Energy Balance and Dynamic Scarcity Pricing in an Asynchronous Power Grid

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Abstract

The synchronous European power grid faces constraints in accommodating rising shares of renewable electricity. This is manifesting as price volatility, escalating redispatch expenditure, and a growing reliance on curtailment. This paper explores the economics of electricity market clear in the SAFErGrid, a proposed decentralized and asynchronous power system architecture. Drawing on standard electricity-market theory, two synchronous-grid challenges – power balance and transmission congestion – are formalized and the potential advantages of the SAFErGrid illustrated. Potential design risks – such as the sensitivity of dynamic pricing to forecasting error and the incentives of incumbent grid operators are discussed.

Keywords: Energy, Renewables, Power Grids, Electricity Markets

JEL Codes: Q41, I32, L94, O33

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1 Introduction

Europe's power grid is a synchronous alternating-current (AC) system – the Continental Europe Synchronous Area (CESA) – that has to keep frequency stable at 50 Hz across 32 interconnected countries (Westphal et al., 2022; Alexandrin, 2025). Because the network is centralized, a local fault can propagate instantaneously across borders, as the near-collapse of the European grid in 2021 (Stankovski et al., 2023) and the Iberian Peninsula blackout of 2025 (ENTSO-E, 2026) illustrated. Maintaining stability in such a system requires that grid operators continuously solve three related challenges: instantaneously balancing power supply and demand, dealing with congestion, and maintaining sufficient physical inertia to slow down any rate of change of frequency (RoCoF).

None of these problems is new, but all three are intensifying as renewable electricity sources (RES) displaces the large spinning turbines of coal, gas and nuclear plants that have historically supplied inertia, and from which power and that could be dispatched flexibly to keep supply and demand in balance. The consequence for Europe is high and volatile – including negative – wholesale electricity prices (Liebensteiner et al., 2025; Pavlík et al., 2025), rapidly rising redispatch and curtailment costs (Donnelly, 2025; Allianz Research, 2025), and continued dependence on fossil-fuel capacity retained purely for its stabilizing properties rather than its energy content (Newbery, 2023).

A growing literature proposes decentralized and asynchronous alternatives to the synchronous grid, see e.g. Ecker et al. (2017), Kendziorski et al. (2022) and European Parliament (2010). One recent proposal is *SAFErGrid* (Schwarz et al., 2026), which envisages compartmentalization of power systems into "independent but interconnected asynchronous subgrids (A-grids), each with distributed, localized roles and technologies, to exchange energy without synchronism" (Schwarz et al., 2026, p.3). SAFErGrid draws on "Energy Internet" concepts, in which electricity is managed somewhat like a routed, packetized information good (Joseph and Balachandra, 2020).

What has been neglected in this literature is the economics of how market clearing can be established in such an asynchronous, decentralized system: if the physical architecture of the grid changes from continuous synchronism to discrete, routed energy packets, how should the underlying economic problems of energy balancing, inertia, and congestion be priced? As Khan et al. (2025, p.709) conclude from a systematic review of renewable energy and grid research, "a critical gap persists in understanding the integrated economic and policy frameworks necessary for cost-effective, stable grid operation with high renewable penetration." This paper addresses that gap with reference to the case of SAFErGrid, focusing on two challenges: energy balance in electricity markets, and the pricing of congestion. The challenge of maintaining inertia is the topic of a separate paper - see Naudé (2026a).

The paper proceeds as follows. Section 2 describes the synchronous-grid constraints facing the CESA and the economic costs that follow from it. Section 3 introduces the SAFErGrid concept. Sections 4 to 5 form the core of the paper: each takes one of the two synchronous-grid constraints – power balance and congestion – and develops the corresponding SAFErGrid market mechanism. Section 6 discusses the principal vulnerabilities or risks facing the functioning of these market mechanisms. Section 7 concludes.

It should be pointed out at the outset that the SAFErGrid proposal is just that: a theoretical proposal grounded in power engineering principles. Therefore this paper does not deal with technical aspects such as the technological readiness of SAFErGrid, or its possible regulatory and political implementation challenges. Rather, the approach is to image a blank slate on which a decentralized, asynchronous grid for Europe can be redesigned, and to explore whether and how such a grid can offer economic value.

2 The Synchronous Grid Constraint: Renewables, Prices and Stability

2.1 The Rise of Renewable Electricity

Between 1985 and 2025 the share of electricity supplied by renewables globally, and in Europe, doubled[1] – from 17% to 34% globally and from 21% to 42% in Europe. By 2024, renewables (solar, wind, hydro and biomass) had become the single largest source of electricity in the EU, supplying 48% of the continent's electricity, and by 2025 "wind and solar generated more electricity than all fossil sources in 14 of the 27 EU countries" (Petrovich, 2026, p.11). The European Commission expects EU electricity demand to increase by 60% between 2023 and 2030 (EC, 2023), driven in part by electric vehicles, AI and ICT load, and increased electrification of heating(EC, 2025; OECD, 2025).

Germany, Europe's largest electricity market, illustrates the pace of this transition. Following the 2000 Renewable Energy Sources Act (*Erneuerbare-Energien-Gesetz*, EEG), Germany raised the renewable share of its electricity supply to 59% by 2025,[2] with more than 5.5 million solar PV installations and over 29,300 onshore wind turbines feeding into the grid.[3] Germany aims for an 80% renewable electricity share by 2030,[4] and the European Commission projects renewables will supply over 90% of all EU electricity by 2040.[5]

[1] See Our World in Data, at: `https://tinyurl.com/2x8zbczb`
[2] See: `https://ember-energy.org/countries-and-regions/germany`
[3] See: `https://tinyurl.com/573suwsc`
[4] See `https://tinyurl.com/wevhz5b`
[5] See `https://flowbatterieseurope.eu/news/eus-2040-climate-target/`.

