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Harnessing Flexibility in the Energy Transition: Lessons for Energinet

Introduction: Rising Renewables, Electrification, and Balancing Challenges

Denmark and many countries are experiencing a surge in renewable energy and electrification. Wind energy already supplies over half of Denmark's electricity [1], and national power consumption is expected to **double by 2030** (and grow fivefold by 2050) due to transport and heating electrification [2]. This green transition brings tremendous benefits but also poses **grid balancing challenges**. Intermittent resources like wind and solar introduce greater real-time supply variability and forecasting errors, while new electric loads (EVs, heat pumps, electrolysis, etc.) add volatility on the demand side. Together, these trends demand new strategies to keep the grid stable (frequency at 50 Hz) and **resilient** against imbalances. Traditional balancing approaches must adapt to ensure reliability as renewable capacity in many countries will soon exceed peak loads [3] [4]. At the same time, the proliferation of **distributed flexible resources** (from EV batteries to smart appliances) presents an opportunity to help balance the system – if harnessed effectively [5] [6].

In this context, grid operators like Energinet are rethinking how to balance supply and demand in real-time. Two broad models are emerging: **centralized balancing** (TSO-controlled, via contracted reserves) and **decentralized balancing** (market-driven, via widespread response to price signals). This report, drawing on Elia's recent white paper *"Harnessing Flexibility in the Energy Transition"*, analyzes these models' pros and cons in light of Energinet's goals: reducing system costs, integrating renewables, and increasing grid resilience. We examine economic and operational trade-offs of each model – including balancing cost, system precision, capacity needs, and demand-side flexibility – and explore the technological enablers that make decentralized approaches feasible (e.g. smart meters, digital tools, real-time pricing). We also highlight Belgium's experience as a pioneer of decentralized balancing, extracting lessons applicable to Denmark. Finally, we provide actionable recommendations for Energinet on adopting or adapting decentralized balancing strategies, encompassing market design, organizational changes, regulatory tweaks, and technical infrastructure.

Balancing Models Overview: Centralized vs. Decentralized Approaches

Centralized Balancing Model: In a centralized model, the Transmission System Operator (TSO) takes full control of balancing actions after a certain cutoff time before delivery. In practice, this means that beyond a gate closure (e.g. 1 hour before real-time in some systems [7]), *market participants are no longer allowed to adjust their positions* to help balance the grid. The TSO exclusively handles any last-minute imbalances by activating reserved flexibility via explicit control signals (calling on generators or loads that bid into balancing markets) [7]. Under this model, **Balance Responsible Parties (BRPs)** must finalize their trades ahead of the gate and are generally expected to remain balanced; any deviation after the cutoff is meant to be corrected only by TSO-dispatched reserves. In theory, this centralized approach gives the system operator a **tight grip on balancing**. The TSO has a clear real-time overview of available reserves and can dispatch them as needed, enabling *precise frequency control* with fast-acting reserves (e.g. automatic Frequency Restoration Reserve regulating every few seconds) [8] [9]. Service providers under this model have firm delivery obligations – if the TSO activates a reserve, the provider must comply or face penalties – which bolsters reliability from the TSO's perspective [10] [11]. These features make the centralized model traditionally appealing for maintaining strict control over system balance.

However, in the evolving energy landscape, centralized balancing reveals significant limitations. By design, it **excludes** many flexible resources that cannot meet the prequalification or bidding requirements for reserve markets [12]. Small or distributed assets (e.g. residential batteries, EV chargers, smart appliances) often lack the technical ability or prefer not to invest in the systems needed to provide explicit balancing services [12] [13]. The process of bidding into reserves is complex – requiring 24/7 operations, ICT integrations, and compliance with TSO specifications – which deters smaller players or those for whom energy is not a core business [13] [14]. There are also time lags: resources must be pre-contracted and scheduled, and some must be kept running (part-loaded) to provide upward or downward regulation, incurring efficiency losses. Additionally, many flexible loads have **intrinsic constraints** (e.g. an industrial process or a household's comfort needs) that are *difficult to encapsulate in a simple bid*. Such constraints might prevent these assets from offering explicit bids even if they have flexibility, because reserve products don't easily accommodate non-electrical considerations (like a factory's production cycle) [15]. In short, centralized models tend to utilize a narrower pool of flexibility – mainly conventional power plants or large controllable units – leaving a growing segment of **decentralized and behind-the-meter flexibility untapped** [16]. This reduced participation can make balancing less efficient and drive up costs, especially as renewable volatility increases. Indeed, Elia's analysis notes that excluding many flexible assets from balancing "reduces overall efficiency and likely increases balancing costs" in the long run [17]. Another consequence is greater reliance on **balancing capacity procurement**: if the TSO cannot count on the natural flexibility of demand or distributed resources, it must contract more standby reserves to cover worst-case imbalances. Procuring these reserves (capacity payments to keep plants on call) is expensive and can even distort the energy market by locking capacity out of day-to-day trading [18]. In a future with soaring flexibility needs, a purely centralized model might struggle to *find and finance* all the reserves required [19] [20]. The relevance of this model in systems with high renewables and abundant distributed flexible load is increasingly questionable [21].

It's also important to recognize a **practical reality**: even when a TSO tries to enforce centralized control (legally forbidding any balancing by market parties after gate closure), completely stopping **implicit reactions** is nearly impossible. If imbalance prices are high or low enough, some market participants will find ways to adjust their generation or consumption in real time – for example, by intentionally deviating from schedules if they anticipate the imbalance price will reward that deviation [22] [23]. Experience in countries like Germany shows that a few well-informed BRPs can forecast imbalance prices (due to portfolio size or market savvy) and will respond despite rules, since it's hard to prove their moves weren't just "forecast error" [23] [24]. Enforcing a ban on after-the-fact balancing is thus both impractical and, arguably, counterproductive. If the TSO ignores these implicit adjustments, it may end up **over-correcting** the system. For instance, a TSO that assumes BRPs are inelastic might activate more reserve power than needed, only to find the system overshoots in the opposite direction because some demand dropped off in response to price – leading to an oscillation that requires counter-activation [25]. This kind of seesaw (deploying too much reserve, then having to correct back) adds unnecessary cost. In summary, while centralized balancing offers control and simplicity on paper, it faces efficiency and implementation challenges in a world with abundant renewables and active consumers.

Decentralized Balancing Model: In a decentralized model, the TSO **allows and incentivizes market participants to help balance the system all the way up to real-time**. There is no strict cut-off after which only the TSO can act; instead, **Balance Responsible Parties adjust their positions continuously** in response to price signals, even during the final balancing timeframe [26]. The TSO still maintains reserve capacity for fine-tuning, but its explicit activations are meant to cover only the **residual imbalance** that the market cannot solve through its own actions [26] [27]. In practice, this means BRPs are *rewarded for deviating from a strict balance* if doing so aids the overall system. The primary signal guiding them is the **imbalance price** – essentially a real-time price for energy that reflects system conditions. If the system is short (not enough generation), the imbalance price spikes, encouraging any asset that can increase supply or reduce demand to do so; if the system is long, the price may go negative or very low, encouraging consumption or curtailing excess generation. By "reacting implicitly" to these prices (rather than awaiting a direct instruction from the TSO), flexible assets throughout the grid help correct imbalances. Decentralized balancing thus explicitly leverages the **demand-side and distributed resources** that centralized models tend to ignore. Even assets that never placed bids in the reserve market (e.g. a fleet of EV chargers, or a factory with flexible processes) can contribute simply by ramping down or up at critical moments due to the price incentive [16]. This model taps *the full breadth of system flexibility*: the traditional explicit reserves (generators, big batteries, etc. that bid into aFRR/mFRR) **plus** the "implicit" responders who act on price signals outside any direct contract [27] [16]. In theory, decentralized balancing dispatches the **cheapest or most easily available resources first**, wherever they are in the system, to handle last-minute mismatches. This should improve efficiency and lower overall costs, a point we discuss in detail in the next section.

