The Economics of Inertia in a Decentralized and Asynchronous Power Grid

Wim Naudé* SAFeRGrid Team†

September 22, 2026

Abstract

The expansion of renewable energy sources (RES) in Europe is eroding the physical inertia that is necessary for stabilizing its synchronous AC power grid. This is transforming grid stability from a free byproduct into a high-cost service. To address this, this paper provides an exploratory economic analysis of inertia within a decentralized, asynchronous power grid model, focusing on the internet-inspired SAFErGrid proposal. With reference to SAFErGrid the paper formalizes (virtual) inertia as a localized club good, conduct a welfare comparison against shadow-priced redispatch, argue for a real-options perspective on BESS under volatility, and addressing the long-term revenue-adequacy problem inherent in virtual inertia markets.

Keywords: Energy, Renewables, Power Grids, Inertia

JEL Codes: Q41, I32, L94, O33

*TIME Research Area, RWTH Aachen University, Germany and Faculty of Economics, University of Coimbra, Portugal. Email: naude@time.rwth-aachen.de

†SAFErGrid Consortium

1 Introduction

Electricity is unique among traded commodities: in a traditional synchronous alternating-current (AC) system, production and consumption must match instantaneously at every node to maintain grid frequency (Biggar and Hesamzadeh, 2014). For over a century, this balance was maintained mechanically by the kinetic energy - or rotational inertia - inherent in large synchronous generators (SGs) (Ulbig et al., 2014).

However, the rapid expansion of renewable energy sources (RES), which are decoupled from grid frequency via power electronic converters, has structurally eroded this physical buffer (Tielens and Van Hertem, 2016; Tofighi-Milani et al., 2025; Ali et al., 2025; Mehrzad et al., 2026). As the share of RES rises, the total grid inertia therefore falls - potentially threatening power system stability (PSS)(Fernández-Guillamón et al., 2019; Smahi and Makhloufi, 2025).

Thus, to facilitate higher penetrations of RES without jeopardizing PSS, power systems engineering is shifting toward decentralized, asynchronous grid architectures supported by virtual inertia (VI) technologies (Wald et al., 2023; Schwarz et al., 2026). Virtual inertia is programmable inertia, which allows adaptive tuning to the grid's needs; which can provide multi-functionality to the grid - such as reactive power and not only kinetic energy; and which can react faster than rotational inertia technology, since it is limited only by the switching speed of silicon transistors (Gurski et al., 2024; García-Hoyos et al., 2025; Soares et al., 2023; Fernández-Guillamón et al., 2021). It is the case that the "shift from synchronous generators (SGs) - historical providers of inertia, fault current, and voltage and frequency support - to digitally controlled converters fundamentally alters fault dynamics, effort sharing, and overall frequency response (García-Hoyos et al., 2025, p.1).

While much research and development is taking place with respect to VI technologies, and the economic importance thereof is understood, the economics of VI is a scarcely explored topic. Although governments are have started to procure VI (EirGrid, 2021; MPS, 2025)) or is helping fund BESS systems to help provide inertia (Potomac Economics, 2026), there are no real-time, daily spot markets for inertia (as there is for instance for electricity). Inertia still tends to be seen in the economics of electricity as a "free" byproduct or if not free, then not economically significant. Wholesale electricity markets in the synchronous grid were designed around the marginal cost of active energy production, while treating ancillary stability services - inertia - as unpriced physical constraints.

In this light, the purpose of this paper is to explore some of the economics of (virtual) inertia. It does so with reference to the SAFErGrid proposal[1] (Schwarz et al., 2026) – a theoretical architecture for a fully asynchronous, internet-inspired power system composed of interconnected but electrically decoupled "A-grids" – as an asynchronous grid alternative to incremental synthetic-inertia procurement within the existing synchronous grid. The way in which inertia can be generated and potentially priced in the SAFErGrid can turn the current shadow cost of grid stability into a transparent and competitively priced service. As such, this paper compliments the economic exploration of SAFErGrid developed in Naudé (2026a), Naudé (2026c) and Naudé (2026b).

The remainder of the paper is organized as follows. Section 2 defines the core engineering and economic concepts. Section 3 reviews the market mechanisms currently pricing declining inertia. Section 4 formalizes the SAFErGrid architecture and localized pricing. Section 5 explores inertia in the SAFErGrid from four economic perspectives. Section 6 concludes.

2 Concepts and Definitions

This section sets out the key definitions and concepts, in particular of the electrical engineering notions, that are the focus of concern in the rest of the paper.

[1]The SAFErGrid project is supported by the European Research Council (ERC), see https://cordis.europa.eu/project/id/101166783

2.1 Continental Europe Synchronous Area

It is useful to start with the broader context - for present purposes, the Continental Europe Synchronous Area (CESA). It is the largest synchronous grid in the world, covering 32 countries, and connected to various proximate synchronous grids via direct current (DC) lines, such as the Nordic Grid, the electricity grids of the United Kingdom and Ireland, and the Baltic electricity grid (Westphal et al., 2022; Alexandrin, 2025).

The CESA consists of centralized power plants, decentralized RES, and transmission and distribution networks[2] that connects producers with consumers (Overbye and Weber, 2015; Kundur, 1994). The operators of this grid are the Transmission System Operators (TSOs) and Distribution System Operators (DSOs) responsible among other to maintain the real-time balance between electricity supply and demand (Gyalai-Korpos et al., 2020; Haucap et al., 2014).

The CESA is a Alternating Current (AC) grid, with AC meaning [3] "*an electric current that periodically reverses direction and changes its magnitude continuously with time, in contrast to direct current (DC), which flows only in one direction.*" In Europe, the AC changes direction 100 times per second - completing 50 cycles. Hence its frequency is 50 Hz. "A decrease in frequency indicates that demand exceeds generation, and vice versa" (Smahi and Makhloufi, 2025, p.1).

2.2 Rate of Change of Frequency

Failure by the grid operators to maintain this 50 Hz frequency could lead to equipment damage or grid failure. When there is for instance a sudden drop in electricity generation,

[2]The electricity transmission networks in the EU is currently around 523 000 km and is expected to double by 2050, while distribution grids will expand by 30% to around 13 million km(OECD, 2025).