2.2 The Threefold Grid Management Challenge

The rise of RES as described in the previous sub-section is occurring within a physical grid architecture designed around large, centralized, dispatchable fossil-fuel and nuclear plants. The Continental Europe Synchronous Area operates as alternating current at a frequency of 50 Hz, which must be kept stable: "a decrease in frequency indicates that demand exceeds generation, and vice versa" (Smahi and Makhloufi, 2025, p.1). Failure to maintain frequency can damage equipment or trigger grid failure. This confronts Transmission System Operators (TSOs) and Distribution System Operators (DSOs) with three linked challenges: (i) maintaining an instantaneous power balance between supply and demand so as to keep frequency at 50 Hz; (ii) maintaining sufficient inertia in the system to slow the rate of change of frequency following a disturbance; and (iii) keeping transmission lines free of congestion that would itself threaten frequency and inertia (Gyalai-Korpos et al., 2020; Haucap et al., 2014; Alkandari et al., 2017; Radi et al., 2021).

In the AC synchronous grid, the spinning rotors of coal, gas, and nuclear turbines provide inertia – kinetic energy that slows any rate of change of frequency (RoCoF) and buys automated control systems a few seconds to adjust mechanical power and restore stability. Because renewable energy sources (RES) lack this rotational mass, a system with a large share of renewables may lack sufficient inertia to slow RoCoF enough for control systems to react, risking cascading blackouts (Homan and Brown, 2020; González-Pozo, 2025; Ulbig et al., 2014). At the same time, geographically uneven renewable supply increases the risk of transmission congestion, which itself threatens inertia and frequency stability (Titz et al., 2023).

The economic consequences of this threefold challenge are already visible. The average German household electricity bill reached roughly €116 per month by 2025, more than double its 2005 level.[6] The country's average 2023-2026 residential electricity price was the fifth highest in the world (Amelang, 2025). Wholesale day-ahead prices can swing by more than €700/MWh within a single day. Redispatch costs in Germany rose from roughly €400–600 million in 2014 to €4.2 billion in 2022, and Allianz Research (Allianz Research, 2025, p.3) projects German grid congestion costs will reach €12.3 billion by 2030 and €56.7 billion by 2040 without upgrades, potentially raising electricity prices by up to 103% by 2040 under a business-as-usual scenario. The European Commission separately estimates that "€584 billion in investments are necessary for the electricity grids this decade" (EC, 2023, p.2), largely to extend and reinforce the existing synchronous architecture.

Although the current European system is adopting synthetic management tools such as grid-forming inverters (Tofighi-Milani et al., 2025) and hybrid synchronous–asynchronous elements (Navarro et al., 2025), it remains fundamentally based on synchronous principles, and hence to the underlying economics of that architecture.

The remainder of this paper asks how two of these challenges – balance and congestion – could instead be priced under a fully asynchronous market design, with reference to the SAFErGrid proposal.

3 SAFErGrid: A Decentralized, Asynchronous Alternative

The SAFErGrid concept (Schwarz et al., 2026) rests on three linked proposals. First, the power grid is compartmentalized into autonomous "A-grids," each functioning on a layered architecture. Second, smart Energy Routers act as gateways between A-grids, routing energy streams the way routers direct data packets on the internet. Third, energy is managed by

[6] See: https://www.statista.com/statistics/1346248/electricity-bill-average-household-germany/

priority using the AFSC principle: *Aggregate* locally, *Forward* to neighbors, *Store* in buffers, and/or *Convert* to other carriers such as hydrogen.

As Schwarz et al. (2026, p.3) explain, the key technical element is that "smart power electronics converters act as energy router devices that decouple the a-grids and manage energy streams between them. These energy routers enable a store-and-forward energy routing paradigm, delivering energy from generators to end-consumers across a-grids as needed." Rather than continuous, synchronized streams of electricity flowing outward from central plants, SAFErGrid breaks power into discrete packets managed through digital packet-priority signals – communications sent by the Energy Router to connected devices indicating the current urgency of grid stability and the priority level of the energy being delivered (Serpanos and Wolf, 2011).

The store-and-forward mechanism relies on distributed energy storage – batteries and supercapacitors – to create an energy buffer, so that any A-grid can receive energy, store it, and forward it onward, decoupling generation and consumption in time across the wider network. Schwarz et al. (2026) argue that this design can generate substantial savings relative to conventional grid expansion, since it maximizes the use of existing infrastructure through flexible routing rather than requiring continuous investment in new transmission capacity.

The architecture is layered, bottom-up, and explicitly inspired by the Internet's Open Systems Interconnection (OSI) model, summarized in Table 1.

Each A-grid (Layer 1) functions as an autonomous island managing its own internal frequency and voltage, and can support any mix of AC or DC technologies, legacy equipment, or renewable sources.

The Energy Routing Layer (Layer 2) is where interconnection with neighboring A-grids occurs, applying the AFSC store-and-forward paradigm to decouple electricity supply and demand over time.

Table 1: Proposed A-grid Architecture

Layer	Primary Function	Key Features
4. Energy Application Layer	Enables high-level services and business models.	Supports dynamic pricing, demand response, and power-on-demand services.
3. Energy Streaming Layer	Coordinates global energy balance across the grid.	Replaces traditional secondary and tertiary control; manages energy availability without overloading segments.
2. Energy Routing Layer	Physically forwards energy between neighboring A-grids.	Uses the AFSC principle (Aggregate, Forward, Store, then Convert) to move energy streams.
1. A-Grid Layer	Manages local power flow within a single subgrid.	Operates on existing technology and primary control principles; performs local balancing and energy distribution.

The Energy Streaming Layer (Layer 3) uses internet-inspired protocols to schedule energy streams rather than requiring the instantaneous matching of a traditional synchronous grid, treating electricity as a stream of energy packets and abstracting away local technical details such as whether a subgrid runs at 50 Hz, 60 Hz, or DC.

The Energy Application Layer (Layer 4) is a service layer enabling a plug-and-play ecosystem of new business models – for example peer-to-peer energy trading – without requiring redesign of the underlying electrical infrastructure.

This layered architecture provides the structure within which the remainder of the paper develops SAFErGrid's market design: Section 4 addresses how power balance is re-cast as energy balance and priced at the Energy Application Layer; Section 5 aaddresses how congestion is priced continuously rather than corrected after the fact through redispatch.