Adopting a decentralized balancing model is not without **challenges**. The **design and operational coordination** must be carefully managed to reap the benefits without compromising reliability [28]. Key conditions for success include:

- **Efficient use of all assets:** The model should be set up so that each flexible asset participates in the way that brings the most value to the system [29]. For example, fast-reacting resources that can provide quality regulated response (like large batteries or demand response capable of following a 4-second signal) should still be attracted to offer *explicit* services (e.g. aFRR) where their precision is needed [30]. Decentralized balancing doesn't eliminate the need for explicit reserves – rather, it complements them. The system should encourage high-value flexibility to enter reserve markets (where they can also be used across borders), while using price-based implicit response for the remaining needs. This ensures, for instance, that a new battery doesn't sit idle waiting for price spikes when it could be helping with continuous regulation; we want it participating in aFRR and *then* any extra margin can still respond to price if needed.

- **Complementarity of actions:** Implicit market responses and explicit TSO activations must work in concert, not at cross purposes. The combined effect of (a) the volume the TSO activates and (b) the voluntary response of BRPs to prices should **closely match the actual imbalance** that needs correcting [31]. If the two are uncoordinated – for example, if both the TSO and many BRPs try to correct the same shortfall – the system could over-shoot. Achieving this complementarity requires good **forecasting and real-time information**, so that the TSO anticipates how much the market will self-correct and adjusts its activation volume accordingly [32] [33]. Conversely, BRPs need to understand the system state to respond appropriately. Thus, information flows and predictions are crucial (more on the technological enablers soon).

- **Clear and stable price signals:** Decentralized balancing relies on the imbalance price as the stimulus for BRPs. It's vital that this price be designed to **truly reflect the real-time value of energy** and remain reasonably stable on the timescale of response [34]. If the price is erratic (flipping from high to low within seconds) or not aligned with actual system needs, it could either confuse market participants or even incentivize harmful reactions. A stable price over the imbalance settlement period (e.g. a 15-minute averaging or smoothing) can prevent intra-interval oscillations [35] [36]. Belgium's experience shows the importance of this: publishing a one-minute imbalance price was helpful, but it also led to some rapid swings, so now a **forecasted imbalance price** is being trialed to guide BRPs with a forward-looking indicator [37] [38]. The price mechanism must also be *trustworthy and transparent* – BRPs will only act if they trust that responding to price will ultimately benefit them (or at least minimize their imbalance costs). In practice, most systems implementing decentralized balancing use a **single marginal imbalance price** (one price for short or long positions, set by the cost of the marginal activated resource or value of avoided activation) to strongly incentivize any help to the system [39]. Dual pricing or average pricing tends to dull the incentive to respond. Energinet is already moving toward a "full cost" imbalance settlement (single-price) by 2025-2026, aligning with this principle.

- **Low barriers for entry and response:** To truly unlock broad flexibility, it must be easy for both **explicit** participants and **implicit** responders to participate. For explicit balancing services, Energinet and regulators should simplify qualification, allow aggregation, and reduce transaction costs (without compromising reliability of delivery) [40]. For implicit participation, virtually **any device or consumer** that can react should have a pathway to do so. That means ensuring **price signals reach all the way to end-users**, even those behind a single connection or meter. One important enabler here is allowing "**asset differentiation behind the meter**." For example, a factory or household might have flexible load (say an EV charger or a heat pump) and inflexible load (critical processes or appliances). If they are on one meter under one BRP, the flexible portion might never get the price signal. By allowing *sub-metering or contractual splitting*, the flexible device could be handled by an independent aggregator or on a dynamic tariff, while the rest of the load stays on a fixed plan [41]. Energinet's upcoming **independent aggregator role** (approved in 2024 and to be implemented by 2026) is exactly intended to address this: it will let new actors aggregate behind-the-meter resources and sell their flexibility without needing the primary supplier's involvement [42]. This is crucial so that "every flexible asset…finds an accessible alternative to participate in the system" even if it cannot be in traditional markets [43] [41].

- **Advanced forecasting and control tools:** The decentralized approach shifts some responsibility to forecasting and coordination. The TSO must develop **robust predictive models** for system imbalance and the likely response of the market to prices [33]. Unlike in a fully centralized system (where the TSO might simply activate a set MW and know the result), in a decentralized model the TSO has to guess how much the *market* will self-correct at a given imbalance price. This calls for sophisticated tools – for example, AI-driven models that learn the price responsiveness of different types of demand. Elia even suggests a paradigm shift in control center computing toward **"digital twin" models** that can simulate the near-real-time behavior of the system under different price signals [44]. Such tools, coupled with high-quality data (smart meter readings, EV charging patterns, weather forecasts, etc.), help the TSO determine the optimal volume to activate explicitly while trusting the rest to implicit action [45] [46]. Energinet and other TSOs will need to invest in these analytical capabilities. Indeed, managing high wind and solar shares will *"depend on digitalisation, use of AI and data-driven solutions that enhance demand-side flexibility"* [47].

Operationally, running a decentralized balancing model requires a **mindset shift**. The grid operator's role evolves from direct controller to market facilitator and coordinator. There is a greater onus on real-time communication, data transparency, and collaboration with market players (generators, suppliers, aggregators, consumers). If implemented well, the decentralized model can be very efficient; if implemented poorly (e.g. price signals are noisy or rules are unclear), it could lead to instability like intra-interval power swings [35]. Thus, the success of this model hinges on **careful market design** and **modernized tools**, as outlined above.

Economic Trade-offs and Operational Implications

Having characterized the two models, we now delve into their **economic and operational trade-offs**, especially under conditions of high renewables and widespread electrification. We consider balancing costs and social welfare, the need for reserve capacity, system precision and stability, and the extent of flexibility unlocked. Throughout, the focus is on how each model supports (or hinders) Energinet's strategic objectives: cost efficiency, renewable integration, and grid resilience.

Balancing Costs and Social Welfare

A central question is which model minimizes the **cost of balancing the grid** and maximizes overall economic welfare. Balancing costs refer to the expenses the TSO incurs in real-time to correct imbalances (e.g. payments to activated reserves), which ultimately flow through to consumers. Social welfare, in this context, relates to using the most cost-efficient (and ideally least polluting) resources to meet electricity needs, avoiding unnecessary curtailment or expensive activations.

In **centralized models**, once the TSO assumes control after gate closure, any deviation between generation and load is resolved by deploying reserve power. Picture a sudden shortfall (maybe a forecast error on wind output): the TSO must activate *volume V_{CB}* of balancing reserves to cover it [48] [49]. If the reserves are procured on a pay-as-cleared basis (as per European target models), the cost for that imbalance is essentially *V_{CB}* × *(Marginal Reserve Price)* [50]. The marginal price is set by the most expensive resource the TSO had to activate. In a scenario with tight supply, this might be a costly gas peaker or even load shedding bid – meaning the imbalance price can be very high. Crucially, in a centralized setup, **BRPs are assumed inelastic** during this period [51]. They are not permitted to react to this price spike by balancing themselves, so the entire volume *V_{CB}* must be handled through the TSO's actions. The imbalance price in many centralized systems is also often **neutralized or averaged** (aimed at recovering costs without incentivizing extra moves) [52] [53], which further ensures BRPs don't try to arbitrage in real-time – but at the cost of providing no help either. The result is that the **full burden of balancing falls on a limited set of resources**, and if those happen to be costly, the system pays that cost. This can be exacerbated when renewables spike or crash unexpectedly: the TSO might have to activate a large volume of reserves (raising V_{CB}) and potentially call on very expensive last-resort units (raising the marginal price). All of that cost is then smeared across the market (often via imbalance charges or uplifts).

