while also enhancing resilience during periods of stress.

In summary, from a system functionality perspective, Scenario III is clearly the most robust. Scenario II represents an improvement over full reliance on renewables but still entails significant integration demands. Scenario I appears to be the most fragile, requiring comprehensive and expensive support systems to ensure reliable operation.

As the European Union accelerates its transition toward weather-dependent electricity generation, the structural demands placed on the electricity system grow accordingly. The increasing reliance on weather-dependent sources such as wind and solar introduces variability that must be managed in real time. This puts pressure on the system to provide sufficient flexibility—both in terms of supply and demand—to uphold operational reliability. But this flexibility comes at a high cost and results in a less efficient society with loss of production and services.

According to the European Commission's Joint Research Centre (JRC), the need for system flexibility will more than double by 2030 and increase sevenfold by 2050, compared to 2021 levels. This steep rise is directly linked to the variable nature of renewable power and the current shortage of large-scale, cost-effective storage solutions (Joint Research Centre, 2023). Without adequate flexibility, the power system becomes more vulnerable to imbalances, frequency deviations and price spikes, particularly during periods of low wind and solar output (cf. the Spanish blackout).

The EU Agency for the Cooperation of Energy Regulators (ACER) emphasizes that the rapid phase-out of conventional thermal generation, combined with the growth of intermittent renewables, intensifies the challenge of ensuring security of supply. Maintaining a stable system under these conditions requires both technical and market-based mechanisms that can deliver rapid balancing services (ACER, 2023).

In parallel, there are growing concerns regarding the physical infrastructure required to support this transformation. The European Parliamentary Research Service (EPRS) notes that much of the existing electricity grid in Europe is outdated and poorly adapted to the decentralized production patterns introduced by wind and solar power. Significant investment is needed to modernize transmission and distribution systems, integrate digital control technologies, and increase the grid's ability to handle bidirectional and fluctuating flows of electricity (EPRS, 2023). Without these upgrades, congestion costs and curtailment rates are likely to rise, eroding both efficiency and public acceptance of the transition.

Together, these developments point to a fundamental system challenge: the move toward high shares of variable renewables demands not only new generation capacity, but a deep transformation of how the electricity system operates and is governed. Flexibility, redundancy, and infrastructure resilience must become central design criteria, not afterthoughts.

Countries with a high share of solar and wind power have major system problems and are partly forced to ensure the functioning of the system by means of fossil fuel power plants.

To manage the intermittency of wind and solar power, there must be other power sources that can be switched on and off whenever needed to balance supply and demand. The more wind and solar power in the system, the more capacity must be available in balancing power plants to replace solar and wind power when the sun is not shining and/or there is insufficient or no wind. The capacity utilization of these balancing power plants will be lower the more wind and solar power is installed, which means that their revenue will be lower. To compensate for this fact, either balancing power prices have to be higher, or the owners of the balancing power plants have to be paid for availability and not only for electricity produced. Therefore, even if intermittent power were cheaper than traditional baseload power, it will not only lead to more volatile prices but also to higher electricity prices overall. Average household electricity prices have therefore increased in countries with high shares of wind and solar power.

The System-Level Economy

It is reasonable to require that system-level externalities be internalized, ideally down to the power plant level. However, such internalization must be based on accurate and comprehensive cost assessments. Cost estimates that omit key system services—such as frequency control, reactive power, inertia, and regulating capacity—fail to capture the true economic and operational impact of electricity production.

The LCOE is defined as the average cost required to build and operate a power plant over its expected lifetime, expressed per unit of electricity produced. While useful under conditions of stable demand and dispatchable generation, the LCOE fails to account for a number of key factors. These include financing conditions, real operational lifetimes, availability, and maintenance costs. Importantly, it does not include any allowance for system-level impacts such as grid integration costs, profile effects, or balancing requirements. The International Energy Agency (IEA) has noted that this metric is particularly misleading in systems with a high share of intermittent generation, where system interaction effects are substantial.

