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From scarcity to scale: The new economics of energy

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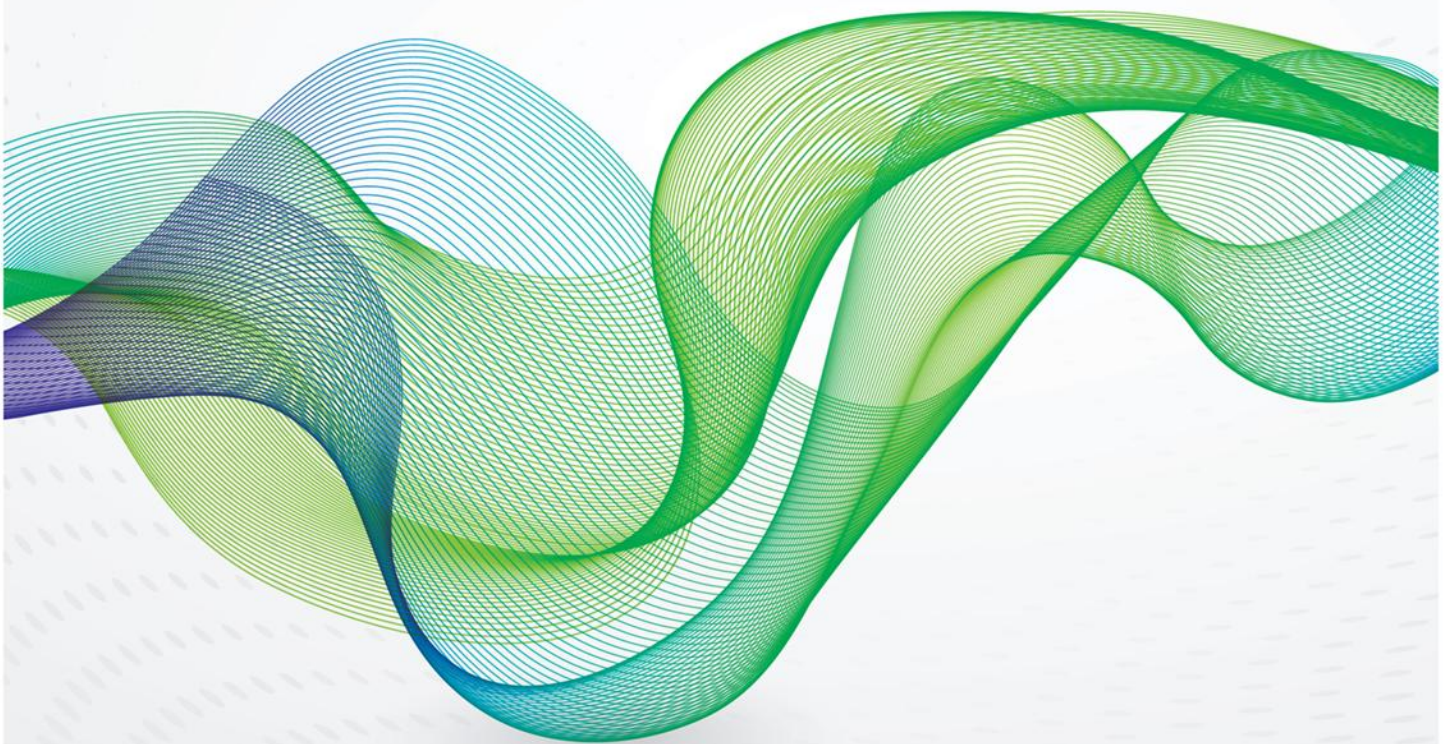
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April 2025

From Scarcity to Scale: The New Economics of Energy



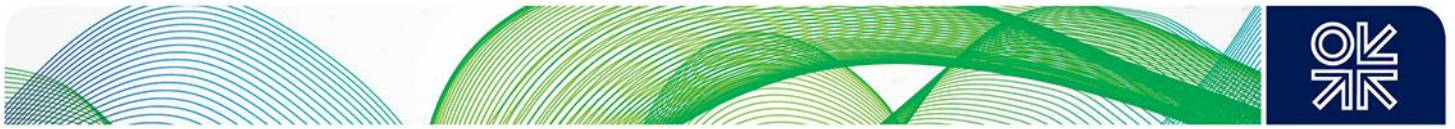


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Abstract

The global energy landscape is undergoing a major transformation, upending decades of economic thinking built around resource scarcity. Unlike fossil fuels—continuously extracted from finite, geographically fixed deposits—renewable energy revolves around manufacturing technology that harvests essentially free and limitless resources. This shifts our economic framework from Hotelling’s Rule, where scarcity drives rising costs, to a learning curve model where costs fall with cumulative production—creating a deflationary trajectory contradicting traditional energy economics. While natural endowments of solar irradiation and wind resources vary globally, geographic accident no longer fundamentally determines energy wealth; instead, technological innovation, manufacturing scale, and early-mover advantages determine market leaders, creating a ‘winner-takes-most’ dynamic exemplified by China’s dominance in solar PV and battery manufacturing. The concept of energy security transforms from dependence on fuel imports to reliance on imported equipment, making domestic production capacity and resilient supply chains critical to national interests and driving a global resurgence of industrial policy. The nature of risk undergoes fundamental transformation in this paradigm, shifting from volatile commodity prices, concentrated resource control, and environmental impacts of fossil fuel systems to new considerations including critical minerals access, grid flexibility requirements, storage solutions, and land-use planning for renewable infrastructure. Market design experiences philosophical inversion as fossil fuel markets designed to price extracted commodities give way to clean-energy markets that must accommodate near zero-marginal cost resources, reward flexibility, and prioritise integration. Renewable energy blurs traditional boundaries between production and consumption through ‘prosumers’, while simultaneously integrating previously separate sectors through electrification and digitalisation. These evolving system boundaries produce novel emergent behaviours that necessitate new approaches to market design and regulation—marking a decisive shift from an energy paradigm rooted in scarcity towards one characterised by scale and abundance.



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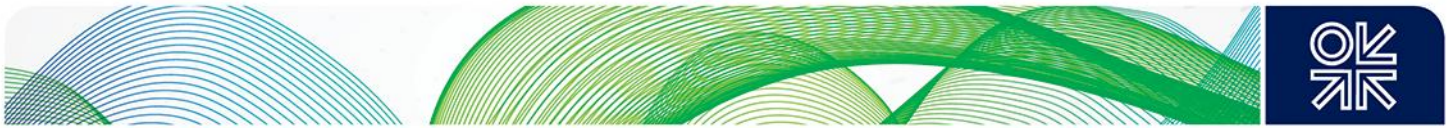
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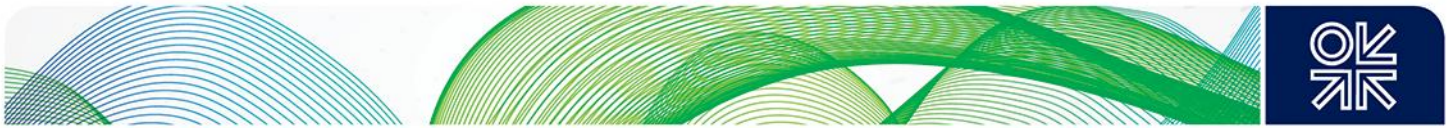
1. Introduction

The global energy sector is exhibiting fundamentally different characteristics compared with two decades ago. The key components of renewable energy systems (solar panels, wind turbines, batteries, electrolyzers) are manufactured goods. We see production concentrated in certain regions (e.g., solar PV in China) not because of rare natural resource endowments, but due to industrial policy, supply chain efficiencies, and economies of scale. The potential for such production exists wherever there is industrial capacity and investment. Governments worldwide are recognising the economic and strategic benefits of controlling supply chains for low-carbon technologies. Specifically, China's dominance in solar PV module production (almost 85% of global production as of 2023) (Statista, 2024a) and battery manufacturing (79% of global EV Li-ion batteries as of 2021) (Statista, 2024b) has spurred rival policies. The U.S. Inflation Reduction Act (IRA) (U.S. Department of Energy, 2022a) and the EU's Net-Zero Industry Act (Sciencebusiness, 2024) offer subsidies, tax breaks, and other incentives to attract clean tech manufacturing. Japan's "Green Growth Strategy" (Ministry of Economy, Trade and Industry, 2024) and South Korea's "Green New Deal" (Intralink, 2021) outline specific targets and incentives for hydrogen and battery technology manufacturing, indicating that competition for future manufacturing leadership is escalating across Asia as well.