[3]See `https://en.wikipedia.org/wiki/Alternating_current`

the grid frequency will decline. The physics is captured by the swing equation (Ulbig et al., 2014, p.4):

$$\dot{f}_m = -\frac{f_0}{2HS_B D_{load}} f_m + \frac{f_0}{2HS_B}(P_{m,0} - P_e) \tag{1}$$

Where $\dot{f}_m$ is the time derivative of the frequency (df/dt), representing the Rate of Change of Frequency (RoCoF)[4]; f_0 is the nominal system frequency (e.g., 50 Hz); S_B is the rated power (base power) of the system, D_{load} the load damping coefficient, and $(P_{m,0} - P_e)$ the mismatch between mechanical power setpoint and actual electrical demand.

Here H is the inertia constant of the system (in seconds). *Inertia is defined as the resistance of a physical object to a change in its state of motion including changes in speed and direction*" (Rezkalla et al., 2018, p.2679).

A synchronous generator's (SG) rotor, has a moment of inertia $J(kg \cdot m^2)$, and rotates at an angular velocity ω_m mechanically linked to the electrical grid frequency f. The kinetic energy stored in the rotor is

$$E_{\text{kin}} = \tfrac{1}{2} J \omega_m^2 \tag{2}$$

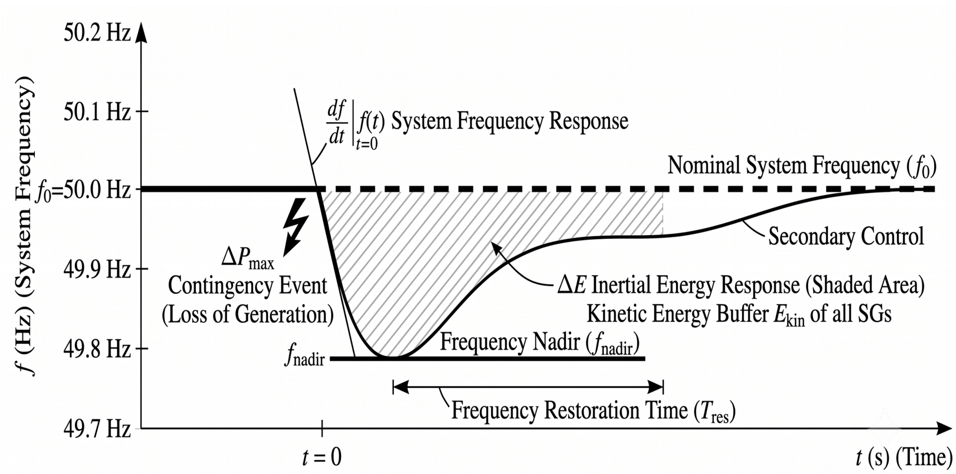
If $df/dt \neq 0$, the kinetic energy stored in the rotor (see equation 1) - will automatically resist further changes in frequency so as to limit the *nadir* - the depth of the decline. It will provide a few seconds - frequency restoration time - for control systems to detect a disturbance and to respond to it before the imbalance between supply and demand could trigger grid collapse (Homan and Brown, 2020; Kundur, 1994; Ulbig et al., 2014).

[4]Rate of Change of Frequency (RoCoF) quantifies how fast grid frequency departs from 50 Hz after a disturbance and is a key stability metric (Homan and Brown, 2020).

2.3 The Importance of Inertia

Figure 1 illustrates the role of inertia in the traditional synchronous grid in providing this frequency restoration time following a sudden contingency event—such as the loss of a major generation unit ($\Delta P_{\max}$) occurring at time $t = 0$.

Figure 1: System Frequency Response and Inertia in a Synchronous Grid



Source: Author, based on Poolla et al. (2018, p.283)

Figure 1 indicates that, under normal operating conditions, the power system frequency is maintained at its nominal value f_0 (50Hz). Immediately following the disturbance, the mismatch between electrical demand and mechanical generation causes the frequency to decay. The initial rate of this decline, the Rate of Change of Frequency (RoCoF), is shown as $df/dt|_{t=0}$. The physical inertia inherent in the rotating masses of synchronous generators acts as an immediate, automatic stabilizer. By injecting their stored kinetic energy (E_{kin}) into the grid, these rotating machines damp the rapid decline, limiting the depth of the frequency excursion to its lowest point, already mentioned as the frequency nadir (f_{nadir}).

In Figure 1, the shaded area between the nominal frequency f_0 and the actual frequency trajectory represents the active energy imbalance (ΔE). This imbalance must be mitigated by fast frequency and secondary control reserves to stop the fall and eventually guide the system through the frequency restoration time (T_{res}) back to its stable, nominal state.

With reference to Figure 1, a TSO must ensure that system inertia is sufficient to keep both RoCoF and the frequency nadir within statutory limits for the largest credible single contingency. In Europe the “N-1” criterion can be written as $\dot{f}_{\text{max}}$ which is the statutory maximum permissible RoCoF, commonly 1–$2Hz/s$ in Europe.

Inertia in the traditional synchronous grid is thus an inherent byproduct of the SGs. However, with the rise in the quantity and share of renewable energy sources (RES) the inertia in the system has been falling. This is because RES are decoupled from the grid frequency - they are interfaced with the grid using power electronic converters - and do not possess synchronously rotating mass to provide inertia (Tielens and Van Hertem, 2016; Tofighi-Milani et al., 2025; Ali et al., 2025; Mehrzad et al., 2026). As the share of RES rises, the total grid inertia therefore falls (Fernández-Guillamón et al., 2019; Smahi and Makhloufi, 2025).

2.4 Implications of Declining Rotational Inertia

As Rezkalla et al. (2018, p.2678) explains, “the reduction of system inertia has mainly two implications on system frequency stability, namely: (1) larger RoCoF, which results in possible tripping of grid components, especially embedded renewable generation; and (2) higher frequency deviations (nadirs/zeniths), potentially leading to load shedding and, in the worst case, system collapse.”