4 From Power Balance to Energy Balance

This section draws on standard texts in electricity and energy economics, such as Stoft (2002), Biggar and Hesamzadeh (2014), Kirschen and Strbac (2018) and Zweifel et al. (2017)

- especially their chapter 12.

4.1 Market Clearing in the Synchronous Grid

In a synchronous AC grid electricity must be produced and consumed simultaneously, which constrains how the electricity market can function. What is traded is not a physical object but the right to inject or withdraw energy from the grid during a specific window of time (Zweifel et al., 2017), typically denominated in Megawatts (MW), the instantaneous rate of transfer, and Megawatt-hours (MWh), the volume delivered at a given rate over an hour.

European wholesale electricity is organized in large pricing ("bidding") zones within which price is uniform for each time step (Ehrhart et al., 2026, p.78). In Germany, wholesale prices are set through uniform-price auctions on the European Energy Exchange (EEX, Leipzig) and EPEX SPOT (Paris), where suppliers submit hourly bids of volume and marginal-cost-based price. The resulting supply curve follows the "merit order" (Cludius et al., 2014; Sensfuss et al., 2008; Stoft, 2002; Kirschen and Strbac, 2018; Zweifel et al., 2017). This indicates that if there are n power plants, each with a capacity K_i and a constant marginal cost MC_i, ordered such that $MC_1 < MC_2 < \cdots < MC_n$, then the supply price for a given quantity Q is defined by a piecewise constant function (Stoft, 2002; Biggar and Hesamzadeh, 2014):

$$P_s(Q) = MC_i \quad \text{for} \quad \sum_{j=1}^{i-1} K_j < Q \leq \sum_{j=1}^{i} K_j \tag{1}$$

Where MC_i denotes the marginal cost of the i-th generator (e.g., fuel + CO_2 costs); K_j is the installed capacity of plant j; Q is the total instantaneous demand (load) on the grid (Kirschen and Strbac, 2018).

Over the short-term the demand curve (Q_d) for electricity is highly price inelastic because consumers do not change their behavior immediately based on price fluctuations (Newbery et al., 2017). It can be written as:

$$Q_d(P) = D_{fixed} \tag{2}$$

From (1) and (2) the equilibrium price P^* is the market clearing price (MCP). It is set by the marginal cost of the last unit dispatched to meet the fixed demand D_{fixed}.

$$P^* = P_s(D_{fixed})$$

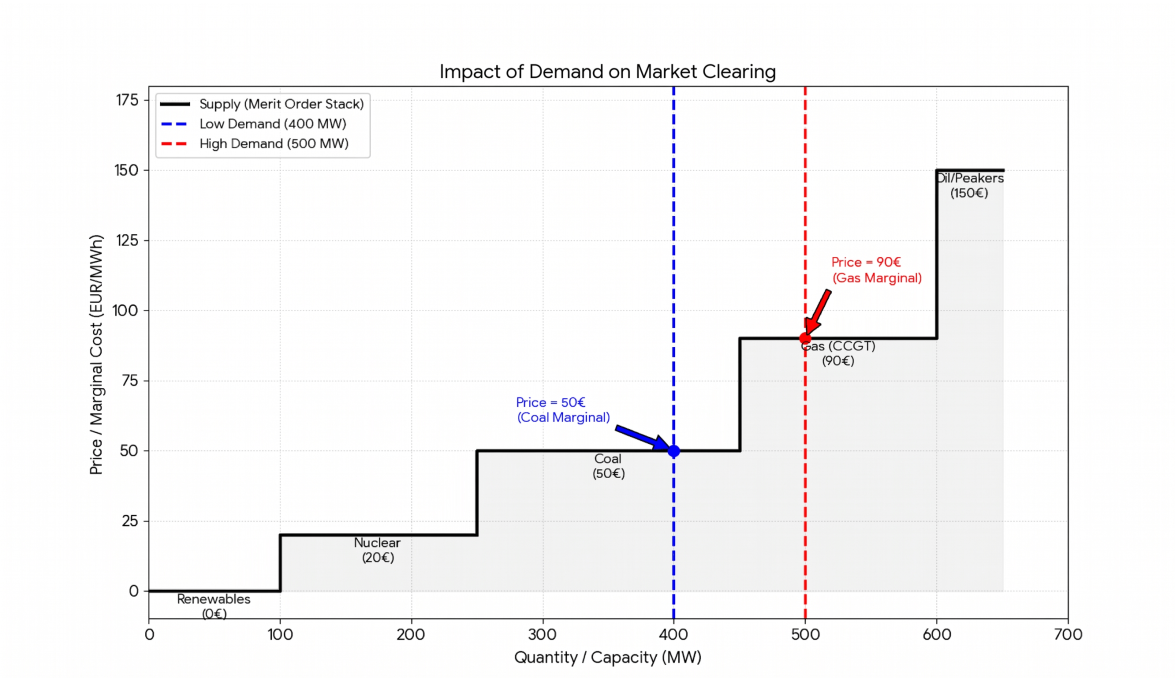
Figure 1 provides an example of the merit order supply curve, and the demand curve for electricity, and how the market clearing price and quantity is obtained for a hypothetical case[7] - for a discussion of this supply curve, see e.g. Castro (2024), Appunn (2015) and Zweifel et al. (2017, p.280).

Figure 1 illustrates the mechanism for a hypothetical system in which renewables and nuclear together supply 250 MW at low cost, coal adds a further 200 MW (total 450 MW at €50/MWh), and gas (CCGT) adds a further 150 MW (total 600 MW at €90/MWh). At demand of 400 MW the market clears on the coal segment at €50/MWh; if demand rises to 500 MW, gas plants are called upon and the price jumps to €90/MWh – the entire market clearing at the cost of the single most expensive unit dispatched, even though only 50 MW of that expensive capacity is actually required.

This wholesale price is only one component of what German households ultimately pay. The household bill divides roughly into energy and supplier margin (≈ 30%), taxes and levies (≈ 40%), and grid fees (≈ 25%) that recover the cost of operating, maintaining and

[7] See also https://www.next-kraftwerke.com/knowledge/what-does-merit-order-mean.