As a result of these new industrial strategies, solar panel and battery manufacturing is gradually expanding beyond traditional hubs (e.g., China) to regions like the U.S., EU, India, and Southeast Asia. Some nations (e.g., Vietnam, Malaysia) have grown PV production by leveraging advantages such as access to skilled labour, supportive policies, and existing manufacturing bases (Asian Development Bank, 2023). Similarly, battery production for electric vehicles (EVs) is scaling across multiple countries (e.g., South Korea, Japan, the United States, Germany) (Invest KOREA, 2025), underscoring that manufacturing is "footloose" relative to fossil fuel extraction. The key resources (e.g., lithium, nickel, cobalt) can be shipped, and battery assembly can take place wherever policy and market conditions are favourable. This stands in sharp contrast with fossil fuels, where extraction is tied to specific geological formations; low-carbon manufacturing relies on technology and supply chains that can be established globally, reducing geographic constraints. Nations are actively competing to capture market share, reflecting a profound shift from resource control to industrial strategy.

This transformation has redefined our understanding of energy security. Governments are increasingly framing energy security in terms of stable access to clean energy technologies—solar panels, wind turbines, batteries—rather than merely securing oil or gas supply routes. For instance, the U.S. Department of Energy's supply chain reviews highlight vulnerabilities in imported solar cells and battery components and emphasise domestic production capacity (U.S. Department of Energy, 2022b; White House Council on Supply Chain Resilience, 2024). The COVID-19 pandemic and the war in Ukraine exposed vulnerabilities in global supply chains, including those for clean energy technologies, highlighting the importance of domestic manufacturing capacity and resilient supply chains. Countries are also seeking to secure intellectual property and manufacturing know-how for emergent technologies like solid-state batteries or hydrogen electrolyzers. Furthermore, policymakers are increasingly using export controls on advanced technologies to protect domestic industries, demonstrating the shift towards technology control as a tool of energy security. As renewable energy systems become more integrated with digital grids, cybersecurity emerges as a critical aspect of energy security—a technology-focused concern rather than a traditional fuel-access issue. These developments signal that technology leadership is becoming a core pillar of energy security strategies.

The nature of innovation in the energy sector is also changing dramatically. Manufacturing innovation is becoming more critical than resource extraction innovation. In the fossil fuel era, innovation primarily focused on discovering new reserves and extracting them more efficiently. In contrast, renewable energy innovation centres on improving manufacturing processes, reducing costs, and enhancing technological



efficiency. Consequently, countries are gradually shifting their R&D investments and talent pipelines to address manufacturing and technological challenges of renewable energy, rather than traditional fossil fuel extraction. Data from the International Energy Agency (IEA) indicate that over the past two decades, renewable energy patents have grown at a faster rate than fossil-fuel-related patents (IEA, 2024)¹. While fossil fuel patents historically outnumbered those for renewables, the gap has narrowed or reversed in many technology categories. Since approximately 2010—and particularly after 2015—renewable technologies, including solar, wind, and enabling technologies such as storage, have driven most energy-sector patent growth. However, recent trends suggest a slowdown in renewable energy patent growth, indicating the maturation of some technologies, while innovation in traditional fossil fuel extraction continues to decline.

The faster growth of renewable energy patents is significant, as the dramatic cost reductions in solar PV over the past decade have primarily resulted from manufacturing innovations—such as larger wafers, thinner silicon, and improved cell designs—rather than breakthroughs in discovering new “solar reserves.” Similarly, intensive R&D efforts are focused on improving battery performance (energy density, charging speed, and lifespan) and reducing costs through advances in materials science and manufacturing processes. The development of larger, more efficient wind turbines has been driven by innovations in advanced materials, aerodynamics, and manufacturing techniques, rather than new methods of “finding wind.” As a result, expertise in materials science, manufacturing engineering, and systems integration is becoming increasingly vital for the energy sector.

These shifts carry profound implications for decarbonisation strategies. Countries have realised that simply subsidising renewable energy deployment (e.g., feed-in tariffs) does not automatically reduce vulnerabilities and dependencies. Consequently, emphasis has shifted to coordinating deployment support with manufacturing development. Countries are increasingly coupling deployment incentives with local content requirements, tax credits for local manufacturing, or R&D support. For example, the IRA conditions some tax credits on domestic content (IRS, 2025). This need for coordination is also evident in trade disputes, where countries have begun imposing tariffs on imported clean energy products to protect domestic manufacturers, highlighting the tension between promoting deployment (which may favour cheaper imports) and fostering domestic production.

The trends observed in the global energy system signal a fundamental shift in the economics of energy, diverging from the fossil fuel era’s core principles—scarcity, geographic constraints, and resource control—and embracing new dynamics driven by technology, manufacturing scalability, innovation, and policy coordination. This transformation necessitates a new framework for understanding energy economics, as traditional models rooted in fossil fuel paradigms fail to capture the unique characteristics of low-carbon systems. This paper conceptualises the transition from conventional energy economics to a new paradigm and explores its implications for markets, policy, and the strategic decisions of market participants.

The structure of the paper is as follows. Section 2 provides a historical background on traditional commodity-based energy markets, with a focus on the Hotelling model. It presents key insights from the Hotelling model, highlights its shortcomings, and discusses the economic features of traditional energy markets beyond scarcity. Section 3 introduces the new economics of energy, explains its emergence, and explores its key economic characteristics through the concept of the learning curve. Section 4 examines the implications of this technology-driven energy economics. Finally, Section 5 offers concluding remarks.

¹ It is important to note that this analysis focuses on “Oil, Gas, and Coal Supply.” Carbon Capture, Utilisation, and Storage (CCUS) is often considered separately and exhibits a different growth trend. If CCUS were included with fossil fuels, the overall fossil fuel patent growth rate would be higher, though still significantly lower than that of renewables.



2. Economics of traditional commodity-based energy markets

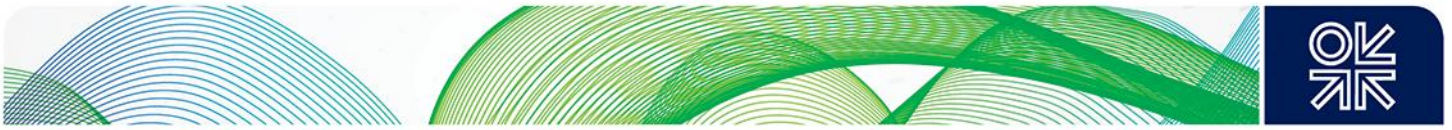
For nearly a century, our understanding of commodity-based energy markets was influenced by the model proposed by Hotelling. Harold Hotelling's 1931 paper "The Economics of Exhaustible Resources" is a foundational work in resource economics, providing a rigorous theoretical framework for understanding the optimal extraction and pricing of non-renewable resources (see Hotelling, 1931). At its core, Hotelling's analysis addresses the intertemporal allocation of exhaustible resources, recognising the trade-offs between current and future consumption.

The Hotelling Rule is the most influential contribution of the paper, establishing a fundamental principle for resource pricing and optimal rate of extraction of an exhaustible resource. The rule states that, in an efficient market (i.e., under conditions of competitive equilibrium) with no technological change or extraction costs, the price of an exhaustible resource should rise at the rate of interest over time. This ensures that resource owners are indifferent between extracting the resource today or deferring production to a future date, as the present value of their holdings remains maximised. The economic rationale is that, as a non-renewable resource becomes scarcer, its opportunity cost increases, leading to a natural rise in price. The Hotelling Rule has been instrumental in shaping models of resource depletion and is widely applied in fields such as fossil fuel economics, environmental policy, and climate mitigation strategies.