The declines in rotational inertia as a result of RES penetration has transformed inertia from an unpriced byproduct of traditional energy generation into a high-value grid service. The high value of inertia is seen for instance in the out-of-market interventions that grid operators perform - such as redispatch measures - and which drives grid costs and grid fees in a country such as Germany.

For instance, redispatch costs ain Germany have surged from €400–600 million in 2014 to €4.2 billion in 2022 and €3.1 billion in 2023 (Donnelly, 2025). In the UK and Ireland, grid operators have resorted to procurement programs for low carbon inertia services (LCIS) (EirGrid, 2021; MPS, 2025). Here for instance, the UK's Stability Pathfinders program has procured such low-carbon inertia at a cost of £1.95 billion, estimating this will save £14.9 billion in costs by alleviating the need to keep running fossil-fuel plants purely for rotational inertia (NESO, 2023). And in the USA (Texas) inertia has been packaged into specialized Fast Frequency Response (FFR) ancillary markets - where the Electric Reliability Council of Texas (ERCOT) has paid battery energy storage systems (BESS) between US$ 30 million and US$ 90 million annually in recent years to provide such inertia (Lavi and Apt, 2023; Potomac Economics, 2026).

2.5 Synthetic and Virtual Inertia

Inertia services include generating either Synthetic inertia (SI) and/or Virtual inertia (VI). SI is that which is provided by a fast RoCoF-linked power response, mostly wind turbine generators (WTGs) - which are Grid-Following -GFL- Inverters. For instance if df/dt drops rapidly, the controller will order the WTG to supply the grid with active power proportionate to the rate of change (Rezkalla et al., 2018). As Hitachi (2026) explains "Synthetic inertia emulates the inertial response of rotating machines by detecting rapid frequency changes and injecting or absorbing active power. It is a RoCoF-driven, continuously modulated response designed to slow the initial acceleration or deceleration of frequency, providing the system with critical time for fast frequency response (FFR) and primary control actions to initiate."

Virtual inertia (VI) refers to broader emulation of synchronous-machines / rotators (Poolla et al., 2019). "*The core of the system is the virtual inertia algorithm that presents the various energy sources interfaced to the grid through power electronics converters as synchronous generators*" (Tamrakar et al., 2017, p.5). Emulating inertia requires stored energy, such as in Battery Energy Storage Systems (BESS). They are Grid-Forming - GFM - and include "synchronverters, swing-equation-based methods, virtual synchronous generators (VSGs), droop control, Virtual Oscillator Control (VOC), and matching control" (Ullah et al., 2026, p.1). A survey of VI techniques are provided by Tamrakar et al. (2017). See also Fernández-Guillamón et al. (2021); Ullah et al. (2026); Poolla et al. (2019).

Virtual inertia is programmable inertia, which allows adaptive tuning to the grid's needs; which can provide multi-functionality to the grid - such as reactive power and not only kinetic energy; and which can react faster than rotational inertia technology, since it is limited only by the switching speed of silicon transistors (Gurski et al., 2024; García-Hoyos et al., 2025; Soares et al., 2023; Fernández-Guillamón et al., 2021). It is the case that the "shift from synchronous generators (SGs) - historical providers of inertia, fault current, and voltage and frequency support - to digitally controlled converters fundamentally alters fault dynamics, effort sharing, and overall frequency response (García-Hoyos et al., 2025, p.1).

Virtual inertia, in short, provides more than just inertia (Ullah et al., 2026). It ultimately facilitates breaking with the synchronicity, the most salient feature of the current European power grid: the Continental Europe Synchronous Area (CESA) is the largest synchronous grid in the world, covering 32 countries (Westphal et al., 2022; Alexandrin, 2025). Because frequency has to be maintained across this grid, a disturbance in one location will affect the entire continent. In this CESA grid, decentralization (better suited to RES uptake) and formation of isolated micro-grids,[5] face significant challenges because local areas will not have sufficient physical inertia to balance its own frequency (Pilehvar and Mirafzal, 2020; Yalaoui et al., 2024). However, with virtual inertia, a local area can function as an autonomous grid

[5]As Yalaoui et al. (2024, p.127655) point out "One of the most practical solutions for achieving green and reliable energy is the use of microgrids."

cell. If the main synchronous grid fails, the virtual inertia technologies (such as batteries with GFM inverters) will form the frequency locally (hence they are referred to as GFM)(Abudyak et al., 2026).

Thus, to facilitate higher penetrations of RES without jeopardizing PSS, power systems engineering is shifting toward decentralized, asynchronous grid architectures supported by virtual inertia technologies (Wald et al., 2023; Schwarz et al., 2026).

3 The SAFErGrid Proposal: Decoupling Stability from Synchronism

3.1 Architecture: A-Grids and the Layered Energy Internet

SAFErGrid, as proposed by Schwarz et al. (2026) and analyzed from an economic perspective in Naudé (2026a,c,b), departs from incremental synthetic-inertia procurement within a still-synchronous grid and instead proposes compartmentalizing the power system into a set of autonomous asynchronous subgrids ("A-grids"). These A-grids are interconnected by smart power-electronic Energy Routers (which still need to be fully innovated) that route power between cells rather than requiring continent-wide electromagnetic synchronization.

The architecture is organized on the model of the Internet's Open Systems Interconnection (OSI) stack, with four layers: (1) an A-Grid layer managing local frequency and voltage; (2) an Energy Routing layer implementing an "Aggregate, Forward, Store, Convert" (AFSC) principle for moving energy between neighboring cells; (3) an Energy Streaming layer that schedules energy availability across the network without requiring instantaneous matching; and (4) an Energy Application layer supporting dynamic pricing and new business models (Schwarz et al., 2026).

A structural element of SAFErGrid, for the purposes of inertia management, can be seen when contrasting the global constraint of a synchronous grid with the local constraint of an A-grid.