Figure 1: Wholesale Electricity Market Clearing: The Merit Order Effect



Source: Author's compilation, based on Biggar and Hesamzadeh (2014, p.100), Appunn (2015) and `https://www.next-kraftwerke.com/knowledge/what-does-merit-order-mean`

expanding the physical network (Wehrmann, 2025). Because redispatch costs and physical capacity constraints are not priced into the daily wholesale auction but instead recovered later through grid fees, "market price signals are distorted [and] electricity prices can no longer serve as an indicator for system scarcities" (Hanny et al., 2022, p.5). Naudé (2026c) discusses how this contributes to energy poverty in Germany where redispatch costs and grid fees have been steeply rising in recent years.

4.2 Energy Balance and Market Clearing in an A-Grid

Within an individual A-grid, supply combines local generation and controlled imports via DC links:

$$Q_s = \sum Q_{\text{gen}} + Q_{\text{import}} \tag{3}$$

Where:$\sum Q_{\text{gen}}$ is the aggregate local renewable energy supply (e.g., from rooftop solar and wind installations), which operates at a marginal cost of near zero ($MC \approx 0$).

And Q_{import} is the energy imported from neighboring A-grids via asynchronous DC interconnectors up to the line's physical capacity.

The equilibrium for an A-Grid is found where:

$$Q_s(P) = Q_{\text{Local Demand}}(P) + \Delta E_{\text{buffer}} \tag{4}$$

Where the Storage Buffer (BESS) is denoted by ΔE_{buffer}. When there is surplus supply, the buffer charges ($\Delta E > 0$), and when there is a supply deficit, it discharges ($\Delta E < 0$).

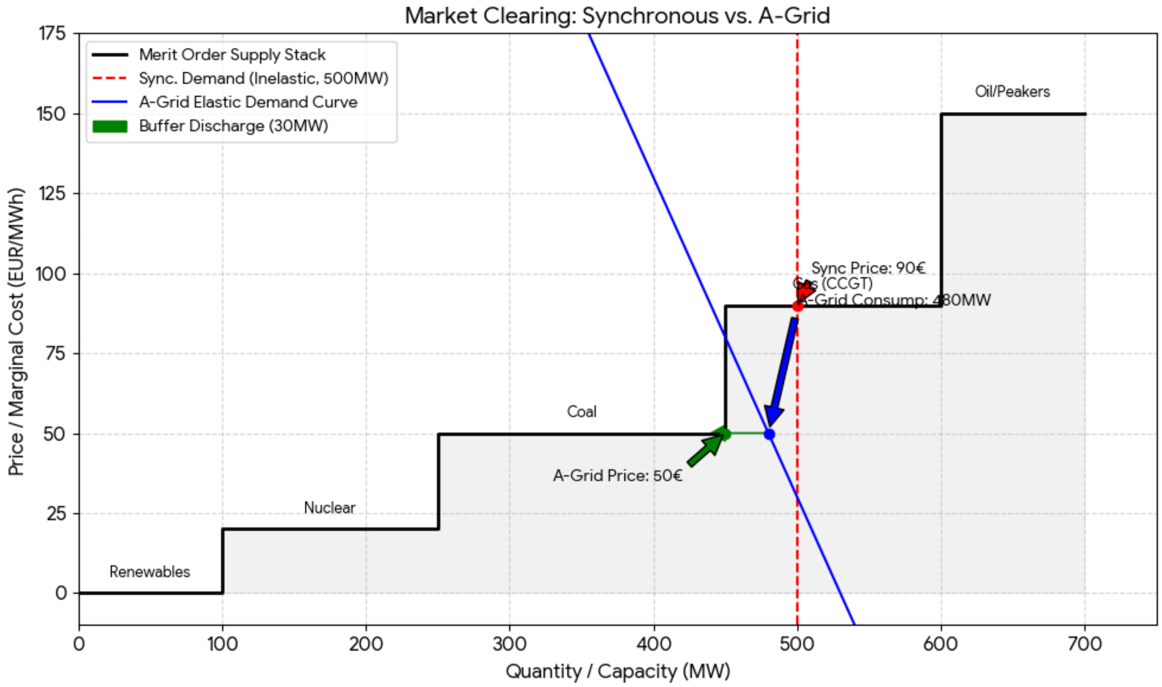
The supply curve (Q_s) is dominated by renewables at $MC \approx 0$. Because the grid is asynchronous, it can accept 100% renewables - it does not have to curtail capacity for managing grid stability.

The demand curve (Q_d) is no longer a vertical, inelastic line as in Figure 1. Through the Energy Router which enables a smart demand response, the demand curve becomes downward-sloping, i.e. price elastic. The new, lower-price equilibrium is shown in Figure 2.

Figure 2 shows that in the synchronous grid, demand for electricity is inelastic, represented by the vertical demand curve (the red dotted line). To meet a demand of say 500 MW, the grid must engage all plants up to the "gas step" in the merit order. The market clears at the marginal cost of the last plant, which is assumed here for exposition purposes to be 90€/MWh. This high wholesale price is the one on top of which redispatch costs will be added as grid fees when retail prices for households are determined.

In contrast, in the A-Grid demand is downward-sloping (the blue line), as a result of the smart demand response through the energy routers as described. Hence, the energy router

Figure 2: Market Clearing: Synchronous vs Asynchronous Grid



Source: Author's compilation

will reduce demand as it rises to 480 MW - as it nears the price ceiling of the cheaper Coal step - and the buffer will discharge say 30 MW of packetized energy directly into the subgrid. Thus, with 480 $MW - 30\ MW = 450\ MW$ the net load is 450 MW, at which the market clears at the *Coal* step price of 50€/MWh. By clearing the market at 50€/MWh instead of 90€/MWh as in the case of the synchronous grid, the A-grid reduces the wholesale component of the electricity bill.

Negative prices arise in the synchronous grid because inflexible fossil generators cannot simply switch off when supply is abundant. In an A-grid, surplus electricity can instead be Stored or Forwarded – for example converted to green hydrogen or routed to heat pumps – with a Local Market Operator (LMO) (perhaps using advanced AI tools) monitoring real-time prices and automatically activating these assets as price approaches zero.