Hotelling's model was developed in response to growing economic and policy concerns regarding the depletion of finite natural resources at the time. He identifies two contrasting perspectives in resource extraction: conservationists, who argue that resources are being exploited too rapidly and cheaply, and monopolists, who restrict production to maximise profits, leading to slower depletion but higher prices. The background to this debate is that during the early 20th century, rapid industrialisation and technological advancements had led to increased extraction of fossil fuels, minerals, and other non-renewable resources. This raised fears among policymakers and conservationists that such resources were being exploited too quickly and inefficiently, potentially leaving future generations without essential supplies. At the time there was an emerging conservation movement in the United States which advocated for policies to prevent excessive depletion of natural resources (Hays, 1959). Influenced by early conservationists like Theodore Roosevelt and Gifford Pinchot (see Pinchot, 1910), policymakers sought to regulate industries such as mining, forestry, and oil extraction to ensure long-term sustainability. Many believed that resources were being extracted too cheaply and wastefully, leading to calls for government intervention, including production quotas, land-use restrictions, and direct state ownership of key reserves. However, the economic justification for such interventions was not well understood.

At the same time, monopolistic control over key resources, particularly in industries like oil and coal, had begun to influence extraction patterns and pricing, prompting debates about the role of market forces versus government intervention in resource management². This creates a paradox: on one hand, resources are said to be exploited too quickly; on the other, monopolistic control can lead to underproduction and inflated prices. While conservation measures restrict supply to ensure long-term availability, monopolies and cartels also advocating for a restrict supply—but for a different reason: profit maximisation. Hotelling points out that the conservation movement, if not carefully managed, could unintentionally benefit monopolies by imposing production restrictions that limit market competition.

² Large firms, such as Standard Oil, had historically exerted significant control over resource markets, restricting output to maintain high prices (Granitz and Klein, 1996). The U.S. government had responded with antitrust legislation, such as the Sherman Antitrust Act (1890) and the breakup of Standard Oil in 1911, in an effort to promote competitive markets (Britannica, 2025). However, the long-term effects of monopolistic control over exhaustible resources remained an open question. Hotelling's work examined how monopolists might manipulate extraction rates differently than competitive firms, showing that they tend to restrict production more than necessary, thereby slowing depletion but also leading to higher prices.



There were also other issues, such as technological advancements and resource discoveries during the early 20th century, that impacted price and rate of extraction of resources and consequently added urgency to the debate over inefficient extraction strategies. The discovery of large oil fields, such as those in Texas (Hinton and Olien, 2002) and California (Nehring, 1975), created cycles of boom-and-bust extraction, where periods of rapid drilling were followed by price collapses and overproduction. These fluctuations raised concerns about wasteful extraction practices, including the inefficient drilling of offset wells and the premature depletion of reservoirs.

Hotelling introduced the idea that there must be an “optimum rate” of extraction that balances present and future needs. He recognised that the observed chaotic extraction patterns were not necessarily due to market failures but could result from imperfect property rights, lack of foresight, or government-imposed inefficiencies. He challenged simplistic conservationist arguments by demonstrating that, under ideal market conditions, rational resource owners would naturally adjust extraction rates to maximise long-term profits, leading to an optimal allocation of resources over time. The total value generated by a resource under free competition tends to maximise social welfare, provided there are no externalities (such as environmental damages or speculative market distortions). This leads to a self-regulating system, where firms extract resources in a way that balances present and future value. This insight provided an economic counterpoint to the more rigid conservation policies being advocated at the time. To correct for market distortions, he argued that rather than imposing outright bans or inefficient restrictions on extraction, taxation mechanisms could regulate depletion in a way that aligns private incentives with broader societal objectives.

In sum, Hotelling’s idea was shaped by a combination of growing conservationist concerns, monopolistic practices in resource industries, gaps in existing economic theory, and technological changes that altered extraction dynamics. His work provided a formal theoretical basis for understanding how market structure influences resource extraction patterns and price and whether regulatory interventions, such as severance taxes or state control, were needed to correct inefficiencies caused by industry distortions. The insight that he provided remained highly influential to debates on energy policy, climate change, and sustainable resource management for many decades and to this date.

2.1 Key insights from the Hotelling model

In order to better understand the insights of Hotelling model, let’s have a closer look at the way which he formulated the problem. Hotelling discusses how free competition, under ideal conditions, tends to maximise the total social value of an exhaustible resource. To show, this let $S(t)$ be the remaining stock of a non-renewable resource at time t . Extraction (or production) at time t is $Q(t)$. The dynamics of the stock are:

$$\dot{S}(t) = -Q(t),$$

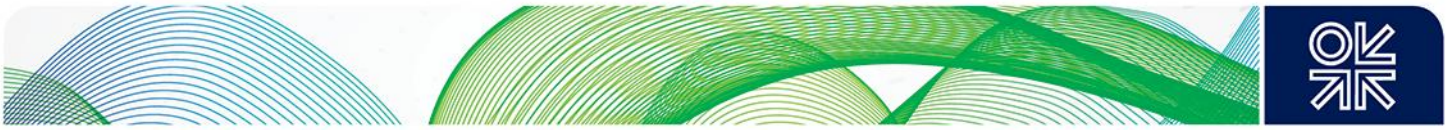
$$S(0) = S_0 \text{ (initial stock),}$$

$$S(T) \geq 0 \text{ (terminal stock, possibly zero).}$$

The market price of the resource at time t is $p(Q(t))$. For simplicity, we assume p is a decreasing function of Q (i.e., higher extraction/production leads to lower price). Marginal extraction cost is c (often taken to be constant in the most basic version). The discount rate (or market rate of interest) is r .

A resource owner (or a social planner, in a perfectly competitive setting) seeks to maximise the present value of profits from extracting and selling the resource:

$$\max_{Q(t)} \int_0^T e^{-rt} \left[\underbrace{p(Q(t)) Q(t)}_{\text{revenue}} - \underbrace{c Q(t)}_{\text{extraction cost}} \right] dt$$



subject to the stock constraint

$$\dot{S}(t) = -Q(t).$$

The solution to this problem leads to (see Appendix A for the solution):

$$p(Q(t)) - c = \lambda(t).$$

and

$$\frac{\dot{P}(t)}{P(t)} = r$$

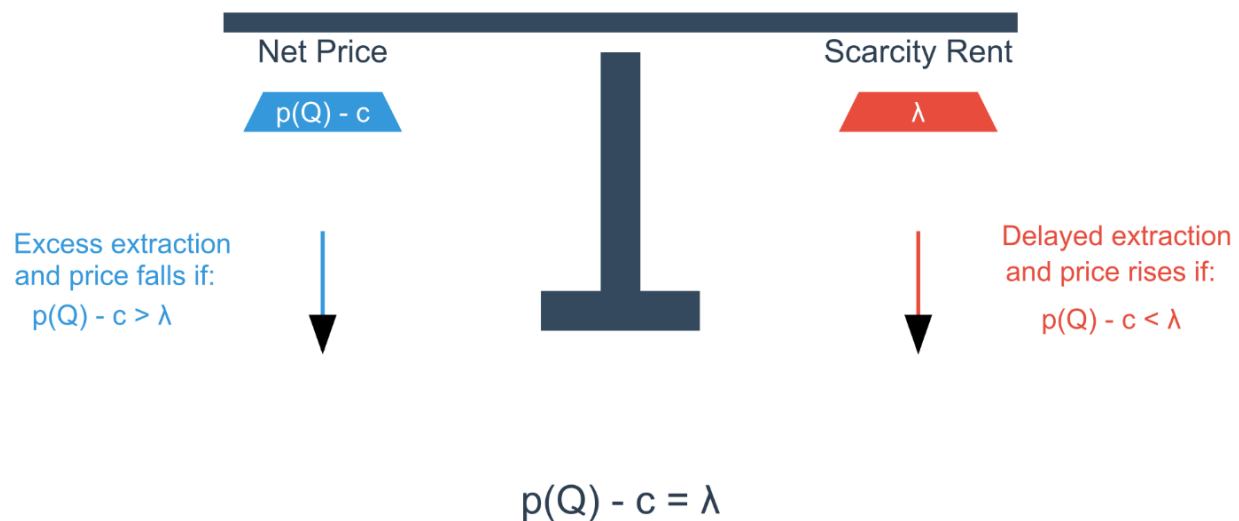
where $P(t) = p(Q(t)) - c$ is the net price of the resource and $\lambda(t)$ is the shadow price (costate variable) of the resource stock $S(t)$ and, in economic terms, measures the value of an additional unit of the resource in the ground at time t (often called the scarcity rent).. This result states that in an efficient market, the net price of an exhaustible resource must grow at the rate of interest over time. This ensures that the resource owner is indifferent between extracting today or postponing extraction, as the expected price increase over time is equal to the return from financial investment at rate r . In other words:

- If market conditions follow the Hotelling Rule, resource prices will rise predictably over time, reflecting increasing scarcity.
- If prices rise slower than the interest rate, firms will extract more today, as investing in financial assets offers a better return.
- If prices rise faster than the interest rate, firms will delay extraction to benefit from greater future prices.
- The extraction rate naturally declines over time, ensuring a smooth depletion process instead of sudden exhaustion.