In a synchronous system, as discussed in the previous section, the centralized, synchronous grid area shares a single frequency and a single H_{sys}; a disturbance anywhere propagates, in principle, everywhere. In contrast, in an A-grid, each cell j must instead satisfy only a local energy balance across its DC interconnections:

$$\sum_k S_{j,k} + \text{NetFlow}_{\text{DC},j} = \sum_l D_{j,l} \pm \text{SyntheticResponse}_j \tag{3}$$

where $S_{j,k}$ denotes local generation sources, $D_{j,l}$ local demand, and $\text{NetFlow}_{\text{DC},j}$ imports or exports across the asynchronous DC interconnection to neighboring cells (Schwarz et al., 2026).

Because cell j is not electromagnetically coupled to the rest of the network, a fault originating in cell $k \neq j$ cannot propagate to j.

3.2 From RoCoF to Action Energy

As illustrated with the help of Figure 1, a synchronous grid detects and responds to a fault by measuring RoCoF – a quantity that is undefined or unstable at very low H_{sys}, and meaningless across an asynchronous boundary.

SAFErGrid's Energy Router therefore replaces the RoCoF-triggered response with a locally computed energy-domain stability metric, termed *Action Energy* (S). This is defined as the time integral of the imbalance between the kinetic and potential energy associated with the fault-induced transient in current and voltage across the cell's interconnecting lines (Schwarz et al., 2026, p.6):

$$S = \int_{t_1}^{t_2} \big(KE(t) - PE(t)\big)\, dt \tag{4}$$

S is agnostic as to whether the compensating response ultimately comes from rotating mass, from a battery, or from a curtailed load – it measures only the total energy that must be supplied, from any source, to arrest the transient within the cell's own boundary. The Energy Router is envisaged to translate the calculated Action Energy requirement into a price signal, which is broadcast to the cell's Application Layer,

$$\Delta p = \frac{S \cdot \lambda}{E_{\text{buf}}} \tag{5}$$

where λ is a scarcity-scaling factor reflecting the dynamic-response capability of neighboring cells and E_{buf} is the energy currently available in the cell's local storage buffer (Schwarz et al., 2026).

Equation (4) is a market-based analogue of a load-shedding relay: rather than physically disconnecting load once frequency nadir breaches a threshold, the price signal Δp is broadcast to price-responsive appliances, which curtail their own demand automatically. This is a form of decentralized frequency response achieved through the price mechanism rather than through direct physical intervention, and contained, by construction, within the affected A-grid and its immediate neighbors, rather than propagating across the entire CESA.

3.3 Pricing Virtual Inertia as a Competitive Local Market

Within an A-grid, *Virtual Inertia* (VI) becomes an explicitly traded ancillary service rather than a bundled byproduct of energy dispatch.

Following Schwarz et al. (2026) and Naudé (2026a), the supply of VI from a battery within a cell (S_{VI} is a step function analogous to the conventional merit-order supply curve in wholesale electricity markets - see also Naudé (2026a):

$$S_{\text{VI}}(P) = \sum_{i=1}^{n} K_i^{\text{VI}} \quad \text{for } MC_i^{\text{VI}} \leq P \tag{6}$$

where the marginal cost of provision from unit i reflects not fuel cost but battery degradation and opportunity cost:

$$MC_i^{\text{VI}} = C_{\text{deg}} + C_{\text{opp}} \tag{7}$$

C_{deg} is the marginal wear-and-tear cost of high-frequency, high-current cycling on the battery cell chemistry, and C_{opp} the forgone energy-market profit from reserving state-of-charge for stability response rather than for arbitrage.

Demand for VI is determined the cell's controller (or, during the transition, the TSO) as the minimum inertia-equivalent capability required to keep local RoCoF and Action Energy requirements within safe bounds.

This demand is typically near-vertical (inelastic) since insufficient stability capability risks cell-level collapse. Market clearing in the Fast Frequency Response (FFR) auction then sets:

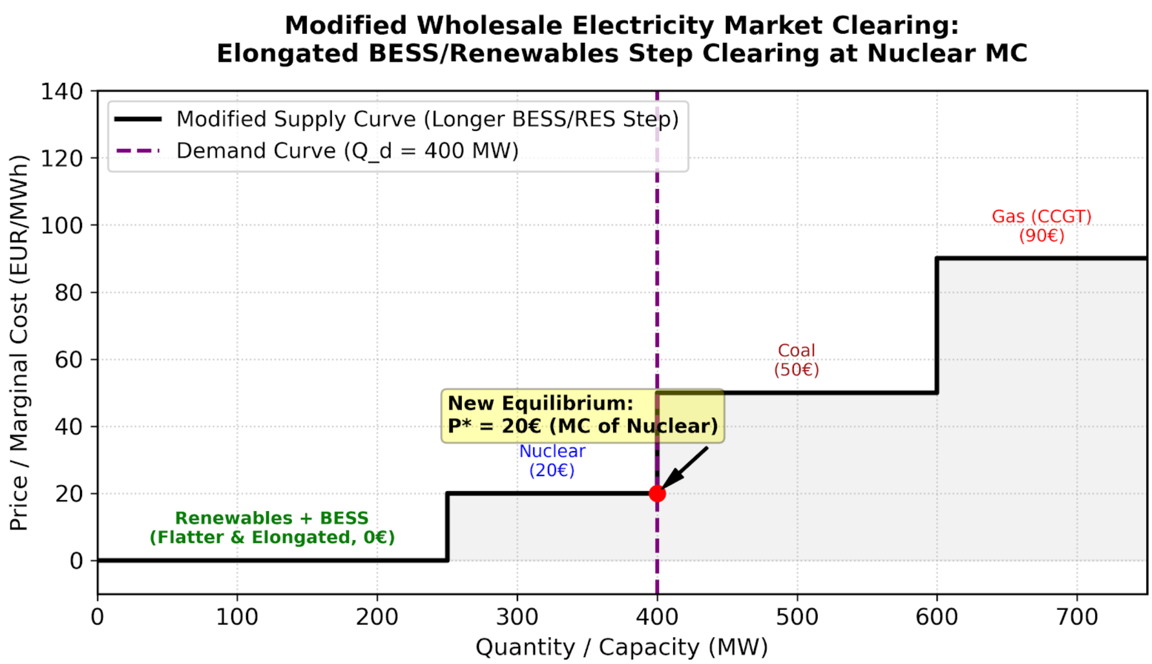
$$P_{\text{VI}}^{*} = \max\left(MC_i^{\text{VI}}\right) \text{ over all dispatched units} \tag{8}$$

This is economically significant for two reasons. First, because BESS responds in milliseconds rather than the multi-second time constants of governor-controlled synchronous plant, the quantity of inertia-equivalent capability required to satisfy (7) for a given $\Delta P_{\max}$ is itself reduced when fast response is available – as Denholm et al. (2020, p.36) put it, storage "can respond much faster than conventional resources, reducing the amount of inertia actually needed."