Formally, the LMO can be represented as solving, in real time,

$$\min \text{Total Cost} = \sum (P_{gen} \cdot Q_{gen}) + \sum (P_{ext} \cdot Q_{ext}) \tag{5}$$

Subject to:

$$\sum Q_{gen} + Q_{import} = \sum Q_{load} + Q_{export} \pm \Delta\text{Storage} \tag{6}$$

In minimizing (4) the LMO performs three critical tasks that humans cannot. The first is *Predictive Forecasting:* It uses machine learning to predict cloud cover (solar drop) or wind gusts 15 minutes ahead. The second is *Price Elasticity Mapping*: It knows at what price specific local consumers (like an EV fleet) are willing to stop charging. The third is *Autonomous Bidding*: It decides whether to sell excess power to the neighboring A-Grid, or save it in the local battery for an expected evening peak.

To illustrate the above, consider a hypothetical A-grid in the City of Aachen consisting of a neighborhood of 100 homes, a school, a sailing club, and a community battery. It is a sunny, windy summer afternoon. Local supply is 500 kW solar plus 200 kW wind = $700kW$ at $MC \approx 0$; local demand is 400 kW; and the DC interconnector to the next A-grid is limited to 100 kW. In a synchronous grid, the 300 kW surplus would have nowhere to go: either the TSO instructs generators to curtail, or the price crashes toward € $-20/MWh$ to induce someone to absorb it.

In the asynchronous A-grid, the LMO instead clears the market as follows. First, it schedules the full 100 kW export to a neighboring A-grid experiencing a deficit. Second, it signals 50 smart EV chargers (including sailing-club battery chargers) that "price is currently €2/MWh," inducing an additional 100 kW of demand. Third, the remaining 100 kW surplus is routed to the community battery. Because the LMO created demand at the €2 mark, the price never needs to go negative, and because the LMO respected the 100 kW DC limit rather than forcing 300 kW through it, no congestion or redispatch cost arises. If a cloud subsequently interrupts solar output, the LMO instantly reverses the EV chargers or draws down the battery.

In routing stored surplus to a neighboring A-grid, the community simultaneously acts as consumer and producer – a prosumer – a role that can equally arise between individual households with their own generation and storage.

5 From Redispatch to Dynamic Scarcity Pricing: Eliminating Congestion

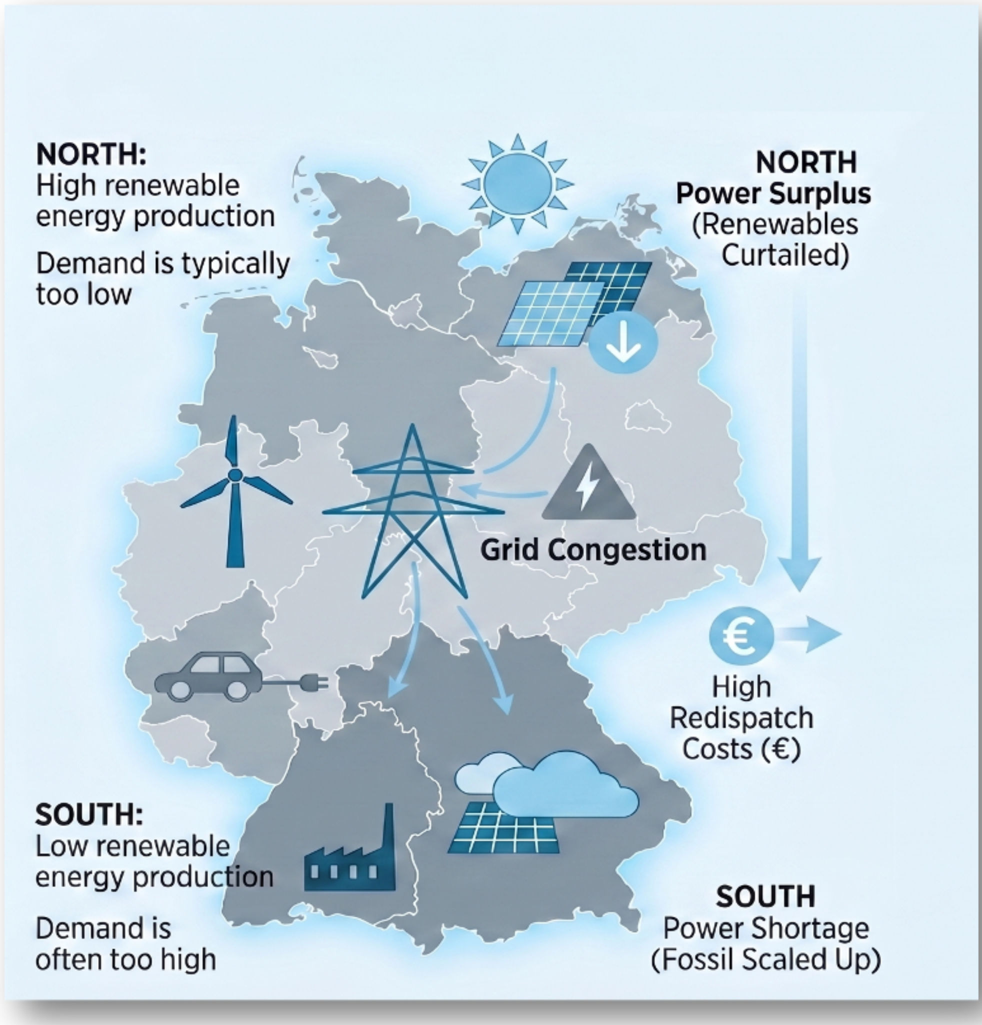
5.1 Congestion and Redispatch in the Synchronous Grid

German wholesale electricity prices are set as if the country were a single bidding zone, so that price "do[es] not reflect intra-zonal transmission constraints [...]as if the entire internal network were a copper plate" (Ehrhart et al., 2026, p.78). In reality, Germany's wind resources are concentrated in the north while demand – especially heavy industry – is concentrated in the south (Schermeyer et al., 2017; Titz et al., 2023), and moving power between the two regions places sustained pressure on transmission capacity.

Figure 4 illustrates the difference between demand and supply of electricity in two regions: the north and the south.

