

Energy Hubs and the Future Power Grid

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*Keywords: Grid congestion, Energy hubs, Hub-and-spoke power system, Cross-border electricity trade,
Energy transition infrastructure*

Cordence Worldwide

Cordence Young Professionals' Network — The Insight Initiative — 1st Edition

Focus Topic: Energy Transition

A System Under Strain: The Rising Cost of Grid Congestion

Transformation is undeniable, every sector is undergoing changes to adapt and thrive in the coming years. This is also the case for the energy sector. The rapid deployment of wind, solar, and other renewable innovations has shifted the challenges from power generation to integration. Clean energy is plentiful and can be found in many forms and regions, whether it is an offshore wind resource in the North Sea, hydropower in the Mekong River, or solar in the Middle East and North Africa.

However, the real challenge lies in the delivery. The current transmission and distribution networks are designed around fossil-fuel plants and centralized generation, which are no longer sufficient to meet modern energy generation. Electrification and the rapid expansion of renewable energy are accelerating at a record speed, faster than the wires and substations needed to deliver the energy. As the result, the infrastructure is falling behind, struggling to keep pace with the shifting supply and demand patterns.

The impact is evident; the grid is clogged, making it harder for electricity to flow and causing congestion where the demand to inject or withdraw electricity at certain points on the network exceeds the physical or operational capacity of the grid. If left at status quo, the grid congestion could turn the energy transition agenda from an engine of growth to an economic burden.

In many countries, new wind and solar projects are being delayed or curtailed, simply because the grid cannot absorb their output. The financial consequences are severe. In the Netherlands, grid congestion costs rose six-fold from 2020 to EUR388 million in 2022. Germany's costs tripled in the same period, topping EUR4 billion. Most of these costs are passed on to the consumers through higher network charges.

Congestion-related costs reached GBP1.9 billion in 2022 for the UK, largely from paying wind farms to stop generating output and fossil plants to ramp up. Without upgrades, that figure is projected to soar to GBP8 billion by 2030. Across the US, congestion costs jumped 82% in a single year, hitting USD11.6 billion in 2022.

Beyond financial losses, the opportunity cost is even greater. It delays the electrification of sectors like transport and heating, slowing down the uptake of EVs, heat pumps, and green hydrogen, which are all essential technologies to achieve net-zero goals.

The deeper barrier lies in the competing interests. Grid operators focus on reliability but have limited incentives to innovate. Renewable developers push for rapid interconnections, even when the local grids cannot absorb them. Industries and communities seek affordable, stable access to power, yet are often sidelined in the planning process. Regulators and policymakers struggle to align

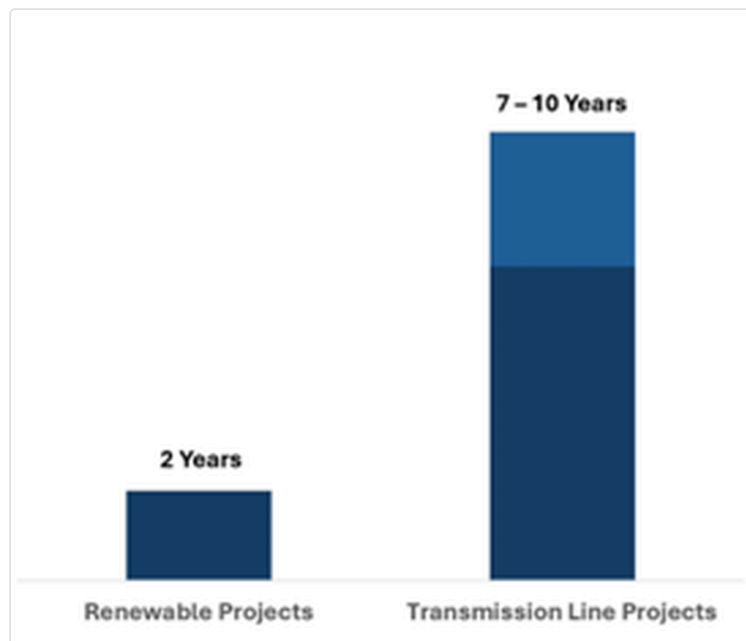
rules across fragmented jurisdictions. Each stakeholder optimizes for their own outcome, yet no single actor can solve it alone.