Second, as battery capacity within A-grids grows, the VI supply curve (15) lengthens and flattens at low marginal cost, progressively displacing more expensive synchronous or gas-turbine-based stability provision from the market – an VI-specific analogue of the familiar merit-order effect of renewables on energy prices (Sensfuss et al., 2008).

As a result, increasing BESS penetration flattens and extends the electricity supply curve, as shown in Figure 2, pushing the equilibrium price of inertia down, and eventually pricing coal and gas plants out of the stability market altogether.

Figure 2: Wholesale Electricity Market Clearing: Effect of Increased Renewables and BESS



Source: Author's compilation

A potential challenge that the SAFErGrid will face here is that as BESS capacity grows, the price of inertia will drop. If the stability market then clears at a very low price due to high BESS efficiency, the revenue may not be sufficient to recover the initial CAPEX of the battery installations. The SAFErGrid concept may have to be complemented by long-term capacity payments or regulatory surcharges to ensure the stability infrastructure remains financially viable, similar to the capacity markets discussed by Zweifel et al. (2017).

4 Extending the Economics of Inertia in an Asynchronous Grid

This section develops four extensions to the SAFErGrid inertia-management framework that are not present, or only implicit, in the underlying proposal: a formal public/club-goods characterization of why compartmentalization changes the economics of inertia provision; a welfare comparison between the shadow-priced and market-priced regimes; a real-options valuation of storage-based inertia buffers; and an analysis of the revenue-adequacy problem that any competitively cleared inertia market is likely to encounter as battery costs continue to fall.

4.1 Inertia as a Public Good, and Why Compartmentalization Changes That

Physical inertia in a synchronous area has the two defining properties of a pure public good: it is non-excludable (any generator's contribution to H_{sys} stabilizes the frequency experienced by every load and generator on the interconnected system, whether or not that load or generator paid for it) and, up to the point of a binding contingency, non-rival (one user's benefit from the stability does not diminish another's).

Tofighi-Milani et al. (2025) formalize this property, modelling voluntary VI provision as a public-goods game in which private incentives, absent intervention, systematically under-provide the socially optimal quantity of stability – the standard free-rider result.

Formally, if unit i's private return from contributing inertia h_i is $u_i(h_i) - c_i(h_i)$, where u_i captures only i's own reduced blackout risk, while the true social benefit is $\sum_j u_j(\sum_i h_i)$, the Nash equilibrium level of voluntary contribution h_i^{NE} satisfies $u_i'(h_i^{NE}) = c_i'(h_i^{NE})$ rather than the socially efficient condition $\sum_j u_j'(\sum_i h_i^*) = c_i'(h_i^*)$, so that $\sum_i h_i^{NE} < \sum_i h_i^*$ whenever there is more than one contributing agent.

This is why for instance inertia procurement, such as in Great Britain and Ireland, utlised an explicit, TSO-designed tender.

SAFErGrid's compartmentalization changes the scope of this public good without eliminating the underlying free-rider logic. Within a single A-grid, local Action Energy provision retains a public-goods character among the households and prosumers sharing that cell – the LMO (Local Market Operator) still needs to solve a local coordination problem, and the price signal in (7) is the mechanism used to do so by converting a non-excludable stability benefit into an excludable (priced) commodity at the point of consumption.

But across A-grid boundaries, the good becomes closer to a *club good:* it is non-rival among a cell's own members (up to capacity) but effectively excludable from neighboring cells, whose demand is met, at most, through a metered and priced DC interconnection rather than an automatic electromagnetic externality.

Formally, whereas in a synchronous grid $\partial \Delta f_k / \partial \Delta P_j \neq 0$ for essentially all pairs of nodes (j, k) on the interconnected system (the externality is continent-wide), in an A-grid, :

$$\frac{\partial \Delta f_k}{\partial \Delta P_j} = 0 \quad \text{for all } k \notin \mathcal{N}(j) \tag{9}$$

where $\mathcal{N}(j)$ is the (typically small) set of cells directly DC-interconnected to j.

This localization of the externality is the formal counterpart of the A-grid's feature that a fault is isolated and cannot cascade into a continent-wide blackout. It converts an n-player public-goods game played across the CESA into a much smaller, more tractable coordination problem within each cell – at the cost, discussed further below, of potentially diluting the risk-pooling benefits of a large shared inertia reservoir.

4.2 Welfare Comparison: Shadow-Priced versus Market-Priced Inertia

As mentioned in the introduction, rotational (mechanical) inertia is not free but shadow-priced through redispatch. It is useful to compare the welfare properties of this regime with the explicit VI market of Section 4.3.

Denote by C^{shadow} the total system cost of maintaining H_{req} through redispatch, and by C^{market} the cost of procuring an equivalent inertia-equivalent stability capability through a competitive SI/VI market clearing at P^*_{SI}.

Under the bundled, shadow-priced regime, the marginal source of inertia at any hour is whichever synchronous unit the TSO happens to keep online to satisfy

$$H_{\text{sys}} \geq H_{\text{req}} \equiv \frac{f_0 \, \Delta P_{\max}}{2 \, S_{\text{sys}} \, \dot{f}_{\max}} \tag{10}$$

where $\dot{f}_{\max}$ is the statutory maximum permissible RoCoF.

This source of inertia is decided after the energy merit order has been fixed in wholesale markets, and therefore is not itself subject to competitive discipline. The realized cost is

$$C^{\text{shadow}} = \sum_{i \in \mathcal{M}} \left[MC_i \cdot g_i^{\min} + \text{redispatch premium}_i \right] \tag{11}$$

where $\mathcal{M}$ is the (TSO-determined, not competitively selected) set of must-run units and $g_i^{\min}$ their minimum stable dispatch.