The core of Hotelling's model lies in the interplay between the shadow price, $\lambda(t)$, the discount rate, r , and the net price, $P(t)$. $\lambda(t)$, the shadow price or scarcity rent, represents the marginal value of leaving one more unit of the resource in the ground at time t . It's crucial to understand that this isn't just the current market price; it's the opportunity cost of extracting that unit. The model elegantly shows that this shadow price grows exponentially at the rate of interest, r . This growth reflects the fundamental trade-off inherent in managing an exhaustible resource: extracting and selling today yields immediate profit, but leaving the resource in the ground allows it to appreciate in value, potentially yielding higher profits in the future. The discount rate, r , acts as the benchmark; it represents the return that could be earned by investing the proceeds from extraction elsewhere in the economy.

Under perfect competition we have $p(Q(t)) - c = \lambda(t)$. This equation is the heart of the Hotelling Rule. It states that, at any given time, the net price (market price minus marginal extraction cost) must equal the scarcity rent (Figure 1). If the net price were higher than the scarcity rent, firms would have an incentive to extract more, driving the price down until the equality was restored. If the net price were lower, firms would delay extraction, increasing scarcity and pushing the price up.

Figure 1: The equilibrium in Hotelling rule



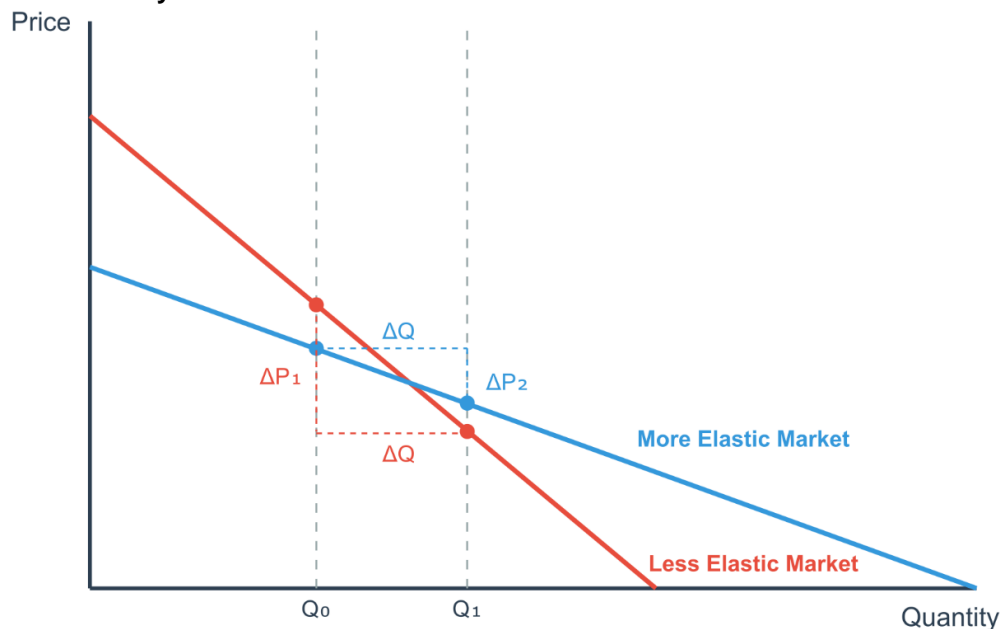
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The derived Hotelling Rule, $\frac{dP(t)/dt}{P(t)} = r$, encapsulates the dynamic efficiency of resource extraction under perfect competition. It's not the market price itself that grows at the rate of interest, but the net price ($P(t) = p(Q(t)) - c$). This distinction is important. The market price, $p(Q(t))$, is influenced by demand, while the net price reflects the true scarcity value of the resource. The rule implies a smooth, predictable increase in the net price over time, reflecting the increasing scarcity of the resource. This smooth price path ensures intertemporal efficiency: resource owners are indifferent between extracting a unit today and extracting it in the future, because the rate of return from holding the resource (the price increase) is equal to the rate of return from alternative investments (r).

Lastly, the resource stock $S(t)$ and the demand function $p(Q)$ jointly determine the time profile of extraction. Larger initial stocks tend to stretch out the period over which the resource is profitably extracted, allowing for a flatter scarcity rent trajectory. Meanwhile, the price function's sensitivity to quantity—captured by $\partial p / \partial Q$ —influences how changes in extraction affect marginal revenue. In highly elastic markets, modest changes in production can significantly affect prices, potentially generating more cautious extraction paths (Figure 2). By contrast, in less elastic markets, the same quantity adjustments have a smaller effect on prices, offering less incentive to deviate from a steady depletion path. In all cases, the fundamental Hotelling insight persists: the net price path that emerges from optimal extraction must grow at the discount rate, balancing the trade-off between extracting now versus waiting for potentially higher prices in the future.

The behaviour of producer under Hotelling's model is not independent of market structure. It is easy to see that market power dramatically alters how firms exploit exhaustible resources. Under *perfect competition*, each firm takes the price as given and extracts resources so that the scarcity rent (net price) rises at the interest rate, ensuring an efficient balance between current and future extraction (Hotelling's Rule). In contrast, a *monopolist* recognises how output affects market price and restricts extraction more aggressively, charging higher prices and depleting the resource more slowly. This behaviour leads to deadweight losses because it keeps prices artificially high and output lower than what would be socially optimal.

Figure 2: The elasticity of demand matters



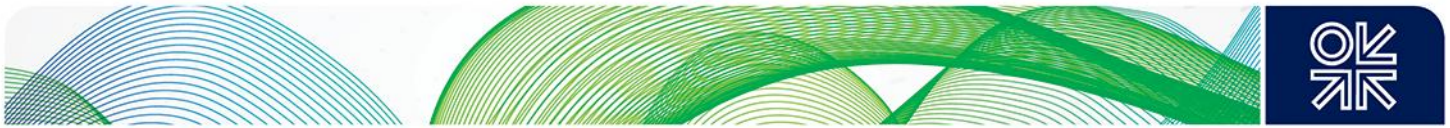
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In *duopoly* or other imperfectly competitive settings, extraction rates and price paths lie somewhere between the competitive and monopolistic extremes. Firms must anticipate and react to each other's decisions, often resulting in unstable production patterns—either price wars with excessive extraction or tacit collusion with under-extraction to sustain high prices. While perfect competition approximates a socially optimal outcome, monopoly and oligopoly create inefficiencies by distorting both the timing and the volume of resource extraction for strategic gain.

Governments play a key role in correcting market failures associated with exhaustible resources. When a single firm or a few firms dominate the market, they can restrict output below socially optimal levels, and when markets are highly competitive, environmental externalities may go unaddressed. To align extraction rates with broader societal goals, policymakers can implement measures such as production quotas, price controls, or regulation of extraction techniques, ensuring resources are not over-exploited or priced excessively high. Other interventions like public ownership and strategic reserves can also mitigate extreme price volatility and secure long-term resource availability.

Hotelling suggests that *market-based interventions*, particularly taxes, can steer resource extraction toward more efficient outcomes while minimising disruptions. A *severance tax* increases the marginal cost of extraction per unit, potentially slowing depletion unless firms expect higher future prices or further tax hikes. By contrast, a *capital value tax* raises the effective discount rate, encouraging faster extraction so companies can avoid ongoing taxation on in-ground reserves. *Resource rent taxes* selectively target profits above a normal return on investment, aiming to capture unearned scarcity gains without deterring new projects; *windfall taxes* capture extraordinary, unforeseen profits but mostly affect behaviour if firms anticipate further taxes in the future.