Decentralized models, by contrast, aim to **share the balancing burden with the market**. If an imbalance event occurs, BRPs and flexible assets are *still free to respond up to real-time*, meaning some portion of the correction will happen via voluntary adjustments. Suppose the total needed correction is the same as before. Under a decentralized approach, the TSO might only need to activate a smaller volume *V_{DB}* of reserves, because the rest of the gap is closed by, say, loads dropping off or extra generation being voluntarily pushed out in response to the price [54] [55]. Moreover, the resources that respond implicitly are **the ones with the lowest opportunity cost** – basically, whoever can afford to turn down consumption or ramp up production at the current imbalance price will do so, up until the point that the residual imbalance is small. This means the *marginal resource used to balance the system in real-time is likely cheaper* in a decentralized setting, since the really expensive options would only be called if the entire market can't solve the issue [56]. Formally, Elia's study finds **both the activated volume and the marginal price (V_{DB} and MP_{DB}) are lower than in the centralized case (V_{CB} and MP_{CB})** [57]. Consequently, the **total balancing cost drops significantly**, by the area representing the avoided expensive activations [57] [58]. Decentralized balancing *"allows reducing the overall balancing costs"* because fewer MWh are procured from reserves and the clearing price of those that are procured is lower [57]. In addition, the implicit self-balancing dispatches resources that are often **cheaper and greener** than the ones the TSO might have had to call upon [56]. For example, instead of firing up an oil-fired unit at €1000/MWh, a cluster of electric vehicles may simply stop charging (effectively providing the same energy reduction at a far lower "cost" – perhaps the owners were willing to do so at €200/MWh equivalent). The social welfare gain is the difference between those costs: using flexible demand or fast distributed generation avoids using a more expensive plant, saving money and likely emissions [56]. In brief, **economic theory strongly favors decentralized models in a high-flexibility system**: they lead to a more economically optimal dispatch in real-time, engaging *all* resources in merit order of their willingness to pay or be paid. The Elia analysis illustrates this with supply/demand curves: BRPs provide a sloped "price elasticity" of demand for balancing, instead of a vertical inelastic demand, resulting in a lower clearing price and a welfare gain (the light blue area in their Fig.2) [54] [56].

Real-world evidence backs up these theoretical gains. Belgium's experience (detailed in the next section) showed that enabling widespread BRP response **significantly lowered reserve deployment and costs**. One large industrial consumer's price-driven load reductions in 2022 cut the 95th percentile of balancing reserve activation needs by about **50 MW**, and reduced the price peaks of activated reserves by **€60/MWh**; this saved considerable balancing cost because without that implicit demand response, the system operator would have had to procure more volume at higher prices [59] [60]. By consuming less when power was scarce and expensive, that consumer not only saved on its own bill but directly *lowered the market-wide balancing price* (the marginal activated resource was no longer a super-expensive one) – *"leading to an overall reduction of the mFRR costs"* for the system [61]. This is a concrete example of the cost savings decentralized balancing can unlock.

From Energinet's perspective, containing balancing costs is increasingly important as renewable variability grows. Denmark's participation in Nordic balancing markets and upcoming EU platforms will expose the country to imbalance price spikes if large swings occur. A decentralized approach can mitigate extreme prices by softening the demand for balancing energy – effectively **"shaving" the peaks of imbalance with demand-side response**. It is worth noting that cheaper balancing not only saves money, but also tends to reinforce renewable integration: when the system can inexpensively handle fluctuations, TSOs don't need to curtail renewables as much or keep as large a reserve margin. This synergy between economic efficiency and green integration is a key argument in favor of a decentralized model **under the right conditions** [62] [63]. Elia's study concludes that, if designed well, decentralized balancing *"captures more social welfare and reduces overall balancing costs"*, making it better suited for the ongoing energy transition [64].

Capacity Needs and Reserve Procurement

Another trade-off lies in **how each model manages capacity for balancing** – i.e. the amount of reserve power that must be pre-contracted or kept online to secure the system. In a centralized model, because only certain resources can provide balancing, the TSO often must maintain a sizable "book" of reserves (aFRR, mFRR, etc.) to cover potential imbalances. If the universe of eligible resources is limited, scaling up the reserve pool to meet growing needs (due to more renewables) can be challenging. Many TSOs resort to **capacity reservation mechanisms**: paying generators (or large loads) to stand by with headroom or footroom for balancing. These capacity contracts ensure resource availability but come at a cost to society (capacity payments often running into tens of millions of Euros annually). Moreover, such reservations can **distort energy markets** – for example, a power plant that is paid to hold capacity for balancing might run at a loss in the energy market or might be kept running at minimum load just to be ready for downward regulation, which is economically and environmentally suboptimal [18]. If an increasing share of flexibility is locked into reserve commitments, it means that capacity is not fully utilized in the energy market, potentially raising energy prices or causing inefficiencies. In the worst case, if new flexible capacity is insufficient, a centralized paradigm might pressure governments/TSOs to **subsidize new build** of peaking plants or storage (essentially to ensure enough reserves). Elia warns that without tapping the emerging "implicit" flexibility of electrified demand, it's unclear *"how we will manage to attract the required additional flexibility volumes"* for balancing explicitly – the implication being that one might have to pay for new centralized assets to fill the gap [19] [65]. This route (building extra peakers or large batteries purely for balancing) not only is costly, but could be seen as a step backward if those assets run on fossil fuels or sit idle most of the time.

Decentralized balancing offers a way to **minimize reserve capacity procurement** by unleashing latent flexibility in the system. If EVs, heat pumps, industrial processes, and other loads can adjust consumption on the fly, the *effective balancing capacity* of the system increases without the TSO signing contracts for each megawatt. In theory, a broad base of demand response can serve as an **implicit reserve** that automatically helps correct deviations. This reduces the need for the TSO to procure additional balancing capacity as a safety net [20] [18]. For instance, instead of contracting a 100 MW gas turbine to handle possible evening ramps, perhaps 200,000 EV chargers can each drop 0.5 kW for a short while if needed, providing the same 100 MW response distributed across many endpoints – and they'll do it motivated by price rather than a standing payment. Naturally, the TSO still needs some **dedicated reserves** for extremely fast or precise control (like inertia or frequency containment within seconds). But for the bulk of balancing (on the order of tens of minutes), decentralized reaction can carry a lot of the weight. By **"unlocking the flexibility which will naturally emerge with electrification"** (rather than ignoring it), we avoid a scenario where we scramble to find new explicit reserves for every additional MW of renewable variability [66] [67]. If Denmark can activate the flexibility of future electric vehicles, heating, and industry, it may not need to pay for as many backup gas engines or imports for balancing.

In fact, relying too heavily on capacity procurement has several **drawbacks**. Besides cost, it can impede earlier markets. For example, if a chunk of capacity is reserved for balancing, it cannot participate in the day-ahead or intraday markets, potentially driving up energy prices or resulting in inefficient dispatch (some plants might even run at a loss just to provide downward reserve) [18]. Energinet's own strategy recognizes this: the goal is to avoid excessive balancing capacity procurement and instead **utilize market-based flex** wherever possible. The Elia study goes so far as to suggest that procuring additional balancing capacity should be a *"last resort"*, only after confirming that a decentralized model cannot unlock enough flexibility on its own [68]. The message for Energinet is that **embracing decentralized balancing can defer or reduce investments in new reserve capacity**. This is economically prudent and aligns with Denmark's preference for market solutions over subsidies. It's also timely: Energinet expects to introduce an independent aggregator role by 2026 specifically "with the purpose of releasing flexibility potential among distributed energy resources" [42]. By enabling more resources to participate, Energinet can meet rising flexibility needs without simply buying more from the same limited pool. In summary, decentralized balancing helps **"keep the lights on"** with the assets we already have (just operated smarter), rather than having to build or contract significant new balancing assets. This not only reduces direct costs but avoids distorting energy markets and promotes a more **efficient overall system utilization**.

System Control, Precision, and Stability

One of the strongest arguments for centralized control has been the **precision and certainty** it provides in balancing. The TSO can monitor system frequency and imbalance in real time and take direct action (activating reserves) to correct any deviation, thus tightly managing the system state. With automatic reserves like aFRR (which adjust output every few seconds) and manual reserves dispatched as needed, a centralized model in theory can maintain system frequency very close to 50 Hz at all times with minimal error [8]. There's a clear accountability: the TSO gives an order, a known resource responds, and the TSO measures the result. Any shortfall can be addressed by further orders. **Compliance is enforceable** (providers are penalized if they fail to deliver) [69], which adds confidence that the intended balancing action will occur. This top-down control model has kept power systems stable for decades, including in Denmark's highly wind-integrated grid – historically, conventional plants or interconnectors were adjusted to counter wind fluctuations, with the TSO ensuring the balance.