Conventional Grid Reinforcement: Current Approach and Limitation

Historically, the first and foremost obvious response to grid congestion is to expand and reinforce transmission networks by building more lines and upgrading capacity. Countries worldwide are planning unprecedented investments; the EU plans to invest more than EUR500 billion in projects by 2030 through its Ten-Year Network Development Plan (TYNDP). China is already ahead; as the leader in ultra-high-voltage (UHV) transmission, it has already put thousands of kilometers of long-distance lines into operation.

While it is still important, it is no longer enough. These infrastructure reinforcements face structural barriers:

- **Long Permit Timeline:** transmission projects in the US averaged 7 to 10 years to secure permits. In Europe, many projects face local resistance that often delays the projects by more than a decade
- **Capital Intensity:** building the long transmission lines requires billions in upfront capital which often exceeds the appetite of utilities companies and the regulators



Graph 1. Average lead time of renewable vs transmission line projects. Source: Consultant Analysis, 2025

There is also this issue on the pace mismatch; renewables projects can be deployed in 1 to 2 years, whilst transmission line projects typically take over three times longer. In emerging countries, it can

take even longer. Trying to build the everywhere-to-everywhere concept is inefficient and not financially realistic.

Other solutions revolve around market-based instruments to reallocate demand and supply within existing grid constraints:

- **Locational Marginal Pricing (LMP):** Regional Transmission Organizations in the US charges higher prices in congested zones
- **Congestion Rents and Redispatch Costs:** Transmission System Operators in Europe pay generators to reduce or increase output in response to bottleneck
- **Demand Response Programs:** Incentives for consumers to shift consumption to off peak times to ease congestion pressures

These tools improve efficiency but cannot fundamentally expand the transfer capacity. It focuses more on redistributing the congestion costs rather than eliminating them.

Battery energy storage and flexible generation like gas turbines are currently increasingly deployed to serve as buffers against grid congestion. California added more than 5 GW of grid scale batteries between 2020 to 2023, helping to stabilize supply during peak hours. Europe is also having accelerated deployment of grid-scale batteries. But the battery storage has scale limitations:

- **Volume Limit:** Batteries can shift power for hours, but the grid congestion often lasts for days or weeks, especially during Dunkelflaute (dark doldrums) period where there are little wind and sun in Europe.
- **High Cost:** Large-scale seasonal storage technologies like hydrogen are often not yet commercially viable. Germany has piloted hydrogen storage projects but mostly remain at demonstration scale with limited contribution to grid reliability.
- **Fragmentation:** Storage deployment today is often local and specific to each project rather than integrated across the grid. In Texas, batteries are concentrated in certain nodes to capture price spikes but does not necessarily address broader transmission bottlenecks.

While storage system is growing rapidly, its current form is still fragmented and limited compared to the scale of renewable integration required.

These current solutions are often more reactive rather than systemic. Congestion pricing, flexibility services, demand response and storage batteries can provide temporary relief, but the impact is partial and uneven across jurisdictions.

The next decade will be decisive. The International Energy Agency (IEA) warns that unless the annual investment in grid doubles to over USD600 billion by 2030, grid congestion will become a structural barrier to decarbonization.

Energy Hubs: Decentralized Solutions to a Centralized Problem

Investment alone, if uncoordinated, may lead to inefficient and redundant infrastructure. Energy hubs emerge as a practical alignment mechanism, a way to reconcile the needs of grid operators, renewable developers, industries, and communities by creating shared value at the local level. Instead of waiting for slow, top-down grid expansion, energy hubs offer a bottom up local response, offering a decentralized alternative. It offers a way to align investment with systemic efficiency and cross-border trade. An energy hub can be understood as:

- **A Physical Node:** Infrastructure that aggregates multiple renewable generation sources (wind, solar, hydro) and storage (batteries, hydrogen)
- **A Market Platform:** A cross-border trading point where multiple countries or regions can make transactions for electricity and related services
- **A Governance Structure:** Institutions and regulatory bodies that manage operations, allocate costs, and settle transactions

In practice, energy hubs are both technical systems and market constructs. It is designed to reduce congestion, maximize renewable utilization, and create stable frameworks for cross border trade. Energy hubs transform grid congestion from a bottleneck into an opportunity. By absorbing renewable output locally, they reduce curtailment and accelerate interconnections, unlocking growth that would otherwise be stranded. They also defer or even eliminate the need for costly high-voltage upgrades, allowing system operators to relieve pressure without massive capital outlays. The hubs secure reliable and affordable power for industries and strengthening economic competitiveness while advancing the energy transition.