Because $\mathcal{M}$ is typically small and geographically constrained (the units must be electrically close enough to be effective, and few plants may be available on a given day), C^{shadow} is set by whichever unit happens to be available, not by the cheapest technically capable source of inertia across the whole system.

Under the unbundled, market-priced regime as shown in the next section - Section 4.3 - $C^{\text{market}} = P^*_{\text{VI}} \cdot H_{\text{req}}$, where P^*_{VI} is set competitively following

$$P^*_{\text{VI}} = \max \left(MC_i^{\text{VI}} \right) \text{ over all dispatched units.} \tag{12}$$

In other words, P^*_{VI} is set across all technically eligible providers – SGs, SI and VI (e.g. grid-forming batteries) alike.

Two results follow directly from standard auction-theoretic reasoning.

First, whenever the set of eligible inertia providers under the market regime is a super-set of the must-run set $\mathcal{M}$ available under the shadow-cost regime (as it typically will be, since batteries, synchronous condensers, and even demand-response resources can now compete alongside conventional plant), $C^{\text{market}} \leq C^{\text{shadow}}$ by revealed preference: the market-clearing solution could always replicate the shadow-cost dispatch, and does so only if no cheaper alternative exists.

Second, the welfare gain from unbundling is increasing in the heterogeneity of provider marginal costs, $\mathrm{Var}(MC_i^{\mathrm{VI}})$ the more dispersed the cost of provision across technologies, the larger the efficiency loss from allowing the TSO's must-run selection – rather than a competitive auction – to determine which units actually supply the service.

SAFErGrid's Action Energy market goes further by additionally localizing the auction: because Δp in clears within each A-grid rather than across an entire synchronous area, the marginal VI provider selected is the cheapest available locally, avoiding both the transmission losses and the congestion costs that would otherwise be incurred moving stability services across a continental grid, echoing the finding in Naudé (2026a) that A-grid prices "reflect actual local scarcity, not a zonal average distorted by a bottleneck far away."

4.3 Real-Option Value of Storage-Based Inertia Buffers

Section 3.3 characterized VI provision as a static market-clearing problem. But the decision to hold state-of-charge in reserve for a stability event, rather than to sell it into the energy market, is more accurately understood as a real option: the operator of a battery retains the right, but not the obligation, to discharge into a stability event at a moment of its choosing, and the value of retaining that right rises with the volatility of net load and prices.

Adapting the Black–Scholes framework as applied to energy flexibility by Zweifel et al. (2017) and to SAFErGrid buffers by Naudé (2026a), the value of a call option on grid-stability flexibility is

$$\mathrm{CALL}_t(T) = p_t \cdot N(d_1) - e_T \cdot e^{-i(T-t)} \cdot N(d_2) \tag{13}$$

$$d_1 = \frac{\ln(p_t/e_T) + (i + \sigma^2/2)\,(T-t)}{\sigma\sqrt{T-t}}, \qquad d_2 = d_1 - \sigma\sqrt{T-t} \tag{14}$$

where p_t is the present value of avoided redispatch and stability-shortfall costs, e_T the annualized capital and maintenance cost of the storage-router system, i the risk-free rate, and σ the volatility of the underlying avoided-cost stream, driven by the intermittency of renewable output and the resulting volatility of net load.

This paper extends Naudé (2026a) 's treatment by making explicit the comparative static most relevant to inertia specifically: the sensitivity of option value to the minimum inertia requirement itself, $\partial \, \mathrm{CALL}_t(T)/\partial H_{\mathrm{req}}$.

Because p_t – the present value of avoided redispatch and stability costs – is increasing in H_{req} (a tighter inertia requirement raises the shadow cost of synchronous must-run dispatch that a storage buffer displaces), and because the Black–Scholes call value is monotonically increasing in the underlying asset value p_t, it follows that

$$\frac{\partial \, \mathrm{CALL}_t(T)}{\partial H_{\mathrm{req}}} = \frac{\partial \, \mathrm{CALL}_t(T)}{\partial p_t} \cdot \frac{\partial p_t}{\partial H_{\mathrm{req}}} = N(d_1) \cdot \frac{\partial p_t}{\partial H_{\mathrm{req}}} > 0 \tag{15}$$

This yields a testable prediction: as renewable penetration rises and H_{req}'s shadow price (via redispatch cost growth) increases, the option value – and hence the equilibrium investment incentive – for storage-based stability buffers should rise faster than a naive linear extrapolation of falling battery costs alone would suggest, precisely because the option's underlying asset (avoided stability cost) is itself trending upward.

This is consistent with the empirically documented acceleration of battery participation in stability tenders in Great Britain, where grid-forming BESS moved from zero to 12% of contracted inertia between Stability Pathfinder Phases 1 and 3 (Hortrop, 2023).

The volatility sensitivity (Vega) of this option, following Zweifel et al. (2017, p.61) and Naudé (2026a), is

$$\text{Vega} = \frac{\partial\,\text{CALL}}{\partial \sigma} = p_t \cdot \sqrt{T-t} \cdot \frac{1}{\sqrt{2\pi}}\, e^{-d_1^2/2} \; > \; 0 \tag{16}$$

This indicates that, unlike a conventional physical asset, the value of a storage-based inertia buffer rises with the volatility that a low-inertia, high-renewable system otherwise treats purely as a cost.

4.4 The Revenue-Adequacy Problem in Inertia Markets

The SAFErGrid VI market of Section 3.3 confront a structural risk, familiar from the broader "missing money" literature on capacity and ancillary-service markets (cf. Stoft (2002)): if the VI supply curve becomes sufficiently long and flat as battery costs fall and storage capacity proliferates, the market-clearing price P^*_{VI} may fall to a level that fails to recover the annualized capital cost of the marginal (and, eventually, of all) providers (Savelli, 2025).