When transmission lines approach capacity, TSOs order northern wind farms to curtail output and southern power plants to increase production – redispatch – compensating both sides (Schermeyer et al., 2017; Appunn, 2016; Hofer and Madlener, 2021; Neuhoff et al., 2025; Neuhoff and Stolle, 2026). Because redispatch shuts down cheap northern capacity

Figure 3: Grid Stability and Redispatch Costs



Source: Based on Neuhoff and Stolle (2026, p.113)

while ramping up expensive southern capacity, it raises total system cost, and because the bidding zone is uniform, neither producers nor consumers receive locational price signals reflecting actual regional scarcity (Nüssler, 2012). German redispatch costs rose from roughly €400–600 million in 2014 to €4.2 billion in 2022 and €3.1 billion in 2023 (Donnelly, 2025). Allianz Research (projects German congestion costs of €12.3 billion by 2030 and €56.7 billion by 2040 without upgrades (Allianz Research, 2025). For the EU as a whole, redispatch cost roughly €5 billion in 2022, forecast to rise to between €11 billion and €26 billion by 2030 (Thomassen et al., 2024).

Because these costs are recovered with a lag – typically folded into the following year's grid fees rather than the current day's wholesale price – physical capacity constraints are not priced into daily market clearing (Smahi and Makhloufi, 2025; Fazeli et al., 2020) , and the "current grid fee system in Germany[...] does not take into account the specific grid situation when purchasing electricity" (Beranek et al., 2026, p.2). Grid fees themselves vary substantially by region – an average family in rural Brandenburg pays roughly double the grid fee of an equivalent family in Bremen for the same consumption (Amelang, 2017) – while Germany's 2025 introduction of time-variable grid fees under Section 14a EnWG represents only a partial, non-truly-dynamic step toward reflecting network conditions in price.

5.2 Negative Prices and the Value of Lost Load

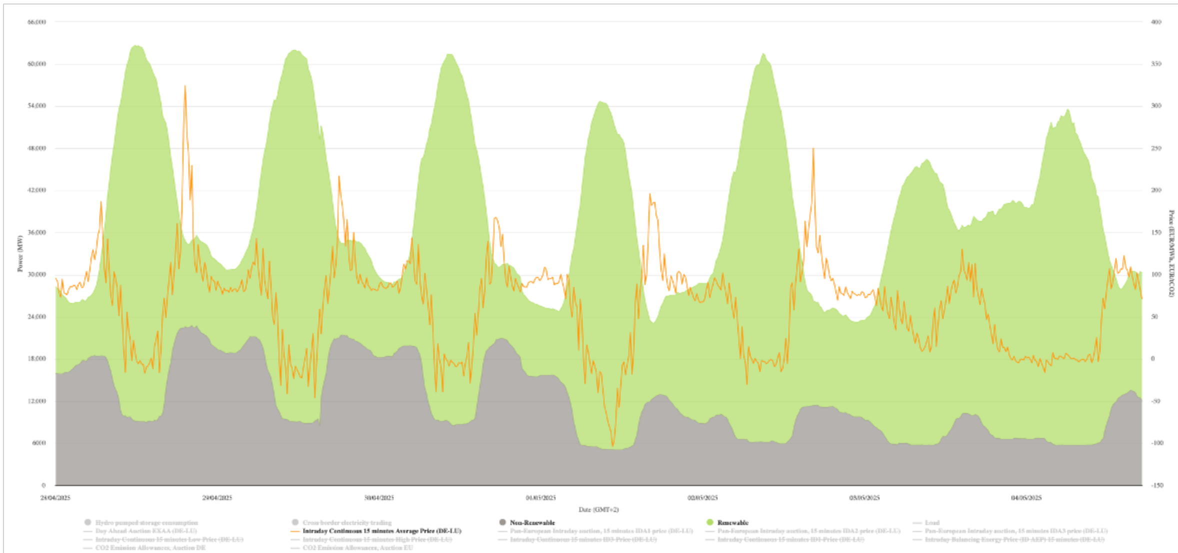
A related consequence of the synchronous grid's rigid balancing requirement is negative pricing: because inflexible generators cannot cheaply switch off, and because fixed feed-in subsidies mean renewable generators lose support entirely if they stop producing, some generators prefer to pay the market to take their electricity rather than curtail (Nuikina, 2025; Günner, 2025). The supply curve of equation (1) then admits negative marginal costs:

$$P_s(Q) = MC_i \quad \text{where} \quad MC_i < 0 \tag{7}$$

As illustrated in Figure 5 for Germany on 1 May 2025, where midday solar generation drove day-ahead prices to €$-130/MWh$ before they rebounded to roughly €164/MWh in the evening: a swing of about €294/MWh in a single day (ACER, 2026, p.39).

The opposite extreme is if demand cannot be met at all, that is, if fixed demand exceeds total available capacity, i.e.

Figure 4: Generation mix per production type, load and day-ahead price in Germany, 1 May 2025 (MWh, EUR/MWh)



Source: https://energy-charts.info/

$$D_{fixed} > \sum_{i=1}^{n} K_i \tag{8}$$

Where $\sum K_i$ is the total available capacity of every single plant on the grid.

In this case the market cannot clear and a blackout results, with the Value of Lost Load (VoLL) representing the maximum amount consumers would pay to avoid disruption (Schröder and Kuckshinrichs, 2015). Under the EU Clean Energy Package (Regulation (EU) 2019/943), Member States must establish a single VoLL estimate for their territory; European estimates range from roughly €1,500 to €22,940/MWh (Swinand et al., 2019).

VoLL serves as the benchmark for demand-side response – for example, a facility able to remain cold for two hours without power and valuing lost load at €5,000/MWh will voluntarily reduce demand once the spot price nears that threshold, lowering system load and helping to avert a frequency collapse (Praktiknjo, 2016; Knight, 1921; Stoft, 2002). German regulators additionally maintain a strategic capacity reserve, prohibited from bidding in the wholesale market but available on TSO instruction, to avoid this blackout break-point altogether.