Across regions, pioneering projects are already showing how localized balancing can relieve congestion, unlock renewables, and generate economic value. The Boekelermeer Energy Hub, launched 2025 in the Netherlands combined a 5MWh battery with a Congestion Service Provider model, which allows local businesses to share grid capacity, align usage, and secure access to renewable power without waiting years for new transmission lines. Australia's Renewable Energy Zones (REZs) combine generation, storage, and targeted upgrades to address congestion.

Denmark, Netherlands, and Germany are collaborating to develop offshore energy islands that collect offshore wind, integrate storage, and dispatch power via high-voltage direct current (HVDC) corridors to multiple countries. The Lao-Thailand-Malaysia-Singapore (LTMS) project in ASEAN, while still linear, has already shown that multi-country power trade is possible.

While not being hubs in the physical sense, the US Regional Transmission Organizations' market structures demonstrate that coordinated dispatch across wide geographies can reduce grid

congestion. Middle East and North Africa region is planning to export solar power and green hydrogen to Europe through interconnectors that reflects the hub concept.

Energy hubs rely on specific technologies and frameworks:

- **HVDC Interconnectors:** high-voltage direct current cables that efficiently transmit power over long distances and underwater
- **Digital Grid Management:** advanced forecasting, AI-driven balancing, and real-time monitoring
- **Hybrid Infrastructure:** co-location of generation and storage (batteries, hydrogen electrolyzers, pumped hydro)
- **Standardized Market:** harmonized regulations across jurisdictions to manage cross border flows and settlement.

Without these enablers, the hubs risk becoming stranded assets. With these, energy hubs can serve as the keystones to regional integration.

Beyond power, energy hubs can evolve into multi-vector hubs that integrate different parts of the energy system. For instance, surplus renewables can be converted into green hydrogen and exported through pipelines or shipping. Hubs can also support shared heat networks for industrial clusters, while centralizing carbon capture and storage (CCS) to manage CO₂ transport and storage. This way, energy hubs expand their value proposition, not just moving electrons but also serving as platforms that connect and integrate the entire energy system.

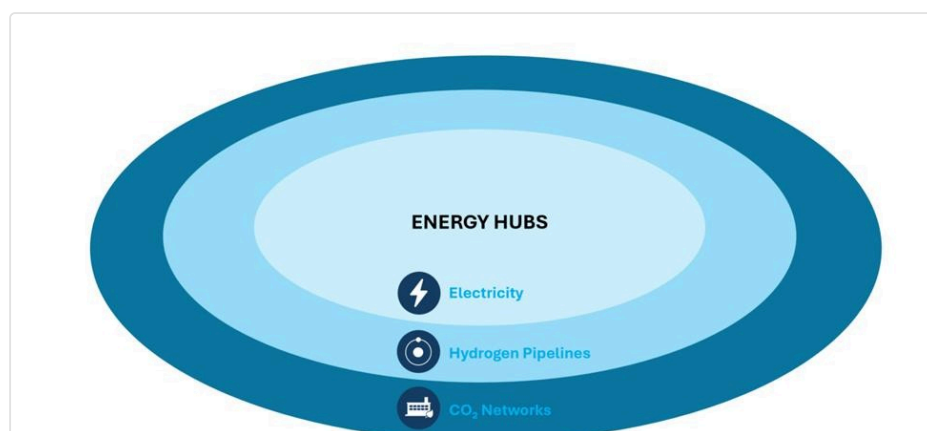


Image 1. Energy Hubs as Multi-Layered System. Source: Consultant Analysis, 2025

Hub and Spoke: A Conceptual Model

Most electricity grids today operate in a linear or radial term: power flows from generation plants to load centers along defined corridors. Cross-border interconnections are typically bilateral links, built project by project. While functional, this approach creates inefficiencies when renewable generation

clusters such as offshore wind zones or desert solar fields produce surplus that cannot be efficiently absorbed.