The Levelized Cost of Electricity (LCOE), commonly used to compare base-load generation technologies, does not include these system-level costs. It only reflects the average cost of building and operating a plant over its lifetime. This metric ignores integration costs, which become significant when a high share of electricity comes from intermittent sources. These costs include profile costs (which capture the mismatch between supply and demand over time),[9] balancing costs, and grid infrastructure costs. To address these omissions, alternative indicators such as system LCOE, Actual Cost of Electricity (ACOE), and Levelized Full System Costs of Electricity (LFSCOE) have been developed.

Ueckerdt et al. (2013) show that when wind power reaches around 20 percent of the electricity market, the costs of integrating it into the system become significant. The main reason is that production does not always coincide with demand. Often a great deal of electricity is generated at the same time, which pushes down prices and reduces the value of the electricity. At a 40 percent market share, these costs are roughly twice as high. The OECD NEA (2012) reaches similar conclusions and emphasizes that integration costs rise rapidly as the share of weather-dependent electricity increases. The ACOE framework expands on the traditional LCOE by factoring in the reduced market value of intermittent generation and the lower capacity utilization that occurs as overcapacity increases. Based on real data from 2022, Manzolini et al. (2024) report that as wind power's market share rises from 0 to 50 percent, the cost per kWh increases from EUR 0.09 to 0.12 in Denmark, from EUR 0.09 to 0.15 in Germany, and from EUR 0.12 to 0.15 in the Netherlands. At a 50% share, curtailment is as large as 20–40% due to the high overcapacity. The study also shows that irrespective of market share, the use of battery storage for the excess capacity will always make wind power more expensive.

A more radical approach is the LFSCOE, which estimates the full cost of a system in which electricity is produced entirely by one type of technology. Idel (2022) calculates that for Germany, the LFSCOE is USD 0.106 per kWh for nuclear, USD 0.504 for wind, and USD 1.55 for solar power. These figures illustrate the sharp cost escalation associated with high shares of weather-dependent electricity sources.

In some countries, hydropower has historically played a key role as balancing power. However, its flexibility is now fully utilized in many systems. In Sweden, for example, balancing costs increased by more than SEK 5 billion (almost

[9] The term "profile effects" refers to the fact that wind and solar power produce electricity according to weather conditions rather than consumption needs. When production is high, prices fall, and when production is low, other capacity must cover the gap. In the academic literature this is also called "profile costs" (Hirth, 2013).

EUR 0.5 billion) from 2021 to 2023, during which time wind power production rose by roughly 7 TWh. While not all the cost increase can be directly attributed to wind, it remains the principal factor. The marginal balancing cost in this case exceeded the assumed LCOE of wind power by a wide margin, pointing to a systematic underestimation of its full cost.

A growing challenge arises from the increasing use of fixed-price Power Purchase Agreements (PPAs) in the wind sector. These contracts provide producers with a guaranteed price per kWh, regardless of market conditions. As long as the negative market price is not in absolute terms greater than the guaranteed price set by the PPA, it is rational for producers to continue generating power even when the electricity is not needed. Such electricity is typically excluded from exchange trading and is often exported, thereby bypassing domestic consumers. In Sweden, this dynamic has coincided with a long-term decline in domestic electricity consumption—not due to reduced demand, but as a result of higher costs and limited ability to connect new users, largely caused by insufficient dispatchable capacity following nuclear phase-outs (Sandström, 2025).

High shares of wind power give rise to periods with insufficient electricity generation. A commonly proposed solution is battery storage. To illustrate the scale of this challenge, consider a scenario in Sweden with one week of low wind in winter leading to a shortfall of 2 TWh. If half the shortfall must be compensated through storage and weekly electricity demand in mid-winter is roughly 4 TWh, then 1 TWh of battery capacity would be needed. This corresponds to roughly one-third of the storage capacity of all batteries produced in the world in 2024.