5.3 Congestion Pricing in SAFErGrid

In a SAFErGrid design, A-grids are connected via HVDC/asynchronous links managed by smart Energy Routers, with each A-grid's LMO setting the $NetFlowDC$ variable. Where the synchronous grid clears the market first and corrects physical imbalances afterward through redispatch, the A-grid instead makes physical capacity a variable within the auction itself, subject to $Flow \leq Capacity$: if a line approaches its limit, the local Energy Router triggers storage discharge or demand adjustment, or – in a near future of cheaper electrolyzers – converts surplus renewable energy to green hydrogen, rather than forcing flow through a constrained line and settling the cost later.

The SAFErGrid concept of *Action* defines the work performed by Energy Routers and buffers to maintain frequency and voltage (Schwarz et al., 2026):

$$A = \int_{t_1}^{t_2} (E_{kinetic} - E_{potential})dt \tag{9}$$

which in an A-grid translates into the energy required to balance local demand and supply. This can yield a dynamic electricity price that is a direct function of the physical work required to keep the grid stable, rather than of scarcity alone:

$$p_t = p_{base} + \omega \cdot \frac{d(E_{action})}{dt} \tag{10}$$

Where $p(t)$ is the price at time t; π_{base} is the cost of energy generation in a particular A-grid; ω with $(\omega > 0)$ is a scaling constant which takes the physical, high-speed workload ($\frac{d(E_{action})}{dt}$) and translates it into an economic scarcity rent.

When the grid operates well below capacity, $d(E_{action})/dt \approx 0$ and price remains close to p_{base}; as utilization approaches the thermal limit, the physical stress – and hence the required Action Energy – rises sharply, and the price signal rises correspondingly, following the logic set out by Zweifel et al. (2017, p.39) for scarcity rents as capacity utilization approaches 100%.

This matters because the traditional synchronous grid, to prevent collapse if one transmission line fails, caps utilization at roughly 60–70% of physical thermal capacity (Priebe et al., 2019). SAFErGrid's continuous pricing of *Action Energy* may allow the same physical wire to be used up to 100% of its thermal capacity, with the marginal risk of instability priced in continuously via $d(E_{action})/dt$ rather than avoided altogether through a blanket capacity cap.

Market clearing at the A-grid level can be organized as a Continuous Double Auction (CDA) hosted on a distributed ledger (Wang et al., 2017), described by Qiu et al. (2021, p.2913) as "*a promising peer-to-peer (P2P) energy trading mechanism that enables interactions among prosumers in a distributed manner.*"

In a CDA, buyers and sellers submit bids and asks continuously; a transaction executes whenever the outstanding bid meets or exceeds the outstanding ask, at a price equal to their average Wang et al. (2017). Managed by an LMO maintaining a virtual order book for each A-grid cell, the clearing condition is:

$$\sum q_{D_i}(p^* + \tau) = \sum s_{S_j}(p^*) - \Delta E_{buffer} \tag{11}$$

Where q_{D_i} is individual household demand at price p^* plus a routing fee $\tau . s_{S_j}$ is local renewable energy supply, e.g. from rooftop solar installations. The price (p^*) fluctuates in real-time based on the instantaneous scarcity of energy in the local buffers and the physical capacity of the local lines.

When the buffer runs low, the LMO issues a dynamic price spike:

$$p_t = p_{base} + \omega \cdot \frac{1}{E_{buffer}(t)} + \tau \tag{12}$$

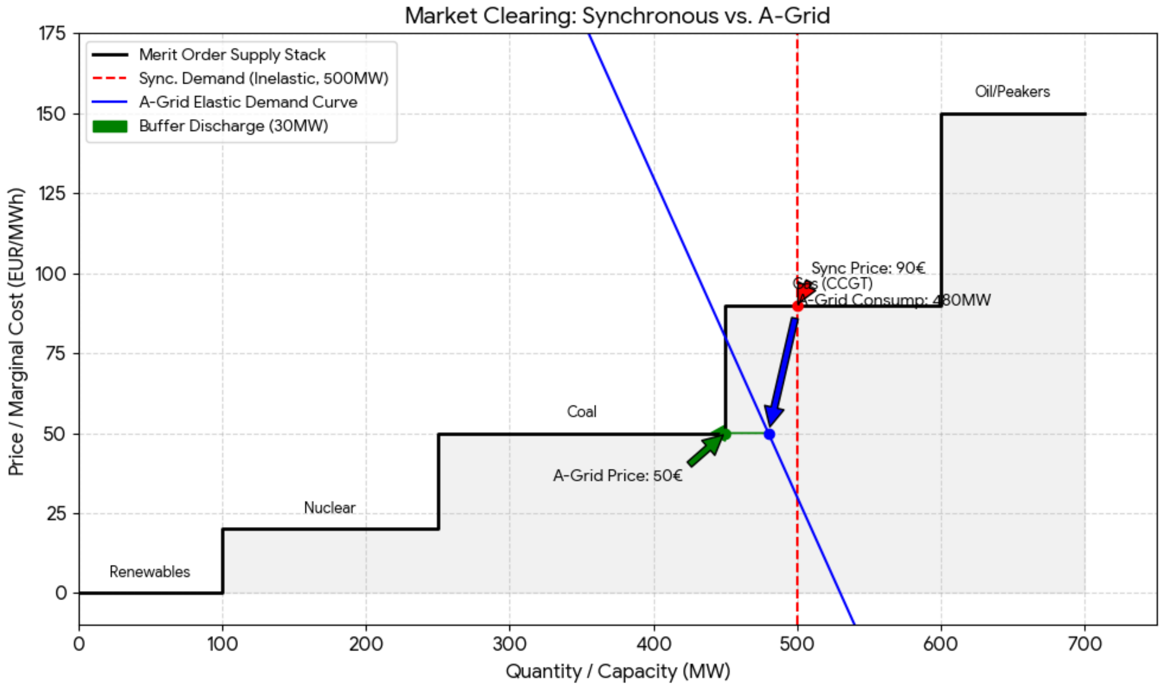
The term $1/E_{buffer}$ is the scarcity premium, which once received by smart appliances within the A-grid, will automatically delay non-essential cycles - for instance it will halt Electrical Vehicle (EV) charging or washing machines - shifting the demand curve to match available supply without expensive redispatch.