Each tax affects extraction timing differently, reflecting its impact on firms' costs, expected returns, and willingness to invest or produce. Severance and capital value taxes can alter depletion paths in ways that either conserve resources longer or hasten extraction prematurely, depending on market conditions and expectations. While resource rent taxes are often considered the most neutral—allowing normal returns to



remain untaxed—overly high rates can still undermine exploration. Consequently, government interventions must balance revenue goals, resource conservation, and industry incentives to achieve outcomes that are both efficient and equitable.

2.2 Critiques of Hotelling model

Although Hotelling's Rule has been pivotal in resource economics, many investigations highlight real-world departures from the simple prediction that resource prices should rise at the interest rate. Empirical data frequently exhibit different price patterns than that predicted by Hotelling including U-shaped, random walks, or near-stagnation, driven by technological innovation, market power, and geological constraints (Livernois, 2009; Krautkraemer, 1998; Slade, 1982; Smith, 1981). Such "real-world" forces can overshadow the straightforward arbitrage logic proposed by Hotelling, challenging its applicability as a comprehensive forecast of price trajectories.

Hotelling's Rule also underpins the Hotelling Valuation Principle (HVP), which posits that the total market value of in-ground reserves should equal the discounted net price. This principle often fails in practice due to volatility, strategic interactions, and imperfect capital markets (Livernois, 2009). Some partial validation appears in the U.S. oil and gas sector (Miller and Upton, 1985), but distortions remain widespread. The assumption of a fixed resource stock has likewise been questioned, as exploration and technological progress can transform ostensibly depletable reserves into dynamic inventories (Cairns and Davis, 2001; Chapman, 1993). In addition, production decisions can be dominated by geological factors rather than intertemporal arbitrage, producing stable extraction even when price signals might suggest delaying output (Anderson et al., 2014).

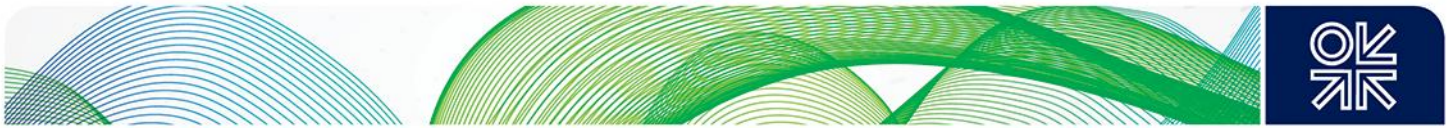
Refined models of resource depletion increasingly incorporate uncertainty, exploration, and diverse cost structures (Gaudet and Howitt, 1989; Cunha and Missemmer, 2020; Slade and Thille, 1997; Pindyck, 1981). Technological progress, for instance, can temper the rise of scarcity rent well below what Hotelling's Rule predicts (Kronenberg, 2008), and close substitutes for certain resources can keep prices stable over time (Gaitan et al., 2006). In some scenarios, scarcity rent may still move toward the interest rate when extraction remains concave (Livernois and Martin, 2001), though non-concavities and market imperfections can obscure this trend, as observed in old-growth timber markets (Livernois et al., 2006).

Overall, these refinements underscore that Hotelling's Rule, despite its theoretical elegance, does not offer a complete explanation of real-world extraction and pricing. Drilling constraints, exploration, capacity expansions, and strategic misrepresentation of reserves all affect outcomes in practice (Anderson et al., 2014; Slade, 1982; Pindyck, 1981; Cairns and Davis, 2001; Kronenberg, 2008). Advanced approaches combine resource economics with asset-pricing tools, such as the Capital Asset Pricing Model (Slade and Thille, 1997) or introduce risk aversion to explain why observed price paths diverge from those implied by perfect foresight (Gaudet and Howitt, 1989). Although scarcity (if exists) does impose a fundamental intertemporal trade-off, policy, geological, technological, and market factors ultimately shape how, when, and why resources are extracted, making Hotelling's framework a useful foundation rather than an all-encompassing predictor.

2.3 Beyond scarcity: other economic features of traditional energy industries

For many decades, concerns about resource depletion, embodied in concepts like "Peak Oil" or "Peak Coal," shaped investment strategies and spurred countries to secure external reserves or diversify energy sources. Depletion anxiety also motivated energy independence policies, stockpiling strategies, and the development of alternative energies. However, in practice, technological advances and new discoveries have repeatedly postponed these doomsday scenarios.

Beyond scarcity, which historically drove anxieties about resource depletion and influenced energy policy, the traditional energy industry, particularly the fossil fuel sector, possesses several other fundamental economic features that profoundly shape its structure, behaviour, corporate strategies, investment patterns,



international trade dynamics, and long-term trajectory. Understanding these characteristics is crucial not only for comprehending the current challenges and future prospects of the industry but also for explaining why the fossil fuel sector has developed its current market structure, institutional arrangements, and competitive dynamics.

One such feature is economies of scale. Production, transportation, and refining of fossil fuels exhibit significant economies of scale (for the petroleum industry, see Hibdon and Mueller, 1990). Larger operations (mines, wells, pipelines, refineries) generally have lower per-unit costs. As a result, firms that invested heavily in capacity were able to outcompete smaller, less efficient producers. Over time, this dynamic accelerated consolidation in the industry, as larger players could operate at a scale that smaller entrants could not match without incurring massive capital expenditures.

Because fossil fuel companies enjoyed these scale economies, the industry's structure evolved to favour large, well-capitalized corporations. This scale-driven consolidation also shaped the geography of production: huge refineries or large coal mines became centralized hubs around which entire supply chains were organized. Governments often supported these large-scale ventures through direct subsidies or beneficial regulation, rationalizing that such facilities were vital national infrastructure. Consequently, the global fossil fuel market features a small number of dominant firms (see Wood et al., 2016) that can leverage their size to influence pricing, production, and technological directions.

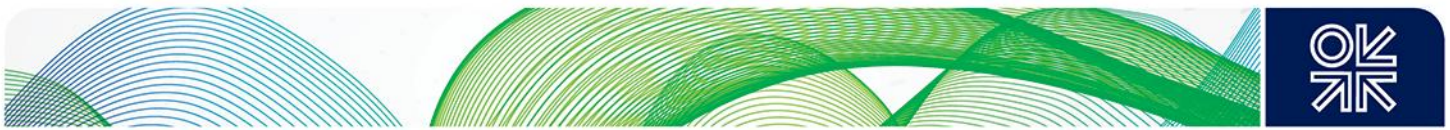
Alongside scale, vertical integration allowed firms to control multiple stages of the fossil fuel value chain, from exploration and extraction to refining and retail distribution. Owning or managing multiple links in the chain reduced uncertainty and transaction costs to some degrees: firms could secure consistent supply, manage refining capacity according to their own upstream output, and distribute to customers under a unified corporate strategy. This model became common in the oil sector in the last century when some of the major international oil companies owned oil fields, transport pipelines or tankers, refineries, and gas stations—enabling them to capture value at every step. However, vertical integration benefits are not linear and companies often pursued it up to the point where its benefit matched its costs as beyond the optimal point there might be inefficiencies associated with integration (Barrera-Rey, 1995)³

Horizontal integration, on the other hand, entailed acquiring or merging with competitors at the same stage of the value chain (e.g., an oil producer buying another oil producer) (for a discussion on some of major horizontal integrations in the late 1990s including that of Exxon-Mobil merger see Weston, 2002). This strategy boosted firms' market share, reduced direct competition, and often led to further cost advantages. The combination of economies of scale with both vertical and horizontal integration has fostered an oligopolistic market structure, especially in the oil industry. A small set of vertically integrated multinational corporations and major national oil companies (NOCs) collectively control a substantial share of global production, refining, and distribution. Oligopolies typically arise when industries demand large scale, heavy capital investment, and specialized technology, all of which limit the number of viable competitors. This structure gives incumbents considerable control over market outcomes, from pricing to supply decisions⁴.