The hub-spoke model transforms this paradigm. Think of airports; the hubs collect passengers (electricity), consolidate, then dispatch via spokes (transmission lines). Without hubs, every city would need direct flights which are inefficient and costly. This concept is also evident in logistic and shipping sector. Ports and distribution centers pool cargos, dispatch it to smaller distribution centers (spokes), then redistribute efficiently to last mile.

We would not want every generator to be connected to every load. Instead of one-to-one connections, hubs serve as multi-directional nodes that aggregate supply (generation), integrate storage, and dispatch power across multiple spokes (interconnectors to demand centers). This system will allow balancing across borders and optimize infrastructure investments by concentrating transmission corridors where they add the most value.

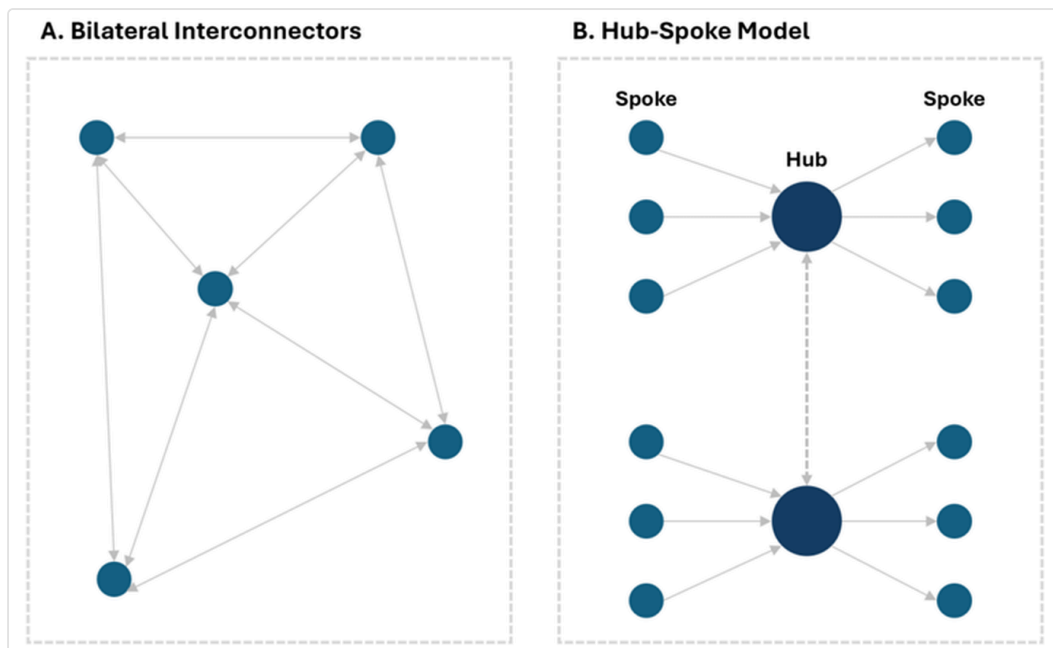


Image 2. Bilateral Interconnectors vs Hub-Spoke Model. Source: Consultant Analysis, 2025

Point-to-point is costly, duplicative, and have limited scalability, whilst hub-spoke model offers several advantages. By aggregating diverse resources, it creates a smoother and more reliable supply. It also reduces the number of cables or transmission lines needed, lowering the cost per MW delivered. At the same time, hub fosters liquidity in power trade by allowing multiple buyers and sellers to connect through a shared platform. The model makes it easier to integrate new renewable projects since they can plug into an existing hub rather than requiring a new, bespoke connection each time.