However, the emerging reality is that **precision can be achieved in new ways**, and ironically, clinging to a purely centralized approach may lead to *less* precise outcomes due to unforeseen feedbacks. As noted, even under centralized regimes, some BRPs will adjust their position if economically motivated [23]. If the TSO is not accounting for these moves, its own actions might overshoot or conflict, resulting in *oscillations*. For example, Germany saw instances of system oscillations when certain BRPs reacted to perceived imbalance conditions that the TSO was simultaneously trying to correct – essentially fighting each other. To illustrate, Elia provided an example of an **oscillating system**: if one minute data shows a surplus and prices go low, loads might increase consumption; by the next minute the surplus is gone and a deficit appears, then loads drop again – causing a swing around the 15-min average [35] [36]. If unmanaged, such swings could pose operational issues (e.g. unnecessary wear on regulating units, or even threatening frequency bounds if severe). The good news is that these issues can be mitigated with better **signal design and forecasting**. A decentralized model does require careful tuning of the "signals" (e.g. imbalance price formula) to avoid unintended instability. By providing BRPs with a stable price signal over the whole quarter-hour and perhaps filtering out very short-term noise, the system can avoid inducing rapid back-and-forth reactions [35]. Additionally, TSOs can use *forecasting tools* to predict BRP behavior and only activate the *net needed* reserves. The Elia paper emphasizes that knowing the **price sensitivity** of the system is key: if the TSO can predict that "for each €10 increase in imbalance price, X MW of demand will drop," it can factor that in before sending manual activation commands [32] [33]. New AI-based decision tools (digital twins) are being explored to assist operators in this very task [45] [44].

So, while a decentralized system is more complex to operate, it can still achieve **high precision balancing** if those operations are augmented with modern technology. In fact, one could argue it achieves precision in a *more efficient way*: instead of one central authority turning a big dial (which may be coarse-grained), thousands of small adjustments happen across the grid guided by price, summing up to a precise response. The Belgian experience is instructive – after allowing decentralized balancing, Belgium's control performance (Area Control Error, ACE) remained robust. The **average system imbalance (SI)** actually decreased when BRPs were first allowed to help in real time, and despite a huge growth in renewables over the next decade, the **system imbalance did not worsen** [70]. In other words, system precision was maintained even as the balance-keeping task was shared with the market. ACE (which reflects how well Elia keeps frequency in sync with the European grid) stayed stable, indicating no loss of control quality [70]. This should give confidence that with proper design, decentralized models can meet operational standards.

Another aspect of "system stability" is how the grid withstands larger disturbances or extreme conditions – essentially, **resilience**. A decentralized approach can enhance resilience by diversifying the portfolio of resources available for response. Instead of relying on, say, a handful of big generators to ramp up during an emergency, you could have thousands of devices ready to adjust. This distributed response is inherently more **redundant**: if one resource fails to act (or one EV doesn't stop charging), it hardly matters if many others can. This reduces single points of failure in grid balancing. It also potentially allows a faster aggregate response for certain disturbances; for example, if frequency starts to dip, many devices with frequency-sensitive controls could instantly reduce load (this is more in the realm of containment, but it shows how demand-side can support stability too). Energinet already uses concepts like automatic low-frequency demand disconnection for extreme events – a decentralized model is like a milder, market-driven version of that principle, engaging loads *before* an emergency threshold. Moreover, when the system is stressed (e.g. a sudden wind drop or a major power plant trip), having consumers respond to real-time prices can provide an extra cushion *immediately*, potentially faster than waiting for the TSO to manually dispatch reserves.

On the flip side, **operational coordination with decentralization does require new safeguards**. Communication networks and data systems become critical – the TSO needs accurate near-real-time data from possibly millions of points (which is feasible with smart metering infrastructure). There's also the need for coordination between **TSO and DSOs**: large-scale demand response could cause power flows and voltage issues in distribution networks if not anticipated. This implies new operational protocols so that DSO constraints (like a local transformer limit) are not violated by a global price signal that, for instance, suddenly encourages every EV in a neighborhood to charge or stop charging simultaneously. Energinet will have to work closely with distribution companies to manage this. One mitigation is for DSOs to set up local flexibility mechanisms or grid traffic control, but that's outside our main scope; suffice it to say, decentralization broadens the operational theater to the **edge of the grid**, requiring more integrated system management.

In summary, **system precision and stability can be maintained under decentralized balancing**, but it shifts the approach from direct control to **indirect, incentivized control**. The TSO's role evolves to ensuring the incentives (prices, info) are right and using advanced tools to supervise the outcome. The Belgian case shows that frequency quality need not degrade – in fact, allowing BRPs to respond helped keep imbalances in check even as volatility increased [70]. The main caution is to design the scheme to avoid rapid unintended oscillations; stable pricing and forecasting are the remedies for that [35] [36]. Energinet, with its strong track record in operating a high-wind system, is well positioned to incorporate these methods. The control center in Fredericia, pictured in many reports, might soon incorporate AI forecasting dashboards next to the traditional SCADA, highlighting how the operator's toolkit is expanding in the decentralized era.

Unlocking Demand-Side Flexibility and Grid Resilience

A critical difference between the models is how much **demand-side and distributed flexibility** they mobilize. Centralized models, as discussed, tend to leave a lot of this potential on the table – they focus on conventional sources of flexibility. Decentralized models actively seek to **unlock flexibility wherever it exists**, especially on the demand side (since consumption can often be shifted in time more easily than non-renewable generation can be conjured). The ability to harness **demand-side flexibility** at scale is like adding a huge new resource for the grid. It means that when the wind is too strong (excess generation), we can flexibly increase consumption – for example, turning up heat pumps or scheduling EV charging early. And when clouds cover solar panels unexpectedly, we can temporarily dial down consumption to ride through the shortfall. This flexibility is **renewable-friendly**: it helps smooth out the inherent variability of green energy sources, making it feasible to integrate more of them without curtailment or blackouts.

Belgium's experience over the last decade provides a vivid demonstration of tapping demand flexibility to support renewables. After implementing the decentralized model, Belgium saw that despite a **huge increase in installed solar and wind capacity**, their average system imbalance did **not** deteriorate [70]. In fact, system imbalance initially *dropped* when BRPs were first allowed to freely adjust, indicating many took action to correct their positions and assist the system [70]. Essentially, the latent flexibility in the demand side was activated once the regulatory framework allowed it. This kept the grid manageable even as intermittent generation grew. For Energinet, which will oversee a major expansion of offshore wind and solar in the coming decade, having a similarly responsive demand side will be crucial. Denmark anticipates large new electricity consumers too (like Power-to-X hydrogen production, data centers, electric heating) – these can be **flexibility assets** if given the right incentives, helping match swings in wind power. A decentralized balancing strategy directly targets this goal: *"harness more flexibility, including [that] which cannot be offered explicitly to the TSO"* [71] [72] .

Grid **resilience** is also enhanced when flexibility is widespread. Resilience refers to the ability to handle extreme conditions or disturbances (like a sudden loss of generation, a system separation, or an unforeseen spike in demand) without collapsing. In a decentralized paradigm, the sheer number of responsive units provides a form of **safety net**. For instance, if a large power plant trips, in a centralized world the TSO might lean on a few other power plants to ramp up – if one of them fails, there's little backup left. In a decentralized world, that same event could trigger thousands of devices to collectively drop load or increase output; even if some subset doesn't respond, many others will, making the overall response more robust. Distributed energy resources can act like shock absorbers for the grid. Additionally, by reducing overall strain (through continuous balancing in normal conditions), the system enters disturbances in a better state (not already carrying large stress). One might also consider resilience to **forecast errors**: if tomorrow's wind is lower than expected, in a decentralized setup many flexible demands would have held back usage (because real-time prices rose), preserving energy to make it through, whereas in a centralized setup we might be caught short and have to resort to emergency measures or load shedding.

That said, harnessing demand-side flexibility requires **enabling technology and engagement**. Denmark has near-100% smart meter coverage, which is an excellent foundation. The next step is ensuring those smart meters (and connected smart appliances) are utilized for sending price signals and automating responses. Many of these flexible actions need to be automated (no one is going to manually turn off their water heater because the frequency dropped – but an IoT device can). Thus, part of Energinet's strategy must involve working with retailers, aggregators, and technology providers to deploy smart charging, smart heating controls, industrial demand response platforms, etc. The **data infrastructure** also plays a role: for example, Energinet's data hub could disseminate real-time imbalance prices and perhaps even dispatch signals if needed. A fully realized decentralized balancing system effectively integrates the power grid with the digital realm – every major flexible asset is like a node that can respond to digital commands (prices or signals). This underscores why digitalization and AI were mentioned earlier as key enablers [47] .