Regulators have sometimes challenged these integrations on antitrust grounds (Archer, 1965), but in many cases, the strategic importance of fossil fuels prompted governments to permit or even facilitate such

³ It's important to note that the degree of vertical integration has evolved over time, with many major oil companies divesting certain retail operations or restructuring their business models in recent decades. Some companies have sold off gas station networks or separated their retail operations into different business units.

⁴ Some argue that during 1970s the industry transformed from an oligopoly controlled by international majors to a cartel with OPEC governments in control (see Al-Moneef, 1998). Although there are diverse views on the evolution of oil market structure and increase in the competition specifically with the rise of independent operators and oil field service companies (OFSCs), one factor remains constant: large players historically have controlled a substantial part of the industry



mergers. Many governments prefer to maintain and nurture large domestic "champions" that can project influence internationally and secure energy supplies. Hence, an oligopolistic industry structure is often tolerated, if not encouraged, for national security or economic reasons.

The Organization of the Petroleum Exporting Countries (OPEC) has historically attempted to influence oil prices by coordinating production quotas among member nations (Brémond et al., 2012). When successful, OPEC's collective actions can drive prices higher by restricting output. However, internal disagreements, cheating on quotas, and external factors like non-OPEC production can weaken its influence. Even so, OPEC's existence highlights the unique position of fossil fuels in global trade: a finite, strategic commodity that producers can (in theory) manage collectively to their economic advantage.⁵

Price volatility is another defining characteristic that has characterized the fossil fuel industry—especially oil—for much of its modern history. Supply disruptions due to geopolitical conflicts, sudden changes in demand driven by global economic cycles, and speculation in commodity markets all contribute to rapid and sometimes extreme swings in prices. For example, wars or political instability in major resource-rich regions (e.g., the Middle East) can restrict supply and cause price spikes. Conversely, global recessions can dampen demand, leading to price collapses. These fluctuations make the industry inherently risky for investors, governments, and consumers.

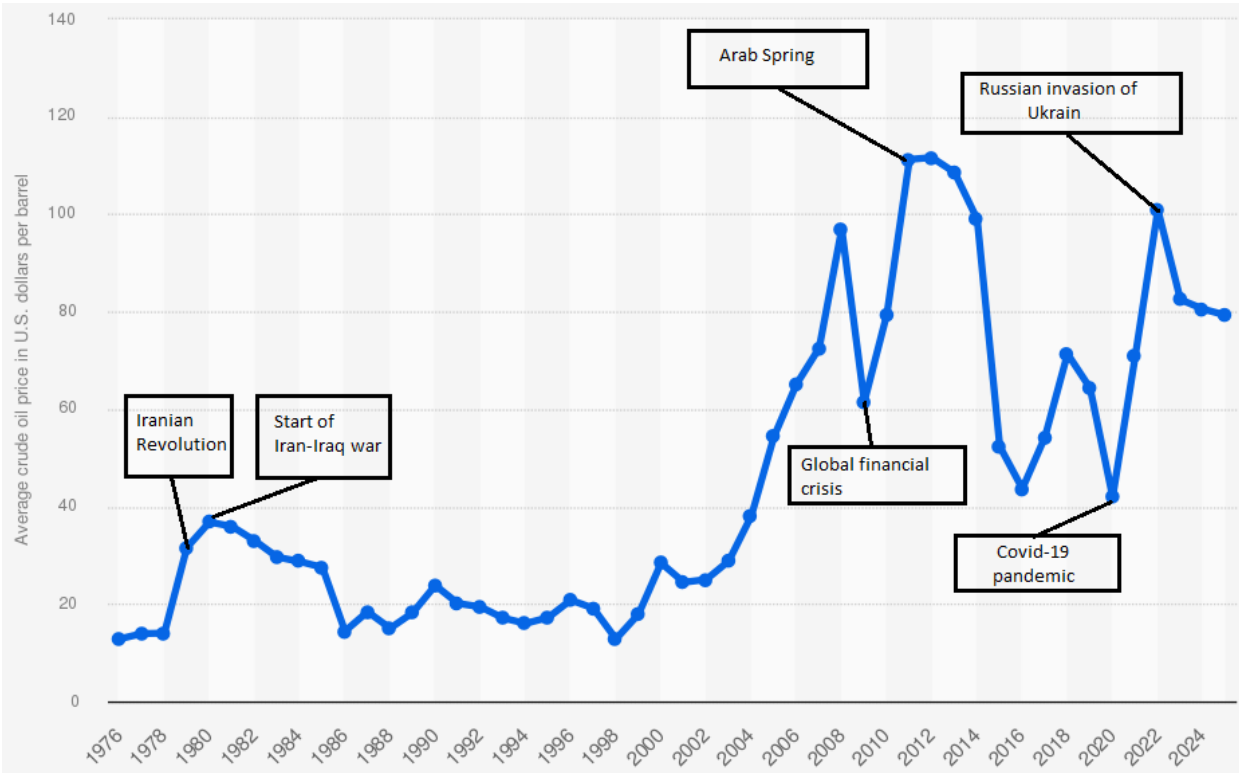
Volatile prices have had major structural implications. Producers often face boom-bust cycles, which influence their investment decisions in new capacity or exploration. When prices surge, firms ramp up exploration and development projects; when they crash, many of these initiatives are postponed or cancelled. Likewise, countries that depend on fossil fuel exports see their economies whipsawed by global price fluctuations, while import-dependent nations can face energy insecurity and inflationary pressures when fuel costs spike. Over decades, this volatility has prompted various mechanisms to stabilize prices or secure supply, including national petroleum reserves, long-term contracts, and hedging instruments.

Geopolitics and fossil fuels are deeply intertwined because resource distribution is geographically uneven. Large reserves concentrated in the Middle East, Russia, and North America have historically given these regions outsized political and economic leverage. For instance, oil supply disruptions can impact the entire global economy (through prices), as occurred during the 1973 oil crisis (Arab oil embargo), the 1979 Iranian revolution, and the 2022 Russian invasion of Ukraine and subsequent sanctions on Russia (a major oil and gas exporter) (see effect on oil prices in Figure 3). Consequently, ensuring access to fossil fuels has become a strategic priority for most industrialized nations. Some have pursued diplomatic ties, military interventions, or trade agreements to secure reliable energy imports. This geopolitical dimension often leads to government policies aimed at protecting domestic fossil fuel industries, whether through subsidies, trade barriers, or control of overseas reserves via state-owned enterprises. Fossil fuels thus serve as a form of economic and political currency, influencing foreign policy, alliances, and conflicts. In turn, the international significance of oil and gas has reinforced the central role of a few global players who can shape market dynamics by aligning with—or countering—the strategic interests of key producing or consuming nations.

⁵ While not all fossil fuel segments have an equivalent organization, the principle of collective action is often mirrored by large players coordinating informally or publicly through trade associations. Such behaviour has shaped price expectations and geopolitical alliances for decades, influencing everything from the cost of consumer gasoline to the viability of alternative energy investments.



Figure 3: Average annual Brent crude oil price from 1976 to 2025 (in U.S. dollars per barrel)

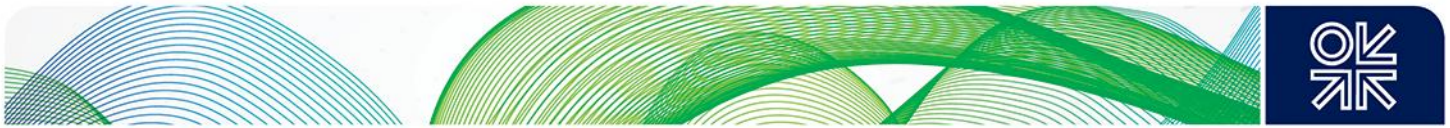


Source of data: Statista (2025)

Another crucial feature is the capital intensity of fossil fuel projects. Developing fossil fuel projects—mining coal, drilling for oil or gas, constructing refineries or pipelines—demands enormous upfront investment. First, these capital requirements impose high barriers to entry, discouraging smaller or underfunded firms from entering. As a result, only well-capitalized multinational firms or state-backed entities can typically bear the risks and scale of such ventures. Second, the capital-intensive character of the industry translates into significant sunk costs that tie companies' fortunes to long-term market and policy conditions. When prices plunge, these sunk investments become more difficult to recoup, intensifying the cycle of boom and bust (Avazkhodjaev et al. 2024).) Price volatility interacts with capital intensity to heighten investment risk: new projects can take years to become profitable, and an unfavourable price environment can undermine their viability (IEA, 2020).