The hub-spoke approach creates value across three dimensions:

Infrastructure Efficiency

- **Reduce Duplications:** instead of each country or region building separate lines, the hubs will pool investment
- **Enable Scaling:** centralized hubs justify larger, more efficient HVDC systems

System Resilience

- **Balance across geographies:** when solar is weak in one region, wind or hydro from another can flow through the hub
- **Enhance reliability:** multiple spokes would mean fewer single points of failure

Market Development

- **Cross-border trade:** establish electricity markets between countries, with hubs as trading points
- **Unlocks ancillary services:** promotes the development of frequency, balancing, and reserve markets at regional scale

The hub-spoke concept fundamentally changes the role of interconnection. Instead of being a supplement to national grids, interconnectors will become the backbone of the regional systems. For governments, hubs demand deeper cooperation and shared sovereignty. For investors, they represent long-term infrastructure opportunities with stable returns, comparable to airports and ports. For consultants, they open demand for advisory services across policy, finance, and operations.

Hub and Spoke: The Preliminary Global Mapping & Trade Gains

Europe is the most advanced region in experimenting with hub-spoke models. The North Sea Energy Hubs initiated by Denmark, Netherlands, and Germany aims to transform artificial islands and offshore platform into multi country connection nodes. Offshore wind is pooled, stored, and transmitted via HVDC interconnectors to multiple load centers, including Germany, UK, Netherlands, and potentially Belgium and France. There are also potential hub candidates in Andalusia, Spain and Norway, focusing on solar and hydropower respectively.

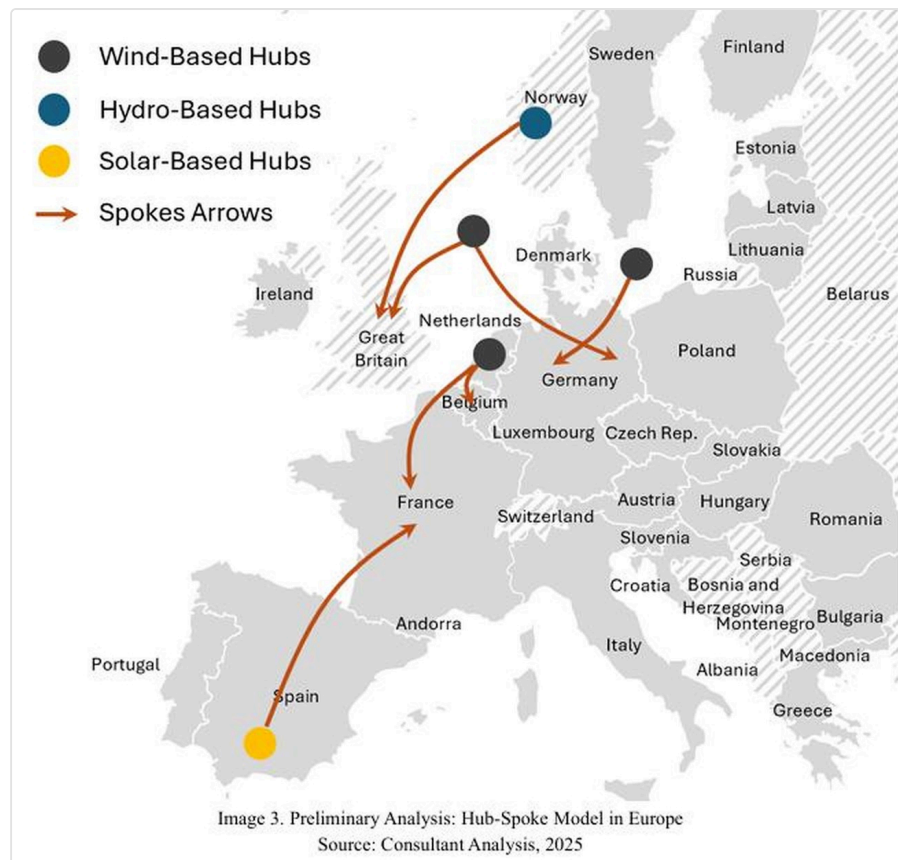


Image 3. Preliminary Analysis: Hub-Spoke Model in Europe. Source: Consultant Analysis, 2025

In Southeast Asia, hubs could emerge in Laos which is rich in hydropower, Sumatra and Borneo which are rich with solar and hydro, exporting to Singapore, Malaysia, and Thailand. China emerges as a central hub with spokes reaching Russia, Mongolia, Central Asia, and Southeast Asia, which is consistent with its ultra-high-voltage export ambitions and global energy interconnection strategy.