In terms of organizational resilience, decentralized balancing spreads responsibility. Instead of the TSO being the sole "balancer", every BRP and many end-users become active participants in maintaining stability. This collective responsibility can lead to innovation (new business models around flexibility) and a more resilient ecosystem. For example, if one aggregator's portfolio fails to respond one day, another independent aggregator might over-respond because of the high price, compensating in aggregate. The system doesn't hinge on any single actor. Furthermore, by encouraging consumers to adapt to grid needs, we foster a culture of **flexibility awareness**, which can extend to energy efficiency and other positive behaviors.

To be clear, decentralized balancing is **not a panacea** – it must be supported by strong **grid infrastructure** (transmission lines, etc.) so that flex in one area can actually help another area. Denmark's interconnectors and upcoming energy islands will continue to play a vital role in sharing resources across regions. But given that renewables will sometimes exceed local demand (Denmark aims to be a net exporter of green power [73] [74]), having a nimble demand side at home ensures you can absorb or adjust to those moments without crises.

In conclusion, unlocking demand-side flexibility via a decentralized balancing model aligns perfectly with Energinet's goals of **integrating renewables** and **boosting resilience**. It turns a challenge (variable demand and supply) into an advantage (a self-balancing system). The Belgian case provides tangible proof: despite renewables growth, their system imbalance stayed in check and balancing costs dropped, thanks in large part to demand response [70] [61]. Denmark, with its even higher wind penetration and ambitious electrification plans, stands to gain even more by activating the flexibility of its consumers. The next section will delve deeper into the Belgian experience for lessons learned, before we move on to recommendations for Energinet's path forward.

The Belgian Experience: Decentralized Balancing in Action

Belgium offers a valuable real-world example of transitioning from a more centralized to a more decentralized balancing approach. About a decade ago, Elia (Belgium's TSO) embarked on this journey, motivated by the same pressures facing Energinet: rising renewable output, more distributed resources, and the need to contain costs.

Timeline of Changes: Belgium's shift began in **2013**, when Elia first **allowed BRPs to deviate from perfect balance in real-time to help the system** [75]. Prior to that, BRPs were essentially expected to be balanced and any deviation was penalized; the 2013 reform meant that if a BRP went out of balance in a direction that assisted the grid (e.g. injecting extra power when there was a shortage), it could earn a benefit via the imbalance price. This was a radical departure from strict centralized doctrine and effectively opened the door for **implicit balancing** by market parties. Over the ensuing years, Elia implemented further supporting measures. They moved to a **single imbalance price** (previously, like many countries, they had dual pricing which limited incentives). The single marginal pricing means the imbalance price directly reflects the cost of the last activated resource, giving BRPs a clear signal of the value of balancing energy [39]. In **2019**, Elia started publishing the imbalance price **every 5 minutes and even on a 1-minute basis** during operations [76]. This high transparency allowed BRPs to see near real-time what the system imbalance and price was, so they could adjust quicker. Most recently (by 2025), Elia has been trialing the publication of an **imbalance price forecast** (e.g. predicting the imbalance price a few minutes ahead) [77]. The goal of that is to further help BRPs "calibrate their implicit reaction" by knowing not just the current price but where it's likely to head [78]. These steps – rule changes, pricing mechanism, and information provision – created an environment where **decentralized balancing could flourish**. Essentially, Elia progressively gave the market participants both the **permission** and the **tools** to contribute to balancing: permission in the form of regulatory freedom and proper incentives, and tools in the form of timely information and price signals.

Observed Benefits: The Belgian experience so far has been very positive and offers several **lessons**:

- **Reduced System Imbalance Despite Renewables:** One key indicator Elia tracked was the **System Imbalance (SI)** – the aggregate imbalance of all BRPs. When BRPs were first allowed to help in real-time (post-2013), the average SI magnitude significantly **decreased** [70]. BRPs took advantage of the opportunity to balance opportunistically, and as a result, the net imbalance that the TSO had to manage shrank. Over the following decade, Belgium's installed wind and solar capacity skyrocketed (solar alone went from ~1 GW to ~7.5 GW in that period, and wind saw similar growth). Normally, one would expect system imbalances to worsen with that much intermittent generation. Yet, Belgium's average SI remained **stable** even as renewables grew to high levels [79] [80]. This suggests that the increased volatility was largely absorbed by improved balancing actions from BRPs and other mechanisms, preventing a degradation in control quality. In parallel, the **Area Control Error (ACE)**, which measures the control area's real-time balance (post-activations), also stayed within good bounds [81]. In short, allowing decentralized balancing did not compromise reliability; on the contrary, it appears to have *offset the potential worsening* that more renewables could have caused. For Energinet, which anticipates even greater renewable penetration, this is an encouraging sign that **distributed flex can keep the system stable** if effectively engaged.

- **Lower Reserve Activation Volumes and Costs:** Belgium also analyzed how implicit response from the market affected the use of their manual Frequency Restoration Reserves (mFRR). A case study examined a particular **large industrial demand facility** that has flexibility but does not participate explicitly in the reserve market [82] . This consumer (likely a chemical plant or steel factory, for example) would reduce its consumption whenever the imbalance price rose high – an implicit, automated response to avoid high costs and help the grid. By comparing 2022 data, Elia found that **without** this facility's implicit reaction, the **95th percentile** of mFRR activation volumes would have been **50 MW higher**, and the **95th percentile** of mFRR prices about **€60/ MWh higher** [83] [60] . In other words, in the most stressful periods, the TSO would have had to call on an extra 50 MW of reserves and would have paid up to €60 more per MWh for some of those activations if that demand response had not occurred. With the demand response present, those extreme activations were avoided: the consumer stopped consuming at critical moments (when the system was deficit and imbalance price spiked), thereby **reducing the system imbalance and the required reserve deployment** [60] . This had a cascading effect: less volume activated means the marginal unit activated was cheaper (maybe the TSO didn't have to start the costliest plant at all), so the price of balancing energy also came down. The net outcome was a significant **reduction in balancing costs** for that period [61] . Elia explicitly notes that this implicit demand facility *"reduced the volume of mFRR to be activated"* and thus the price paid, *"leading to an overall reduction of the mFRR costs."* [61] . For Energinet's context, consider the analogy: Denmark has some large flexible industries (like steel, fertilizer, data centers with backup generation, etc.) and will have more (like PtX hydrogen plants). If those can be incentivized to flex with grid needs, the need for expensive activation (such as importing costly power at peak times or firing up oil-fired units) could be markedly reduced. Belgium's measured 50 MW/€60 impact from just one facility hints at the scale of savings multiple such participants could provide in a larger system like Denmark's.

- **Avoiding Overactivation and Oscillations:** Belgium's journey also highlighted pitfalls to avoid. Initially, when fewer BRPs were actively adjusting and Elia was in "learning mode," there may have been instances of the TSO accidentally counteracting what BRPs were doing (causing minor oscillations). Through experience, Elia learned to factor in expected BRP behavior. They increased transparency (publishing data more frequently) but also realized the **importance of stable signals**. The introduction of an **imbalance price forecast** was partly to dampen oscillatory behavior by guiding BRPs more predictably [35] [38] . Another move was refining the imbalance price formula to avoid sharp swings (for example, avoiding sudden spikes for very short-lived imbalances). These measures are instructive: Energinet should likewise be prepared to refine the price mechanism over time – e.g., implementing an averaging period, or an inertia in the price calculation – to ensure it sends a **consistent message to the market** and avoids prompting everyone to jump one way then the other in rapid succession. The overall Belgian lesson is not that oscillations will doom the system, but that they **must be managed** through careful market design. As a result, Belgium today has a relatively smooth interplay between BRP self-balancing and TSO actions, and they report that *ignoring* implicit behavior would actually be worse (leading to inefficiencies and potential over-corrections) [84] [25] .