Formally, a provider i's participation constraint is

$$P^*_{\text{VI}} \cdot K_i^{\text{VI}} \;\geq\; \left(C_{\text{deg},i} + C_{\text{opp},i}\right) K_i^{\text{VI}} + \frac{\text{CAPEX}_i}{\text{annuity factor}} \tag{17}$$

and, because the VI market clears at the marginal operating cost of the dispatched units rather than at a level that includes a capital-recovery term, (16) can fail even when the market clears at a strictly positive price.

The likely institutional resolution – long-term capacity-style contracts or regulated availability payments layered on top of the short-run FFR clearing price – is analytically identical to the missing-money solutions long proposed for capacity markets in energy-only systems (Stoft, 2002; Zweifel et al., 2017), Naudé (2026a) draws the same conclusion for SAFErGrid specifically: without such a complementary long-term remuneration mechanism, the very success of the VI market in driving down P^*_{SI} risks undermining the future adequacy of stability provision.

5 Concluding Remarks

This paper explored some economics of grid stability under rapid renewable energy source (RES) penetration. The core problem is the steady erosion of traditional rotational inertia historically provided as a free byproduct of synchronous generators. As decoupled, converter-interfaced renewables rise to dominate the generation of electricity, the resulting drop in total system inertia results in greater frequency volatility and higher rates of change of frequency (RoCoF). This raises the risk of a continent-wide grid failure.

The contribution of this paper was to explore the economics of (virtual) inertia markets within a decentralized, asynchronous power grid architecture, with specific reference to the SAFErGrid proposal. Four economic dimensions of VI were explored: (i) local inertia as an excludable club good rather than an unpriced, continent-wide public good; (ii) how an explicit virtual inertia (VI) market may outperform the opaque shadow costs of traditional TSO redispatch mechanisms in the synchronous grid; (iii) how a real-options perspective suggests that the value of BESS will increase alongside net-load volatility; and finally the paper (iv) evaluated the underlying structural risk of the "missing money" revenue-adequacy problem as BESS deployment costs continue to fall.

Ultimately, shifting toward an asynchronous, electrically decoupled grid cell model could transform grid stability from an unpriced physical constraint into a transparent, competitive, and localized market service.

Acknowledgments

I am grateful to Frank Piller and Guillaume Yon for their useful comments and suggestions on an earlier draft. The usual disclaimer applies.

References

Abudyak, Y., Mohammad, R., Ahmad, B. A., Salimian, H., Batarseh, I., and Huang, A. (2026). Grid-Forming Inverters Review: Control, Stability, and the Next Stage With Artificial Intelligence and Digital Twins. *EEE Open Journal of Power Electronics*, 7:351–387.

Alexandrin, M. (2025). What is the CESA and why do we need smart grids? *Blog: https://www.alexandrin.de/*, 7 May.

Ali, J. S., Qiblawey, Y., Alassi, A., Massoud, A. M., Muyeen, S. M., and Abu-Rub, H. (2025). Power System Stability With High Penetration of Renewable Energy Sources: Challenges, Assessment, and Mitigation Strategies. *IEEE Access*, 13:39912–39934.

Biggar, D. and Hesamzadeh, M. (2014). The Economics of Electricity Markets. *Wiley-IEEE Press.*

Denholm, P., Trieu, M., Kenyon, R., Kroposk, B., and O'Malley, M. (2020). Inertia and the Power Grid: A Guide Without the Spin. *Golden, CO: National Renewable Energy Laboratory. NREL/TP-6120-73856.*

Donnelly, N. (2025). ENTSO-E's Proposal to Restructure the Germany-Luxembourg Bidding Zone. *https://www.linkedin.com/pulse/entso-es-proposal-restructure-germany-luxembourg-bidding-donnelly-vekke/*, 6 May.

EirGrid (2021). Low Carbon Inertia Services. *Presentation, available at https://cms.eirgrid.ie/sites/default/files/publications/EirGrid-SONI-Plan-for-procurement-of-LCIS-Webinar.pdf*, 15 Dec.

Fernández-Guillamón, A., Gómez-Lázaro, E., Muljadi, E., and Molina-Garcia, A. (2019). Power Systems with High Renewable Energy Sources: A Review of Inertia and Frequency Control Strategies over Time. *ArXiv, abs/2004.02951.*

Fernández-Guillamón, A., Gómez-Lázaro, E., Muljadi, E., and Molina-Garcia, A. (2021). A Review of Virtual Inertia Techniques for Renewable Energy-Based Generators. *In Renewable Energy - Technologies and Applications. IntechOpen. https://doi.org/10.5772/intechopen.92651.*

García-Hoyos, M., Villena-Ruiz, R., Honrubia-Escribano, A., and Gómez-Lázaro, E. (2025). Stability Analysis of Electricity Grids with High Renewable Penetration Using a Grid-Forming Approach. *Electronics*, 14(24):4871.

Gurski, E., Kuiava, R., Perez, F., Benedito, R., and Damm, G. (2024). A Novel VSG with Adaptive Virtual Inertia and Adaptive Damping Coefficient to Improve Transient Frequency Response of Microgrids. *Energies*, 17(17):4370.

Gyalai-Korpos, M., Zentkó, L., Hegyfalvi, C., Detzky, G., Tildy, P., Hegedusné Baranyai, N., Pinter, G., and Zsiborács, H. (2020). The Role of Electricity Balancing and Storage: Developing Input Parameters for the European Calculator for Concept Modeling. *Sustainability*, 12(3):811.

Haucap, J., Heimeshoff, U., and Jovanovic, D. (2014). Competition in Germany's Minute Reserve Power Market: An Econometric Analysis. *The Energy Journal*, 35(2):137–156.

Hitachi (2026). Bridging the Inertia Gap: How Power Electronics Can Help Stabilize Modern Grids. *Hitachi Blog at https://www.hitachienergy.com/news-and-events/blogs/.*

Homan, S. and Brown, S. (2020). An Analysis of Frequency Events in Great Britain. *Energy Reports*, 6(5):63–69.

Hortrop, W. (2023). Stability Pathfinders: What They Mean for Battery Energy Storage. *Modoenergy, at : https://modoenergy.com/research/en/stability-pathfinders-inertia-short-circuit-level-battery-energy-storage*, 26 September.