India links westward to Nepal and Bhutan, and southward to Sri Lanka, indicating its dual role as both exporter and importer in South Asia. South Korea and Japan are rich in offshore wind and solar hubs, with spokes to each and potentially China, to realize the Northeast Asia Supergrid vision.

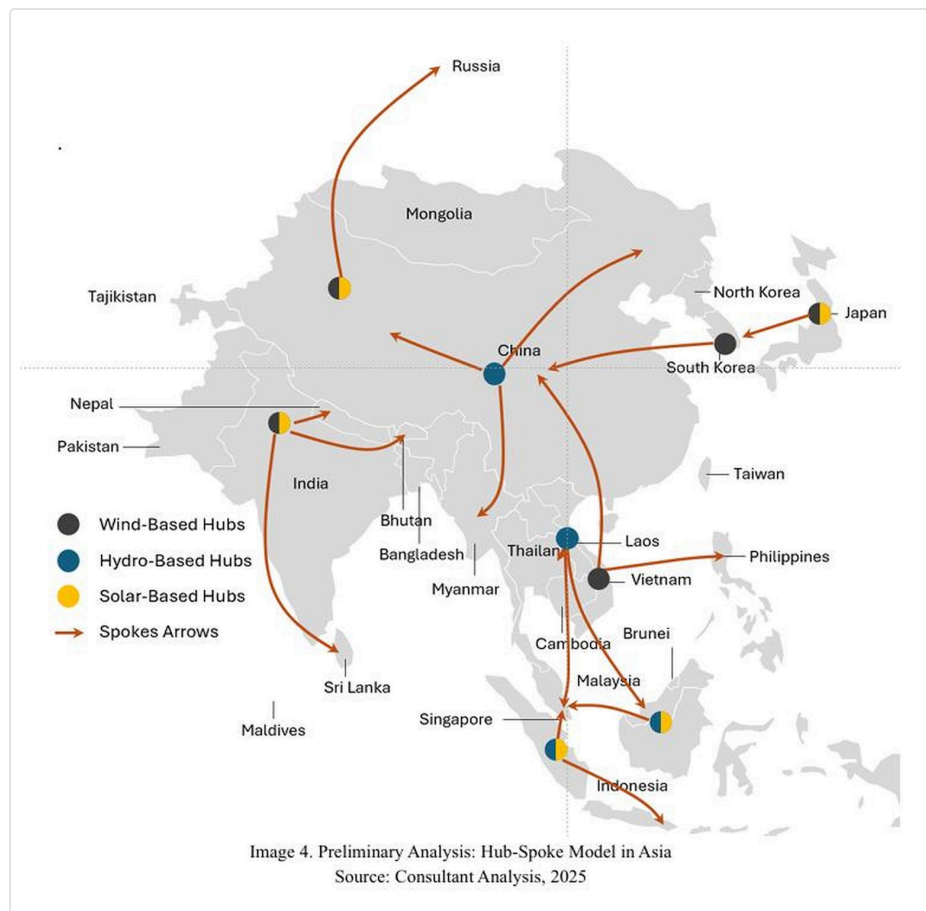


Image 4. Preliminary Analysis: Hub-Spoke Model in Asia. Source: Consultant Analysis, 2025

Currently, many system operators spend billions annually on curtailment payments, compensating renewable generators to stop producing and fossil plants to ramp up. This is a sunk cost with no value creation. In contrast, hub-spoke systems convert stranded energy to tradable flows, turning grid congestion from a cost center into a revenue opportunity. Instead of paying wind farms to stop generating, the surplus power can be exported to neighboring demand centers via hubs.

The economic value creation of this cross-border hub-enabled trade include:

- **Cost Reduction:** reducing redispatch and curtailment costs, the congestion cost could instead be traded as surplus exports
- **Price Convergence:** importing countries benefit from cheaper renewable power, reducing wholesale prices
- **Investment Signals:** stable hub pricing provides bankable revenue streams for renewable developers
- **Resilience Gains:** shared balancing reduces blackouts and system stress.