- **Policy and Culture:** Belgium's example underscores that implementing decentralized balancing is as much about **policy and culture change** as technology. Elia had to work with regulators to change imbalance settlement rules and with market participants to encourage them to take on this new role. Over 10 years, a level of trust and new norms developed: BRPs came to expect that they *should* react to certain system conditions, and the TSO came to rely on the aggregate effect of those reactions. In Denmark, a similar cultural shift can be nurtured. Notably, the Danish Utility Regulator's approval of the independent aggregator role in 2024 is a policy milestone that sets the stage [85] . It signals to the industry that unlocking distributed flexibility is a priority.

Energinet's own communications (e.g. ancillary services outlooks) frequently mention the need for more flexibility and new market participants. By learning from Belgium, Energinet can accelerate the transition – perhaps doing in a few years what took a decade elsewhere, given that the concept is now proven.

In summary, Belgium's experience provides **empirical validation** that a decentralized balancing model can work and deliver the intended benefits: **lower balancing costs, effective renewable integration, and maintained reliability**. Their journey also offers a **roadmap** of practical steps (regulatory changes, IT tools, phased implementation) and warns of challenges (signal design, forecasting complexities) that can be proactively addressed. For Energinet, which has comparable ambitions, Belgium is a natural point of reference. Both are small-to-medium sized European systems tightly interconnected with neighbors, both have high renewable shares, and both aim to be frontrunners in market design innovation. The Belgian case thus strengthens the case for Energinet to pursue decentralized balancing and provides confidence that the **strategic goals** – cost reduction, renewables integration, resilience – are achievable through this path.

Recommendations for Energinet: Adopting Decentralized Balancing

To realize the benefits of decentralized balancing, Energinet will need a coordinated strategy spanning market design, organizational adjustments, regulatory support, and technical upgrades. Below we present **actionable recommendations** in these areas, tailored to Energinet's context as the Danish TSO. The goal is to outline how Energinet can adopt or adapt decentralized balancing to reduce system costs, better integrate renewables, and enhance grid resilience, all while maintaining operational security. These recommendations build on insights from the Elia study and Belgian experience, but are customized for Denmark's situation.

1. Market Design & Regulatory Measures

- **Implement Single Marginal Imbalance Pricing:** If not already in place, move to a single-price imbalance settlement that reflects the full marginal cost of balancing energy. This ensures that any BRP helping the system (by deviating in the beneficial direction) is rewarded at the same price that a balancing service provider would be [39]. Energinet is already planning a "full cost" imbalance fee by 2026, which aligns with this principle. A single, market-based imbalance price gives a strong incentive for all parties to remain flexible up to real-time.

- **Permit BRP Adjustments Closer to Real-Time:** Gradually relax any rules that force BRPs to lock in schedules long before delivery. For example, if intraday gate closure is currently one hour before delivery (a legacy of Nordic practice), consider shortening this or allowing intraday trading/updating closer to real time. Even without formal market trading, make it explicitly allowed (and not penalized) for BRPs to intentionally deviate after gate closure if responding to system needs. This might involve updating balancing market regulations or BRP agreements to clarify that helping balance the system is allowed and encouraged (as Belgium did in 2013) [75]. Essentially, **remove the "red line"** that prevents decentralised action after a certain point, or move it as close to real-time as practical.

- **Enhance Transparency with Real-Time System Data:** Provide BRPs and aggregators with rich, real-time information to facilitate their decision-making. This includes publishing the current system imbalance and the current imbalance price in near real-time (e.g. every 5 minutes or even more frequently if possible) [76]. Energinet could use its online portals or data hubs to share a continuously updated imbalance price, along with perhaps the ACE or total system imbalance MW. Additionally, following Elia's lead, Energinet should develop an **Imbalance Price Forecast** tool and share its output with the market [77]. Even a 5-15 minute ahead forecast of imbalance price or system balance can greatly help BRPs "calibrate" their responses and avoid overreactions [38]. This level of transparency reduces information asymmetry and allows even smaller players (who may not have sophisticated trading desks) to participate in balancing with confidence. It's important to work with the Danish Utility Regulator to ensure such info can be disseminated (the regulator will likely be supportive, as transparency is generally a market good, but any confidentiality issues of data need to be handled).

- **Foster Independent Aggregators and New Entrants:** Ensure the successful implementation of the **independent aggregator role** by 2026 and possibly accelerate pilot programs before then [42] [86]. This involves close collaboration with electricity retailers and BRPs because independent aggregators will operate by abstracting some flexibility from the BRP's portfolio. Energinet should set up clear rules for how independent aggregators' activations will be accounted for in BRP imbalances (the "financial adjustments" mechanism so that BRPs aren't unfairly penalized or rewarded) [87] [86]. The regulator's 2024 approval is a green light; now Energinet can facilitate contracts, data exchange, and possibly standardized products that aggregators can provide. The overarching aim is to **unlock distributed flexibility at scale** – from EV charging companies, to thermostatically controlled loads, to commercial building management systems – by giving aggregators access to markets and letting them earn revenue from balancing services without cumbersome prerequisites. In parallel, review prequalification criteria for ancillary services to allow aggregated units, smaller units, and faster ramping units to participate more easily. Lower the minimum bid sizes and allow pooling across locations (this is already happening in EU guidelines, so Energinet should implement accordingly). All these steps bring more players into play, increasing competition and innovation in balancing.

- **Review and Refine Imbalance Price Formulation:** As decentralized balancing ramps up, regularly assess the imbalance price formula for effectiveness and stability. The price should be high enough in scarcity to motivate response, but not so volatile as to cause control issues. Consider introducing mechanisms like **price stabilization** over short intervals (avoiding drastic changes within a single ISP except when truly necessary) [35], or using an averaging period for the inputs. Also consider whether an adder is needed to incentivize faster response (some systems use an "alpha" component that increases the imbalance price if the system imbalance is large, to stimulate response – Belgium had such a component historically). The guiding principle is to make the imbalance price **"more representative of the true value of energy over [the 15-minute period]"** [34] and to avoid sending misleading signals. Energinet could establish a stakeholder task force (including BRPs, aggregators, academia) to monitor the performance of the imbalance pricing and suggest tweaks. As more data comes in (post-2025 when many EU balancing market changes and the new roles are in place), use empirical evidence to adjust the design.

- **Align with European Platforms but Preserve Incentives:** Denmark is integrating with European balancing platforms (PICASSO for aFRR, MARI for mFRR). While doing so (and following EU electricity balancing guidelines), Energinet should ensure that the move to common platforms doesn't reduce the domestic imbalance price incentive. For instance, when connecting to MARI, Denmark will get a common merit order for mFRR. The imbalance price will likely be set by the marginal activation across the region. This is fine, but Energinet should *not* introduce any dilution (like keeping dual pricing or average pricing) that some countries historically had – rather, go with the flow of the EU target model, which is also single marginal pricing and encourages self-balancing. If anything, Energinet can be a champion at ENTSO-E for designing balancing settlement in a way that **encourages decentralised contributions** (the Elia paper's perspective can be shared internationally). On a regulatory note, coordinate with Nordic neighbors: historically, the Nordics had a "one-hour rule" and other practices; but now all are moving to 15-min ISP and similar models. Ensure that imbalance settlement harmonization in the Nordic region adopts the best practices from Belgium/UK/etc. to encourage flexibility.

- **Dynamic Reserve Dimensioning:** As a corollary to trust in decentralized flex, Energinet can adopt **dynamic reserve sizing** (perhaps already planned in Nordic). This means the amount of reserve procured (especially mFRR) each day/hour can be adjusted based on expected conditions (wind forecast, etc.) [88] . If you expect a lot of implicit help (say it's nighttime with many EVs able to modulate, or summer when industrial demand can drop), you might safely procure a bit less reserve capacity for that period, saving costs. Nordic dynamic dimensioning is coming (as noted in Energinet's outlook), so tie this in with an understanding of how much *implicit* flex is out there. Over time, as confidence in decentralized balancing grows, consider **reducing the procured volume of balancing capacity** (especially expensive emergency reserves) or at least not increasing it, because the gap is filled by the market. This should be done carefully and transparently, demonstrating that reliability criteria are still met (e.g. through probabilistic analysis that the combined explicit + implicit resources cover N-1 contingencies, etc.).