At world market prices, this would require an investment of approximately SEK 3.7 trillion (59% of Sweden's GDP in 2024).[10] With a battery lifespan of ten years, this entails annual depreciation of SEK 370 billion, plus financing costs of about SEK 74 billion per year at an interest rate of 4 percent. Combined, this represents more than 7 percent of Sweden's GDP. The climate impact is also significant: manufacturing this storage would emit around 150 million tons of carbon dioxide. Over ten years, this equates to 15 million tons annually, which is roughly one third of Sweden's current total emissions. These estimates strongly suggest that large-scale battery storage is not a viable solution for managing week-long periods of insufficient wind with current technology.[11]

Finally, the economic viability of other generation types is also undermined in systems with high shares of intermittent power. According to the OECD-NEA (Keppler et al., 2018), nuclear power revenues fall by 24 percent when wind power reaches 10 percent of the market and by 55 percent at a 30 percent share. For open-cycle gas turbines, which are important for balancing, the losses are

[10] The EUR/SEK exchange rate was approximately 11.20 in August 2025.
[11] Calculations are based on data from Ask (2025).

even greater—54 and 87 percent, respectively (Keppler et al., 2018), and these losses require compensation. These findings underscore the high and often overlooked system costs associated with maintaining stable and reliable electricity supply in systems dominated by variable renewables.

The Power-Plant Level Economy for Wind Power

A widely accepted principle in electricity market design is that costs and benefits should, to the greatest extent possible, be attributed to the level where decisions are made, typically the power plant. This principle is consistent with European guidelines for grid connection and market participation. However, in systems with a high share of variable renewables such as wind and solar, the most used cost metric, the Levelized Cost of Electricity (LCOE), becomes increasingly inadequate.

Reported production costs for onshore wind power in Northern Europe typically range from EUR 0.03 to 0.04 per kWh and the presumption is that the cost will continue to decline. However, market data and project tenders suggest considerably higher figures. For example, the guaranteed strike price requested by developers in recent UK auctions for onshore wind was around GBP 0.071 (≈ EUR 0.082) per kWh in 2024, a figure similar to reported contract levels in Germany. This is more than double the typical assertions regarding the plant-level production cost.

Financial performance data from Sweden further illustrates the challenge. Wind power companies in the country lost an average of 0.35 cents for every euro of electricity sold between 2017 and 2023 (Sandström & Steinbeck, 2025). Thus, just to break even, these firms would have needed higher average selling prices that were 35% higher. These losses suggest that the actual levelized production costs are closer to SEK 0.70 or more per kWh, roughly double the typically cited figure (Energiforsk, 2021).

The economics of wind power has also deteriorated due to technical trends. Newer turbine generations, while larger and more powerful, have proven more expensive to operate and maintain. Hughes (2021) documents that wear and tear substantially reduce the capacity factor and that the actual economic life spans are closer to 15 years for onshore and just 12 years for offshore wind, in contrast to the 25 to 30 years typically used in investment models. This is confirmed by significant losses among major wind turbine manufacturers and growing warranty obligations due to performance issues (Matthis, 2023) and it will also increase the LCA (life cycle analysis) environmental impact.

These technical and financial constraints are further compounded by the declining market value of wind power as its share increases. This profile cost, caused by production clustering during high-wind periods when prices are low, weakens the economic return on new investments. Sandström and Steinbeck (2025) show that this effect has already contributed to protracted losses in the Swedish wind power sector. The market has all but collapsed and installations that were valued at EUR

1.5 million per MW a couple of years ago may be for sale at less than EUR 10 per MW (Berg, 2025).

International comparisons reinforce these findings. A detailed review by Hughes (2020) reported average production costs in the UK of GBP 0.091 per kWh for onshore wind and GBP 0.152 for offshore wind, while the average market value was only GBP 0.0013 per kWh. These figures are consistent with guaranteed prices in Germany and recent long-term contracts across Europe.

Ownership and market structure also play an important role. In Sweden, many wind power assets are owned by foreign entities and financed through publicly guaranteed loans, either at the national or EU level. As already mentioned, electricity is often sold through fixed-price power purchase agreements (PPAs) directly to foreign buyers, bypassing the domestic electricity market. As a result, this electricity does not affect local prices and is not available to Swedish consumers, who instead face higher prices and reduced supply flexibility (Fahlén, 2023a; Sandström & Steinbeck, 2024).