In a similar way, fossil fuel projects typically have long lead time—from initial surveys and feasibility studies to construction and final production. This lag makes it hard for producers to respond quickly to shifts in demand or unexpected supply shocks. If an event raises oil demand, it might take years before new drilling programs or refineries can ramp up output in response. Conversely, if demand falls, ongoing projects cannot easily be scaled down quickly without incurring large costs (Kilian, 2009). These long lead times also shape how governments and companies plan their strategies. Investors require strong assurances of demand stability, or they may hesitate to deploy capital. Meanwhile, policymakers seeking energy security often encourage domestic development through subsidies or regulatory relief. Over the decades, this interplay between high capital intensity and long project timelines has contributed to more consolidated markets—large firms have the resources to weather downturns and to wait out extended investment horizons.

Like other sectors, technological innovation has long driven efficiency gains throughout the fossil fuel supply chain. Improved exploration techniques (like advanced seismic imaging) increase the accuracy of reserve

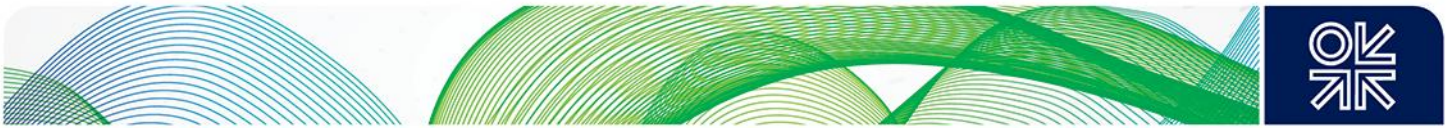


estimates, cutting down on wasted drilling (Sun et al., 2015). Enhanced extraction methods (directional drilling, secondary and tertiary oil recovery) boost output from aging fields, while better refining and combustion technologies heighten energy yields. These advancements lower the effective cost per unit of energy, extend the life of conventional resources and keep consumer prices lower than they might otherwise be under purely depletion-driven conditions. Furthermore, technological breakthroughs have also unlocked so-called "unconventional" resources, such as shale oil and gas, through hydraulic fracturing (fracking). This development significantly shifted global energy dynamics by expanding supply—particularly in the United States—and undermining previous scarcity concerns (Abas et al., 2015). The "shale revolution" exemplifies how innovation can rapidly reshape market power, turning an importer into an exporter and challenging traditional suppliers like OPEC nations.

On the regulatory side, the fossil fuel sector has seen diverse policy approaches depending on the jurisdiction. In some places (like many of the oil producing countries of the middle east and the US under the Trump administration), regulation is minimal, allowing for rapid development with fewer constraints on environmental impacts or safety standards. In others (like the European Union area), environmental laws, labour protections, and price controls can be stringent. However, when it comes to environmental regulation, there is a variation even among those countries that have adopted a net zero target. Only a few G20 nations have enacted laws to phase out specific fossil fuels (for example, Germany has set a coal phase-out target, France has banned new oil and gas exploration, Spain has committed to ending coal mining and power generation.) (Higham, and Koehl, 2021). Over time, as public concern about environmental pollution, accidents (e.g., oil spills) and other side effects of fossil fuel extraction grow, regulatory frameworks are expected to become more complex and comprehensive. Welsby et al. (2021) quantify the proportion of fossil fuel reserves that must remain unextracted to limit global warming to 1.5°C with a 50% probability. Their analysis estimates that by 2050, 58% of global oil reserves, 59% of fossil methane gas reserves, and 89% of coal reserves must remain in the ground to stay within the 1.5°C carbon budget. These figures represent a significant increase in unextractable reserves compared to previous 2°C scenarios, particularly for oil, where an additional 25% of reserves must remain unextracted. The required unextractable shares vary regionally, with Canada needing to leave 83% of its oil reserves untapped, largely due to its high-carbon oil sands, while Russia and the Former Soviet States (FSU) must keep 63% of their gas reserves unextracted. For coal, China and India must leave 76% unmined, reflecting the significant challenge of transitioning away from coal dependency. In the Middle East, 62% of oil reserves must remain unextracted by 2050, reducing to 38% by 2100, as post-2050 consumption shifts towards non-combustible feedstocks. These findings underscore the scale of fossil fuel production constraints required to meet international climate targets.

Finally, fossil fuel industries have historically benefited from a wide range of subsidies, both direct (e.g., tax holidays, reduced royalty rates, capital grants) and indirect (e.g., publicly funded infrastructure like roads or port facilities). Such subsidies have lowered production costs and boosted the profitability of fossil fuel enterprises, reinforcing their dominant position in national energy mixes. In 2023, global government support for fossil fuels amounted to USD 1.5 trillion, with subsidies comprising the largest share. Approximately USD 1 trillion was allocated to fossil fuel subsidies, covering consumer, producer, and general services support, many of which remained in place following energy price surges in 2021 and 2022 (IISD, 2024). Policymakers justify these measures by citing the need for energy affordability, security, job creation, and economic stability—objectives that aligned closely with post-industrialization growth strategies. However, critics argue that these subsidies distort true market costs by making fossil fuels appear cheaper than they actually are when considering externalities and long-term climate risks. The result is a lock-in effect, where economies become heavily dependent on coal, oil, and gas, postponing the transition to cleaner alternatives. Efforts to reduce or eliminate such subsidies often meet resistance from powerful industry lobbies and regions reliant on fossil fuel-related employment.

In conclusion, the fossil fuel sector, far beyond being shaped solely by resource scarcity, is a product of a confluence of powerful economic forces (a summary of these factors is presented in Figure 4). Economies



of scale, vertical and horizontal integration, price volatility, geopolitical significance, capital intensity, long project lead times, technological innovation, subsidies, and regulatory frameworks have all intertwined to create an industry characterized by concentrated market power, oligopolistic structures, and a complex relationship with governments worldwide. These features, developed over more than a century, explain not only the industry’s historical trajectory but also its current challenges and influence the pace at which greener energy solutions penetrate the market.

Figure 4: A summary of other economic features (beyond scarcity) of traditional energy industries



Source: author



3. New economics of energy

While energy transitions are not new phenomena in human history - from biomass to coal during the Industrial Revolution, to oil in the early 20th century, and later to nuclear power - the current transition to renewable energy represents a fundamentally different kind of transformation. Previous energy transitions were primarily additive, with new energy sources supplementing rather than replacing existing ones (Sovacool and Geels, 2016)⁶. Coal did not entirely displace biomass, and oil did not completely replace coal; instead, these new energy sources expanded the total energy mix, each finding its optimal use case while coexisting with previous sources.

The current transition to renewable energy, however, marks a decisive break from this historical pattern. For the first time, we are witnessing a transition driven not by the discovery of more concentrated energy sources or more efficient extraction methods, but by the emergence of energy technologies with fundamentally different economic properties (see Table 1). These new energy sources are not merely adding to the existing energy mix; they are actively displacing incumbent fossil fuels across multiple sectors. This displacement is occurring not merely because of environmental concerns or policy mandates (though these play a huge role), but also because the underlying economics of renewable energy systems - characterised by near-zero marginal costs, manufacturing-based learning curves, and positive network externalities - create an inherently different and more competitive economic paradigm. These developments have catalysed the emergence of a new energy economics whose properties differ substantially from the traditional, commodity-based systems grounded in coal, oil, and gas. In this new energy economics, abundance replaces scarcity as the defining characteristic, and technological innovation and manufacturing prowess, rather than resource control, determine competitive advantage.