2. Organizational & Operational Adaptations

- **Evolve Control Center Operations:** Energinet's control room should evolve from a pure dispatch role to a **monitor, predict, and enable role**. Operators will need training on interpreting new tools like imbalance forecasts, and on the concept that *not* every imbalance requires immediate manual intervention – sometimes the correct action is to "wait and let the market react," or to make a smaller activation trusting BRPs to do the rest. This is a different mindset from always counteracting the full measured imbalance. Training simulations could be used to build intuition: for example, simulate a scenario with a large wind forecast error and show operators the difference between acting centrally versus letting price signals work, to build confidence in the latter. Also, update any operating procedures or handbooks to integrate decentralized actions (e.g. how to account for BRP response in ACE monitoring, when to declare a state of emergency if the market doesn't respond enough, etc.). In essence, **integrate the market as a virtual extension of the control room**. Operators should still intervene if needed, but they'll have more data and should consider market behavior as part of the system response.

- **Develop Decision-Support Tools (Digital Twins/AI):** Invest in advanced decision-support software for real-time operations. As recommended in the Elia paper, a tool that can predict the **net regulation effect** of a given action is extremely valuable [45] . For instance, if the system is short 100 MW, the tool could help answer: "If we activate 50 MW of mFRR, do we expect the remaining 50 MW to be resolved by BRPs adjusting to the price spike?" This involves forecasting the **price elasticity** of the system imbalance. Machine learning models can be trained on historical data to estimate how sensitive different times of day or conditions are to imbalance prices. Energinet could partner with academic institutions or vendors to develop a "digital twin" of the balancing mechanism – essentially a simulator that, given input like current imbalance, weather, time, etc., forecasts BRP response. This may even leverage AI techniques, as Elia suggested moving from traditional optimization to AI-learned models for this purpose [44] . Having such a tool would let the TSO operator test scenarios: "if I ramp up the imbalance price (by activating a high-priced bid) what happens vs if I don't?" It can also assist in setting the **imbalance price forecast** that you publish. Ensure this tool is integrated with the control room EMS (Energy Management System) so operators see its recommendations in real time. Over time, as confidence in its predictions grows, it could even allow for some automation (e.g. automated biasing of ACE setpoints knowing that the market will handle certain deviations).

- **Strengthen TSO-DSO Coordination:** Decentralized balancing blurs the line between transmission and distribution operations. Many implicit actions will occur on the **distribution grid**, potentially affecting power flows and voltages there. Energinet should work closely with Danish DSOs to establish communication protocols and **visibility** for significant flexibility actions. For example, if an aggregator is going to drop 30 MW of load in a city to respond to a high price, the DSO should ideally know to ensure no local issues (though dropping load usually isn't a problem, adding load could be). One idea is to create a real-time feed or platform where DSOs can see aggregated flex response in their areas, or even constraint signals where needed. In the long run, **DSO-integrated flexibility markets** might operate, but in the immediate term, a pragmatic approach is regular info exchange and perhaps DSO "veto" rights if a certain response would harm local security. Another organizational aspect is incident handling: if a distribution-level issue occurs (like an area outage or islanding), how does that get reflected in the imbalance price or TSO actions? These contingencies should be thought through in emergency procedures.

- **Pilot Projects and Simulations:** Before full-scale implementation, run pilot programs to test decentralized balancing concepts. For instance, Energinet could do a pilot where a set of willing BRPs operate under a pseudo-decentralized regime for certain hours (perhaps on a voluntary basis or sandbox environment) to see how they respond and how it affects the system. Another approach is simulating past periods: take historical data of a stressful week and simulate what would have happened with full BRP response enabled vs. not. This can quantify potential benefits and also identify if any instability might have arisen. Share pilot results with stakeholders and use them to fine-tune the design. Belgium's success grew out of iterative improvements – pilots can accelerate that learning in Denmark by identifying issues early (like if one aggregator's algorithm responds too sharply to 1-min price changes, you catch it in a sandbox rather than live).

- **Stakeholder Engagement and Education:** Energinet should continue to engage market participants – not all BRPs or consumers will automatically know how to take advantage of new flexibility opportunities. Conduct workshops or issue guidelines on "implications of the new balancing model" for BRPs and aggregators. Provide clarity on how imbalance settlement will work, examples of scenarios where they could profit by responding, and what tools/data are available to them. Encourage innovative retailers to offer **dynamic pricing** products or automated demand response services to end customers, since those will be vehicles for implicit flexibility. Internally, ensure all departments (market operations, grid planning, IT) are aligned on this strategy, since it touches many aspects (for example, the market team needs to align energy market timelines with balancing signals, the IT team needs to support new data flows, etc.).

3. Technical Infrastructure & Data

- **Leverage Smart Metering and IoT:** Denmark already has advanced metering infrastructure. Use it to its full potential in balancing. That means near-real-time consumption data collection (15-min or 5-min readings) for profiling and settlement – this data can help in analyzing where flexibility came from and maybe even in forecasting who might respond next time. Also, ensure there's a mechanism for **sending price signals to end devices**. This could be via third-party energy management systems or through an open API that publishes the current imbalance price which smart home systems can read. Energinet could collaborate on developing a standardized "signal for flexibility" – perhaps building on the OpenADR standard or similar – to broadcast grid conditions to devices. A concrete example: if the imbalance price is extremely high, a smart EV charger should be able to automatically pause charging; but for that to happen, the charger needs to know the price. So facilitating a data pipeline (through energy suppliers or directly via some public channel) is key.

- **Data Analytics and Forecasting:** Invest in forecasting tools not only for weather and renewables (which Energinet already does) but specifically for **system imbalance and demand elasticity**. Use machine learning on historical imbalance data to see patterns. For example, maybe during morning hours, BRPs tend to underproduce and then correct at last minute, etc. Understanding typical BRP behaviors can improve scheduling and reserve decisions. Also, gather data on how different types of consumers or generators respond to prices. If possible, partner with academia or the Danish TSO-DSO Data Hub to get anonymized data from smart meters to see how residential consumption correlates with price spikes. The better the forecasting, the less the TSO will err in either over-relying on market (and risking a shortfall) or overactivating reserves. Aim to forecast not just one scenario, but provide **probabilistic forecasts** (with confidence bands) of imbalance, so the TSO can make risk-informed decisions on how much reserve to use versus leave to the market. Modern AI techniques like deep learning could be applied here, given the complexity (Elia's mention of AI digital twins points to this direction).

- **IT Upgrades for Communication:** Ensure that the IT systems that publish market data (imbalance prices, etc.) are robust, cyber-secure, and have low latency. If BRPs and devices are relying on these signals, any downtime or delay could cause either loss of efficiency or even issues (imagine if a price signal is frozen and devices act on stale info). So, high availability of these data feeds is critical. Additionally, provide **APIs** for market participants to pull data and maybe even to submit information (e.g., an aggregator might inform the TSO of its expected response curve ahead of time – optional, but if available it could improve forecasts).

- **Cybersecurity and Reliability:** With more decentralized control comes more entry points that could be vulnerable to cyber attacks or failures. Energinet should work with national cybersecurity authorities to safeguard the signals and data exchanges in the balancing system. For example, ensure that price signals can't be spoofed or blocked easily, that only authenticated parties can send control signals to devices, etc. Build redundancies – if the central IT fails, perhaps default to a backup rule (like revert to a conservative balancing approach until systems are restored). Also consider the risk of *misaligned incentives or gaming*: if someone tried to manipulate the imbalance (e.g., intentionally creating an imbalance then profiting from the price move), how to detect and handle that? Monitoring systems for unusual behavior (like a generator deviating to spike price then coming back) should be in place – though this is more market monitoring than IT, it's part of the integrity of the system.

- **Grid Hardware and Automation:** On the electrical side, ensure the physical grid can handle more dynamic flows. While not directly part of balancing market design, it's related: power electronics (STATCOMs, synchronous condensers) might be needed for voltage control as flows become more unpredictable with demand response (though Denmark's grid is strong and interlinked). Consider more automation in distribution (like automated OLTC transformers, etc.) to cope with rapid load changes if they occur. Essentially, make sure the hardware isn't the bottleneck in allowing flexible operations. A resilient grid backbone will complement the market flexibility by ensuring that when loads/generation move, the grid can accommodate it.

- **Digital Twin of the Grid:** In addition to the market digital twin, a **network digital twin** could be helpful. This would simulate how power flows and voltages react when lots of distributed assets change output. It can be used to predict if any distribution network might constrain a response.