The IEA analyzed that increased interconnection will be able to save up to EUR40 billion annually in avoided generation and grid costs in Europe alone by 2030. Investing USD1,7 trillion more in

upgrading global transmission grids by 2040 could yield cost savings of USD3 trillion in net-zero power systems. The energy hubs are the leverage points that make those savings real.

The Consulting Opportunity: A New Advisory Frontier

Grid congestion is not just an energy challenge. It is a strategic, multi-stakeholder challenge that sits squarely in the consulting arena. Solving it requires more than engineering fixes. Energy hubs lie at a rare intersection of technical innovation, business strategy, economic modelling, policy design, and stakeholder alignment; all areas where us as consultants bring value. Our potential role spans across four dimensions:

1. **Policy Advisory.** Governments and regulators face difficult trade-offs between speed, cost, and public acceptance of grid expansion. Consultants can help design policy frameworks, incentive structures, and roadmaps that balance national energy targets with local conditions. We can support clients in navigating market entry and advocate for enabling regulations.
2. **Investment and Business Model Innovation.** Energy hubs require new business models and financing structures to scale. Consultants play a key role in structuring partnerships between utilities, industries, and technology providers, and further, in assessing the bankability of these new solutions. We can structure revenue mechanisms for the clients, including capacity leasing, arbitrage, and ancillary service participation and run sensitivity models to ensure the most efficient structure. Correct placement of energy hubs is critical; consultant can utilize congestion forecasting and investment prioritization tools to pinpoint where hubs will deliver maximum ROI and grid relief.
3. **Multi-Stakeholder Orchestration.** At the heart of grid congestion lies fragmented interest. We as consultants are uniquely positioned to broker alignment among utilities, municipalities, industries, and communities, translating technical solutions into shared economic value propositions. By designing governance models, partnership frameworks, and operational roadmaps, we ensure alignment and project feasibility.
4. **Operational Transformation and Digital Enablement.** Consultant can support clients in deploying digital tools such as congestion forecasting, smart-grid platforms, and demand-response tools that ensures hubs to be scaled effectively and sustainably.

Through these capabilities, consulting firms can transform energy hubs from concept to tangible and scalable solutions. Consider a Southeast Asian hub centered on Sumatra's renewable potential. A consulting team could:

1. Build the case for Singapore and Malaysia as spoke markets
2. Design the PPA and REC frameworks to make flows bankable

3. Structure a blended finance model with Asian Development Bank (ADB) and private equity
4. Manage cross-country negotiations on tariffs and transit fees
5. Integrate hydrogen pilot projects to future-proof the hub

This illustrates the multi-disciplinary nature of the role; no single government or company has the bandwidth to do all this alone. Without structured advisory support, hub initiatives risk fragmentation, financing gaps, governance deadlocks, and technology lock-in.

As congestion risks rise, clients across sectors from government and utilities to energy intensive industries will increasingly demand solutions. For consultants, this represents a new advisory frontier: shaping energy hubs and investment frameworks that are not yet standardized but urgently needed. This positions us not as bystanders to a technical bottleneck, but as a catalyst who bridge policy, finance, operations, and technology, turning grid congestion from a liability into a platform for innovation.

Seizing the Moment: A Call to Action

Energy hubs have the potential to become the data centers of the renewable era: smart, essential nodes that store and route energy efficiently. If pursued decisively, energy hubs could become the ports and airports of the 21st century energy system; critical infrastructure enabling trade, resilience, and prosperity. The difference is that, unlike traditional infrastructure, energy hubs are being built under intense climate and decarbonization deadlines. Governments, utilities, and investors who move early will shape the next phase of energy transition.

The imperative is clear: go beyond diagnosing congestion. We must design, orchestrate, and implement solutions that bridge policy, finance, and operations. Consumers, policymakers, and developers are feeling the cost and pain of wasted renewables and delayed transitions. Energy hubs are not just a technical fix; it is a strategic frontier where consultants are uniquely positioned to lead the transformation.