Examples from across Europe reveal recurring challenges in systems with high shares of wind and solar. In Germany, installed capacity of variable renewables already exceeds twice the maximum hourly demand, yet over half of electricity production still comes from dispatchable fuel-based sources (Karlsson, 2025a). Finland, which has expanded wind capacity rapidly, is together with Spain the European country with the highest share of hours with negative electricity prices (Karlsson, 2025b).

Such systems tend to require substantial overcapacity. In some cases, total installed capacity exceeds 300 percent of peak demand.[12] As a consequence, operators are frequently compensated to curtail production during periods of excess supply. In Sweden, hydropower producers are paid to spill water, and wind operators are paid not to produce. At the same time, fossil-based balancing plants are compensated for remaining idle when wind production is high. This constellation of support mechanisms lowers utilization rates, raises system costs, and increases the environmental footprint of the power system.

Social Benefits and Costs of Externalities

While wind power is often framed as a clean and socially acceptable form of energy, its negative effects tend to receive less attention. These include local disturbances, environmental degradation, and increasing demands on system stability. Although each European country faces unique circumstances, this section focuses

[12] By the end of 2024, Germany's installed capacity of wind and solar power was 72 (of which 9 offshore) and 99 GW, respectively. To this should be added the installed capacity of non-renewable power of 92 GW. Peak demand during the busiest winter hour in 2023 was 73 GW. Hence, installed capacity of solar + wind was 234% of peak demand, while total installed capacity was 360% of peak demand (Bundesnetzagentur 2025).

on the Swedish case, where the interplay between wind power expansion and local impacts is particularly well documented.

In southern Sweden, there are estimates suggesting that the combined cost of compensating local residents for disturbances and of incentivizing municipalities to approve wind power projects amounts to approximately SEK 0.02 (i.e., less than 0.2 cents) per kWh of electricity produced (Tangerås et al., 2024, p. 142; leaning on Lundin, 2024). However, this figure does not include any fall in property values, reduced agricultural productivity, or broader land-use conflicts. Importantly, the structure of these compensation schemes matters. Compensation provided directly to affected households is more transparent and legitimate than indirect transfers to local governments.

The reduction in property values linked to proximity to wind turbines has been quantified in several studies. Estimations based on Westlund and Wilhelmsson (2021) estimate that the total loss in property value due to wind power development in Sweden exceeds SEK 100 billion (≈ USD 10 billion).[13] This sum is roughly equivalent to the total wind power investment in Sweden between 2017 and 2024, and around ten times the annual market value of the electricity generated by these installations. If distributed over the total electricity production from wind during the last decade (about 230 TWh), this implies a hidden cost of approximately SEK 0.43 per kWh—well above commonly cited production costs (LCOE).

Additional effects on rural sectors, such as agriculture, forestry, and fishing, have not been systematically quantified but are often reported to be substantial by local stakeholders. These impacts may include habitat disruption, loss of visual landscape value, and operational restrictions due to turbine placement.

Another key externality is the increased need for balancing power as the share of intermittent electricity grows. Holmberg (2024) estimates that if wind and solar power together expand to 240 TWh annually, the producers should pay a surcharge of about SEK 0.01 (≈ 0.1 cent) per kWh to compensate for the added stress on system balance. However, this figure significantly underestimates the full economic burden, and it is unclear how it was derived.[14] System support costs for balancing power are already today in the same range as the production cost of wind power and continue to grow disproportionately as variability increases.

In addition to balancing costs, increasing shares of weather-dependent electricity also entail higher profile and transmission costs. These include the cost of

[13] In a follow-up study, Westlund and Wilhelmsson (2025) analyze over 600,000 real estate transactions from 2005 to 2018. Their main finding is that property values within 2 km of wind turbines decrease by 10 to 15%. It should be noted that this study concerns transactions that took place when total wind power production was less than half of the current level.