For example, if a certain region has a weak feeder, and a price spike would cause all EVs there to stop charging (suddenly dropping load significantly), is there any downside? Mostly dropping load is fine, but if it's adding load, could a line overload? A network simulation tool can check these. It can also be used to test contingency scenarios with decentralized response.

- **Monitoring and Metrics:** Implement thorough monitoring to measure the impact of decentralized balancing once it's in effect. Track metrics like: total BRP imbalance energy versus TSO activated energy, average ACE, number of imbalance price spikes above a threshold (and their duration), volume of reserves procured vs used, etc. These will show progress towards goals (e.g., decreasing trend in activated reserves would indicate cost savings). Publish some of these metrics transparently – it will help build confidence and show stakeholders the improvements. In Belgium, publishing the results (like showing SI trend flattening while renewables rose) [70] was powerful in validating the approach.

4. Strategic Alignment and Long-Term Considerations

- **Phased Implementation:** Plan a phased rollout of decentralized balancing features. For example, 2025 could focus on getting single imbalance pricing and 15-min ISP in place (as per EU requirements), 2026 on integrating independent aggregators and shortening gate closure, 2027 on introducing near real-time info (if not sooner), etc. This phased approach ensures the system and participants adapt gradually, minimizing risk. It also means early phases can deliver "quick wins" (like single pricing tends to immediately encourage more balancing by BRPs, which is good). Make sure to align these phases with European timelines (since Nordic integration and European platform go-lives are happening around the same period).

- **Regulatory Support & Incentives:** Work with the Danish Utility Regulator and policymakers to remove any regulatory barriers. For instance, ensure that BRPs are not subject to punitive fees or penalties that contradict the imbalance price incentive (in some markets, there are additional imbalance fees – if any exist in DK, consider removing them if they discourage balancing actions). Also, advocate for tariff structures that encourage flexibility: e.g., network tariffs that are dynamic could reinforce signals (though network tariffs are usually DSO realm, Energinet can coordinate). Possibly propose **incentive schemes** or demonstrations funded by public grants to get technologies like smart EV charging more rapidly deployed (since they help the grid, there's a societal benefit).

- **Cross-Border Coordination:** Since Denmark is strongly interconnected (with Nordics and Germany), coordinate with neighboring TSOs to manage balancing in a decentralized context. There's a concept of "expanded balancing area" – if Denmark allows lots of BRP response, how does that interact with Nordic balancing as a whole? Likely positively, but ensure rules for unintended exchanges are sorted (e.g. if DK is long and dropping price, power might flow to Germany; that's fine if accounted for, but TSOs should coordinate so that imbalance netting or collaborative actions happen). The European platforms will handle some of this via imbalance netting algorithms. Just remain engaged in ENTSO-E and Nordics to push the idea that **implicit balancing is a feature, not a bug** – historically some TSOs saw it as "parasitic," but as the Elia study notes, denying it is inefficient [84] . The more regions adopt similar models, the smoother it will be at borders.

- **Grid Resilience and Emergency Readiness:** Even with decentralized balancing, Energinet should prepare for rare situations where the market might under-respond (e.g., an extreme event like a system split or a communication failure that prevents price signal dissemination). Maintain procedures for manual load shedding or emergency reserves as a safety net.

Decentralized does not mean eliminating all central action – it means using it more judiciously. In emergency drills, incorporate the scenario "market didn't solve imbalance X" and ensure operators know when to step in decisively (e.g., if frequency deviation beyond a threshold or ACE beyond control for a certain time). These are last-resort actions but part of a resilient posture.

- **Continuous Learning and Adjustment:** Treat the implementation as iterative. As data pours in from 2025 onward, continuously analyze outcomes. If something isn't working as expected (say imbalance price occasionally oscillates too fast), adjust the parameters (maybe increase the averaging window, etc.). Engage with stakeholders regularly through forums to get feedback – BRPs will tell you if they experience difficulties or unclear incentives. Also keep an eye on technology trends: for example, if vehicle-to-grid (V2G) becomes big, that adds another layer of flexibility that can be integrated (EVs feeding back energy during high price times). Energinet's strategy should remain flexible (no pun intended) to incorporate new developments like home batteries, AI energy management, etc., which could all amplify decentralized balancing.

- **Public and Political Communication:** Emphasize how these changes benefit society: a more efficient balancing system means **lower costs for consumers** (since imbalance costs and ancillary services ultimately feed into grid tariffs), **better use of green energy** (less curtailment, more integration), and **high reliability** (as evidenced by maintaining 99.99% supply even at high wind penetration [89]). Communicating success stories (e.g., "on a windy night, instead of paying to shut off turbines, Denmark's flexible demand soaked up the excess – saving X DKK and reducing CO2") can build broad support. It also helps if any questions arise about why certain market changes are happening – stakeholders will see the end goal.

By following these recommendations, Energinet can effectively **adopt a decentralized balancing strategy** suited to Denmark's needs. This will involve a transformation in the electricity balancing paradigm – from one centered on a few control actions, to one orchestrating the **collective flexibility** of many resources. The prize is substantial: **lower operational costs**, as cheaper flex is utilized [57]; **higher renewable utilization**, as the system readily absorbs fluctuations; and a **more resilient grid**, as balancing capability becomes distributed and redundant.

Energinet is already on the path with initiatives like independent aggregators and European market integration [85] [90]. By learning from pioneers like Elia and implementing the above measures, Energinet can ensure that Denmark's power system remains at the cutting edge of the green transition – reliably keeping the lights on in a future dominated by renewable energy, all while doing so at the lowest societal cost.

Conclusion

The energy transition compels grid operators to rethink traditional balancing models. A decade ago, handling intermittency mainly with centralised reserves might have been sufficient; today, with renewables surging and electrification accelerating, it is **imperative to harness the full flexibility of the system** – from big power plants down to smart thermostats. This report analyzed the two archetypes of balancing (centralized vs decentralized) and found that, under current and future conditions, a well-designed **decentralized balancing model offers clear advantages** for a system like Denmark's. It can **unlock broader flexibility**, including demand-side and behind-the-meter resources that centralized approaches miss, thereby **reducing balancing costs and improving social welfare** by using the most efficient resources available [64] [56]. It can also maintain or even improve operational reliability if managed with modern tools and proper market incentives, as evidenced by the Belgian case [70] [61]. The centralized model's tight control, while conceptually comforting, comes at the price of higher costs, excluded participants, and potential inefficiencies in a high-renewable world [91] [18]. The decentralized model's reliance on distributed action introduces new complexities, but these can be overcome with **smart technology (smart meters, AI forecasting, digital twins) and sound market design**.

For Energinet, embracing decentralized balancing is aligned with its strategic goals of an affordable, green, and secure energy system. By acting on the recommendations in this report – from regulatory changes like single pricing and aggregator integration, to operational upgrades with forecasting tools, to technical reinforcements in data infrastructure – Energinet can **lead the way in modern grid balancing**. The lessons from Belgium show that this journey is feasible and fruitful, and Denmark's strong starting position (advanced grid, high digitalization, proactive policies) provides a solid foundation. Ultimately, decentralized balancing is not an end in itself, but a means to achieve a future where **renewables are integrated at lowest cost**, consumers are empowered to participate in the energy market, and the grid is resilient through flexibility. By harnessing flexibility as a resource, Energinet will not only balance the grid more efficiently, it will help balance the entire energy transition on the path to a sustainable future.

Sources: The analysis and recommendations above are supported by Elia's 2025 white paper on flexibility and balancing models [64] [75], which provides a comparative study of centralized vs decentralized balancing in the European context. Empirical data from Belgium's experience (2013–2023) demonstrates the efficiency gains of decentralized approaches [70] [61]. Energinet's own strategic outlooks and the Danish regulator's decisions have been considered, confirming that Denmark is already moving in this direction (e.g. aggregator role approval in 2024) [42]. Additional statistics on Denmark's renewable integration and electrification projections highlight the urgency and scale of the balancing challenge [1] [2]. All these sources collectively reinforce the case that adapting a decentralized balancing model, tailored to Danish conditions, is a prudent and forward-looking strategy for Energinet to ensure a reliable, renewable-rich energy future.

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