Glebke et al. (2025) show how a CDA of this kind allows households with rooftop solar and storage to act as prosumers whose LMO autonomously buys when local prices are low and sells when prices spike during local grid stress; by reflecting a lower ask when a prosumer permits delayed EV charging during a peak, the CDA allows the market to clear at a cheaper point in the merit order, lowering costs for the entire A-grid cell while minimizing energy exported to the higher-level grid – and with it, congestion and redispatch fees.

Figure 6 compares a 500 MW demand scenario under the two architectures. In the synchronous grid, inelastic demand forces dispatch up to the gas step of the merit order, clearing at €90/MWh - on top of which redispatch costs are later folded into grid fees. In the A-grid, downward-sloping demand from smart response reduces load to 480 MW as price approaches the cheaper coal step, and the buffer discharges a further 30 MW directly into the subgrid; the resulting net load of 450 MW clears at the coal-step price of €50/MWh - a reduction in the wholesale component of the bill of €40/MWh relative to the synchronous outcome.

This comparison abstracts from a further institutional feature of the German market: the market power that incumbent TSOs derive from their sunk investment in grid infrastructure, recovered through grid fees calculated as an annualized cost of capital,

Figure 5: Market Clearing: Synchronous vs Asynchronous Grid



Source: Author's compilation

$$ic = Inv_0 \cdot \frac{i(1+i)^T}{(1+i)^T - 1} \tag{13}$$

Where Inv_0 is the initial investment and i is the interest rate.

A transition to SAFErGrid would itself require substantial investment in Energy Routers and buffers, which would also need to be recovered through some form of tariff; and, given the natural-monopoly position of incumbent TSOs, there remains an incentive to lobby for grid fees that guarantee a return on this investment (Zweifel et al., 2017).

In this respect the decentralized architecture of SAFErGrid may reduce, without fully eliminating, the potential for monopoly rent-seeking in the setting of grid fees, since routing decisions and the resulting congestion charges become distributed across many A-grid operators rather than concentrated in four incumbent TSOs. Where the conventional grid also faces a similar replacement cycle for aging transformers roughly every one to two decades, the marginal additional cost of a SAFErGrid transition is, in principle, limited to the cost difference between a smart Energy Router and a conventional replacement transformer, plus whatever incentives are used to accelerate diffusion.

The dynamic price in equation (17), $p_t = p_{base} + \omega d(E_{action})/dt$, reflects a scarcity rent driven directly by physical grid stress rather than by an administratively-set capacity cap.

A corresponding vulnerability is that if the LMO makes systematic forecasting errors – the market-failure channel Zweifel et al. (2017) identify for energy markets under expectation error – the resulting *Action Energy* price signal could itself become excessively volatile, raising the risk premium investors require and potentially working against, rather than for, affordability.

Finally, redispatch itself is transformed rather than eliminated outright. During a "Dunkelflaute" – a period without wind – renewable supply drops and, in the synchronous grid, the merit-order stack shifts toward expensive oil or peaker plants whose redispatch cost is passed to consumers only in a subsequent billing period, with the result that households facing a flat, lagged price have no incentive to shift consumption during the event itself.

In SAFErGrid, the *Energy Streaming Layer* (see Table 1) instead directs energy from a distant source – offshore wind or imported nuclear power, for example – to the A-grid in real time, while the Energy Router issues an immediate packet-priority signal that can, for instance, pause a heat pump automatically, eliminating the price lag that otherwise prevents household behavior from responding to grid stress. To keep such automated responses reliable despite network latency, Heins et al. (2023) propose Delay-aware Model Predictive Control, showing that explicitly accounting for communication delay in packet-priority signaling preserves fast frequency control and avoids the synchronization errors that could otherwise arise if a digital signal arrives after a physical frequency deviation has already begun.

6 Discussion

The electricity pricing and market clearing explored in Sections 4 and 5 addresses the challenges of the rising penetration of RES into a century-old synchronous grid. It does so by converting a physical engineering constraint into an explicitly priced, tradeable quantity, rather than managing it administratively through curtailment orders, redispatch instructions, or a blanket transmission-capacity cap.

The market dynamics explored with respect to energy balance and congestion management are mutually reinforcing. For instance, the local buffer (BESS) (E_{buffer}) that clears the energy-balance auction also determines the congestion price. As Naudé (2026a) also explores, the local buffer also determines the price of (virtual) inertia. This suggests that investment in distributed BESS is perhaps the one single action that may have the highest economic payoff, and that the interaction between these markets – between the markets for electricity, congestion and inertia - rather than any one in isolation – is likely to determine the broad or aggregate economic value of a decentralized, asynchronous grid such as proposed by SAFErGrid. Naudé (2026b) discusses, as an addition to these sources of economic value, the potential innovation value from the SAFErGrid - for example, peer-to-peer trading and quality-of-service market segmentation.

The analysis suggests a potential design risk that implementation would need to resolve. This is because the markets discussed are cleared by an Local Market Operator (perhaps using advanced AI tools) forecasting local generation, demand elasticity and neighboring-grid conditions, any systematic forecasting errors would propagate into price volatility of electricity and congestion (and inertia).

7 Concluding Remarks

The synchronous AC grid confronts operators with three linked challenges as renewable penetration rises: maintaining instantaneous power balance to keep frequency at 50 Hz, maintaining sufficient inertia to slow the rate of change of frequency following a disturbance, and keeping transmission congestion from itself threatening frequency and inertia.

This paper explored how the SAFErGrid proposal for a decentralized, asynchronous grid – compartmentalized into A-grids connected by smart Energy Routers – offers a market-design response to the challenges of energy balance and congestion management. Power balance in the synchronous grid was modelled as energy balance where electricity markets in decentralized grids clear through a continuous double auction managed by a Local Market Operator, allowing demand to become price-elastic and avoiding both negative prices and unscheduled curtailment. Congestion was modelled as being priced continuously, as a function of the physical Action Energy required in the SAFErGrid architecture to keep each A-grid within its thermal limits, rather than corrected after the fact through administratively-set redispatch.

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