[14] This estimate is at least two orders of magnitude less than the estimates we cited above.

overcapacity during periods of strong winds, reduced market value of generation, and the need to reinforce transmission infrastructure to accommodate geographically dispersed production.

Taken together, both the compensation levels for local impacts and the assumed balancing cost estimates by Holmberg (2024) appear to fall short of empirical realities. More comprehensive and location-specific assessments are required to ensure that wind power expansion aligns with broader objectives of economic efficiency, social acceptance, and environmental integrity.

Environmental and System Impacts of Wind Power

Large-scale wind power differs from dispatchable sources such as nuclear in that it does not contribute to critical system services like inertia and frequency control. This reduces overall grid stability. Life-cycle analyses also suggest that wind and solar energy have higher carbon emissions per unit of electricity than nuclear power (Vattenfall, 2018; Ask, 2025).

In terms of energy return on investment (EROI), wind power performs significantly worse once the need for storage and backup is considered (Weissbach et al., 2013). Wind turbines require extensive amounts of non-renewable materials, including rare earth elements (Department of Energy, 2015). The environmental footprint includes large land requirements, noise, and biodiversity impacts, as well as challenges related to decommissioning and waste management. Recent studies have pointed to problems such as noise emissions (Garcia Forlin et al., 2024; Mattsson et al. 2025), microplastics, and toxic chemicals near wind farms (Karlsson, 2024).

Taken together, these factors underline that environmental and system costs increase sharply with large-scale deployment of wind power, and that these costs must be assessed alongside potential climate benefits.[15]

Conclusions

Official scenarios for a fossil-free "green" transition in Europe assume a huge increase in electricity consumption, driven by the electrification of transport, industry, heating and other activities relying on fossil fuels. However, since policymakers began to talk about a massive increase in electricity consumption as key to a green transition, electricity consumption has decreased in the European Union and even more so in the UK. This is not due to reduced economic activity, but rather a consequence of supply-side constraints, market uncertainty, and high average and volatile prices.

The rapid expansion of wind and solar power in Europe as a key driver of the green transition lacks proper consideration of its cumulative effects on system

[15] Such a holistic approach is consistent with the Brundtland Commission's definition of sustainable development, which emphasizes the need to balance environmental, economic and social objectives in all planning decisions (United Nations, 1987).

functionality, economic viability and environmental sustainability. With wind and solar power approaching 30% of electricity production in the European Union and 35% in the UK, the system is already experiencing growing challenges related to balancing, infrastructure needs and capacity value.

Our analysis shows that the long-term socio-economic value of weather-dependent electric power has been overstated in assessments guiding long-term strategic policy decisions. These assessments rely on narrow production cost metrics that do not sufficiently account for real-world wind-power cost, system integration costs, environmental externalities or lifecycle material demands. These include increased use of non-renewable resources, land use conflicts, and waste management concerns, as well as diminished reliability in systems with a high share of weather-dependent electricity.

A more diversified approach relying on known technologies would have been prudent. A viable alternative would have been investment in nuclear power; a technology first used in submarines in the mid-1950s. This would have provided dispatchable, fossil-free baseload electricity with much lower integration costs. In the short term, gas-fired generation could have served as a transitional balancing resource until additional nuclear capacity became available. This would have maintained system stability, reduced emissions from coal and oil, and improved the ability to meet new demand in the medium term. Despite being fossil-free and widely used, it was not until 2022 that the European Union repealed its policy of phasing out all nuclear power from its energy system.

What we have described here is a clear-cut example of a mission-oriented policy containing both an unequivocal goal to be attained at a pre-specified point in time and how it should be achieved: (i) A goal of zero CO_2 emissions to be attained by 2050; (ii) identification of the key means to achieve this goal: massive electrification of virtually all activities currently relying on fossil fuels; and (iii) pinpointing by which technologies the required electricity should be produced.

This strategy was laid down in the European Union and its member countries as well as the UK at odds with existing evidence and practical experience. In an area pinpointed as key to the green transition, decisive policy decisions were not based on relevant empirical experience, comprehensive system-level analysis and a broad understanding of sustainability that includes environmental, social, and economic dimensions.

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