Kundur, P. (1994). Power System Stability and Control. *New York: McGraw-Hill.*

Lavi, Y. and Apt, J. (2023). Inverter Fast Frequency Response is a Low-Cost Alternative to System Inertia. *Electric Power Systems Research*, 221:109422.

Mehrzad, A., Darmiani, M., Rouhani, S., Su, C.-L., Sepestanaki, M., E., Monti, A., and Anvari-Moghaddam, A. (2026). Inertia in Renewable Power Systems: A Review of Estimation Methods and Practical Implementation. *Renewable & Sustainable Energy Reviews*, 226 (Part A):1–16.

MPS (2025). Improving Grid Stability in the UK, Denmark and Brazil. *Modern Power System, online at https://www.modernpowersystems.com/analysis/improving-grid-stability*, 14 May.

Naudé, W. (2026a). Market Design for Asynchronous Power Grids: Energy Balance, Inertia, and Congestion in SAFErGrid. *IZA Discussion Paper. IZA Discussion Paper. Luxembourg: IZA@LISER Network*.

Naudé, W. (2026b). The Potential for Innovation in a Decentralized, Asynchronized Power Grid. *IZA Discussion Paper. Luxembourg: IZA@LISER Network*.

Naudé, W. (2026c). Reducing Energy Poverty in Germany: The Case for a Decentralized, Asynchronous Power Grid. *IZA Discussion Paper. Luxembourg: IZA@LISER Network*.

NESO (2023). Our Commitment to Delivering Zero Carbon Operations by 2025 on Earth Day. *National Energy System Operator, online at https://www.neso.energy/news/our-commitment-delivering-zero-carbon-operations-2025-earth-day*, 21 April.

OECD (2025). Diagnostic Toolkit for Reducing Regulatory Barriers to Solar, Wind and Pumped Hydro Storage in the European Union: Empowering Policymakers at National, Regional, and Local Levels. *OECD Publishing, Paris*.

Overbye, T. J. and Weber, J. (2015). Smart Grid Wide-Area Transmission System Visualization. *Engineering*, 1(4):466–474.

Pilehvar, M. S. and Mirafzal, B. (2020). A Frequency Control Method for Islanded Microgrids Using Energy Storage Systems. *IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA*, pages 2327–2332.

Poolla, B. K., Gross, D., Borsche, T., Bolognani, S., and Dörfler, F. (2018). Virtual Inertia Placement in Electric Power Grids. *In S. Meyn et al. (eds.), Energy Markets and Responsive Grids, The IMA Volumesin Mathematics and its Applications*, pages 281–305.

Poolla, B. K., Gross, D., and Dörfler, F. (2019). Placement and Implementation of Grid-Forming and Grid-Following Virtual Inertia and Fast Frequency Response. *IEEE Transactions on Power Systems*, 34(4):3035–3046.

Potomac Economics (2026). 2025 State Of The Market Report For The ERCOT Electricity Markets. *Independent Market Monitor for ERCOT*, May.

Rezkalla, M., Pertl, M., and Marinelli, M. (2018). Electric Power System Inertia: Requirements, Challenges and Solutions. *Electrical Engineering*, 100:2677–2693.

Savelli, I. (2025). The Problem of Diminishing Storage Profits from Arbitrage. *46th IAEEE Conference*.

Schwarz, S., Sahoo, S., Stoffers, M., and et al (2026). Resilient Low-Inertia Power Systems through Asynchronous Energy Balancing. *Nat Reviews Electrical Engineering*, 3:101–110.

Sensfuss, F., Ragwitz, M., and Genoese, M. (2008). The Merit-Order Effect: A Detailed Analysis of the Price Effect of Renewable Electricity Generation on Spot Market Prices in Germany. *Energy Policy*, 36(8):3086–3094.

Smahi, A. and Makhloufi, S. (2025). The Power Grid Inertia With High Renewable Energy Sources Integration: A Comprehensive Review. *Journal of Engineering*, Article ID 7975311.

Soares, L., de Souza, A., Silva, W., Pugliese, L., and Alves, G. (2023). Grid-Connected Photovoltaic Systems with Energy Storage for Ancillary Services. *Energies*, 16(21):7379.

Stoft, S. (2002). Power System Economics: Designing Markets for Electricity. *IEEE Press/Wiley-Interscience.*

Tamrakar, U., Shrestha, D., Maharjan, M., Bhattarai, B., Hansen, T., and Tonkoski, R. (2017). Virtual Inertia: Current Trends and Future Directions. *Applied Sciences*, 7(7):654.

Tielens, P. and Van Hertem, D. (2016). The Relevance of Inertia in Power Systems. *Renewable and Sustainable Energy Reviews*, 55:999–1000.

Tofighi-Milani, M., Fattaheian-Dehkordi, S., and Lehtonen, M. (2025). Optimal Inertia Procurement in Future Synthetic-Inertia-Dominated Power Systems: A Public Goods Game Approach. *IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe), Valletta, Malta*, pages 1–5.

Ulbig, A., Borsche, T., and Andersson, G. (2014). Impact of Low Rotational Inertia on Power System Stability and Operation. *ArXiv:1312.6435v4 [math.OC]*.

Ullah, Z., Santis, M. D., and Rubino, L. (2026). Inertia Response and Frequency Stability in Renewable Energy-Dominated Power Systems: Review of Virtual Inertia Techniques. *Energies*, 19(13):3063.

Wald, F., Tao, Q., and De Carne, G. (2023). Virtual Synchronous Machine Control for Asynchronous Grid Connections. *IEEE Transactions on Power Delivery*, 39:397–406.

Westphal, K., Pastukhova, M., and Pepe, J. (2022). Geopolitics of Electricity: Grids, Space and (political) Power. *SWP Research Paper 6.*

Yalaoui, N., Dessaint, L., Reza Dehbozorgi, M., and Al-Haddad, K. (2024). Seamless Transition Between Microgrid Operation Modes Using ADRC Without an Islanding Detection Algorithm nor PLL. *IEEE Access*, 12:127655–127673.

Zweifel, P., Praktiknjo, A., and Erdmann, G. (2017). Energy Economics: Theory and Applications. *Springer*.