Electrification lies at the heart of the emerging energy paradigm not merely as a decarbonisation pathway, but as the foundational vector through which the scale-based, technology-driven dynamics of the new energy economy are realised. Electrification enables a structural shift from high marginal cost, extraction-based systems to one in which energy services are delivered through manufactured technologies with near-zero marginal costs. This dramatically improves thermodynamic efficiency (e.g., heat pumps and electric vehicles outperform combustion-based systems) and enhances system integration (via smart grids and demand response). Moreover, while some hard-to-abate sectors face challenges for direct electrification due to process or energy density requirements (e.g., aviation, shipping, high-temperature industrial heat), the long-term decarbonisation of these sectors will also depend on low-cost, abundant electricity. Many of indirect pathways—such as green hydrogen, synthetic fuels, and electrochemical processes—rely fundamentally on renewable electricity as a feedstock.

Green hydrogen which is the cornerstone of many indirect pathways for decarbonisation directly consumes large amounts of electricity. This dependency extends directly to its derivatives as well. For instance, producing green ammonia (e-ammonia), vital for decarbonising fertilizer production and a potential shipping fuel, requires combining this energy-intensive green hydrogen with nitrogen, often using the Haber-Bosch process which itself is ideally powered or heated renewably. Similarly, synthetic liquid fuels (e-fuels) like e-kerosene, targeted at aviation, and synthetic methane (e-methane) or green methanol (e-methanol), potential solutions for shipping or leveraging existing gas infrastructure, all necessitate green hydrogen produced from electricity and further energy for their synthesis processes (like Fischer-Tropsch or methanation) which must also be clean. Beyond hydrogen-based routes, other key indirect strategies reinforce this reliance on electricity. Direct electrochemical synthesis, for example, aims to replace traditional fossil-fuel-driven chemical reactions with processes directly powered by renewable electricity.

⁶ Another important difference is that previous energy transitions were opportunity-driven but the current energy transition is problem-driven in response to climate change and thus require more direct government intervention through policies, regulations, and incentives to overcome market inertia and accelerate adoption (Sovacool and Geels, 2016).



Therefore, even for sectors where direct electrification of the final service faces hurdles, the viable decarbonisation solutions consistently point back to the fundamental need for abundant, low-cost, renewable electricity.

While pathways like Carbon Capture and Storage (CCS) applied to industrial or biomass sources, and the direct use of sustainable bioenergy for heat or advanced biofuels, offer decarbonisation options without necessarily relying on electrification for their core function, their overall share in future decarbonised energy systems is likely to be significantly smaller compared to electricity-reliant pathways. The fundamental constraints on the global availability of truly sustainable biomass and the geographical limitations and costs associated with geological storage for CCS cap their ultimate scale. As such, the central question for energy system design is not whether electrification can cover 100% of energy demand in all sectors immediately, but how to scale electricity generation and infrastructure rapidly enough to support both direct and indirect decarbonisation pathways. In this context, electrification should be viewed not only as a sectoral strategy but as the backbone of a post-scarcity energy economy that derives its transformative potential from technological learning, manufacturing scale, and systems-level integration.

This section outlines the core features of the new energy economics based on electrification and illustrates how they diverge from fossil-fuel-based models.



Table 1: Evolution of the economics of energy

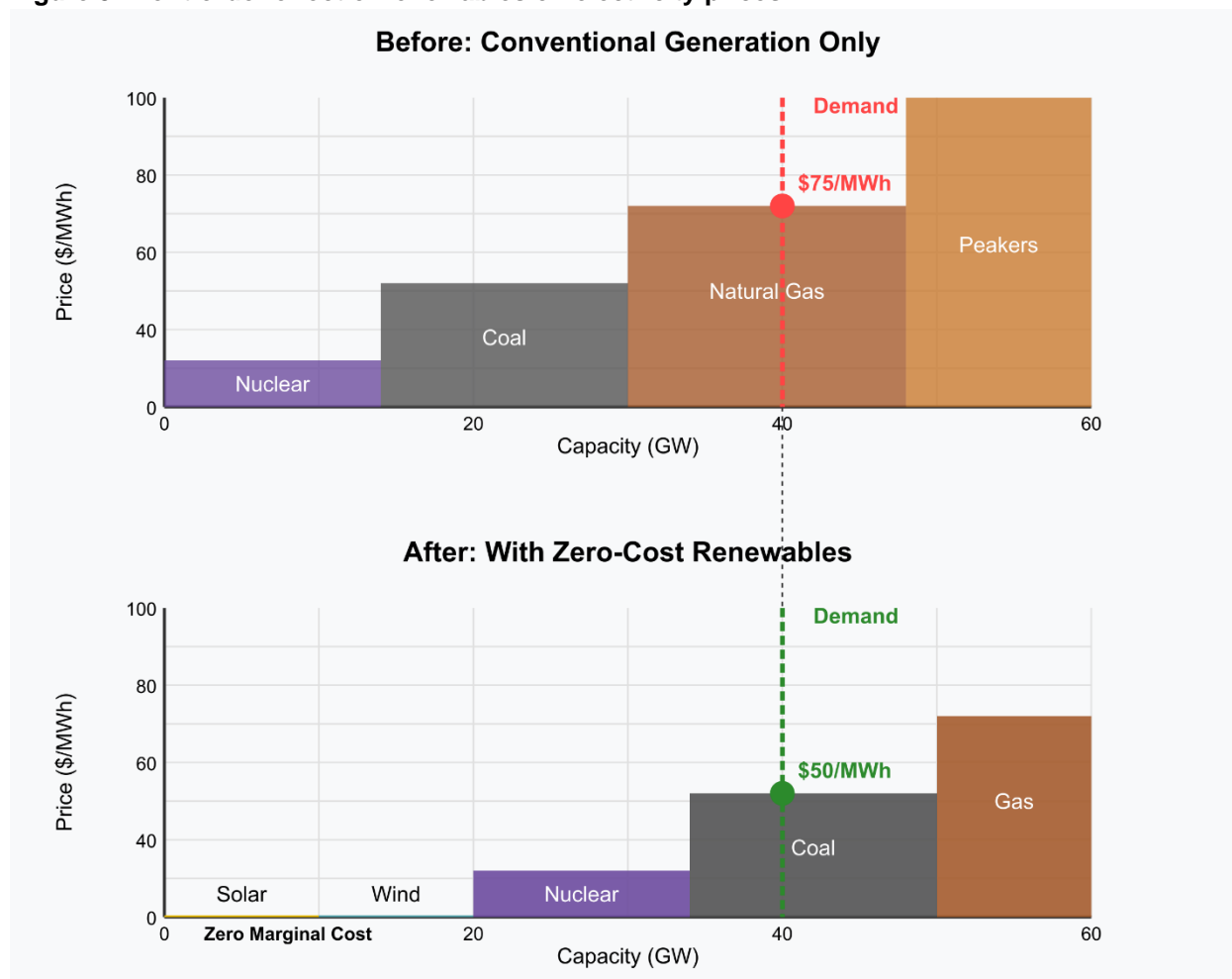
Era	Dominant Energy Source(s)	Key Economic Characteristics	Technological Drivers	Geopolitical/Social Impacts	Limitations/Challenges
Pre-industrial	Biomass (wood), Human/Animal Power, Water/Wind (local)	Subsistence-based, low energy surplus, high labour costs, localized markets, scarcity-driven economics.	Simple tools, water wheels, windmills.	Localized trade, agrarian economies, minimal energy exports.	Energy scarcity limited scalability and economic growth.
Coal-powered Industrial Revolution	Coal	Extraction-based, economies of scale in production, high marginal costs, commodity pricing, rising capital intensity.	Steam engine, railroads, mechanized factories.	Global coal trade emerged, urbanisation fuelled demand, colonial resource competition.	Resource depletion raised costs, market volatility from supply shocks.
Oil Age	Oil, Natural Gas	Extraction-based, high-energy density, vertical integration, global commodity markets, significant marginal costs, scarcity premium.	Internal combustion engine, pipelines, advanced refining.	Oil-driven globalization, geopolitical resource conflicts, energy-dependent trade networks.	Price volatility, geopolitical risks, depletion-driven cost increases.
Nuclear Era	Nuclear (uranium)	High upfront capital costs, low marginal costs, state-subsidized economics, limited scalability, risk-adjusted pricing.	Nuclear fission reactors, grid-scale power plants.	Energy mix diversification, Cold War energy security focus, limited trade impact.	Capital intensity, regulatory costs, waste management expenses.
Renewable Energy Transition	Solar, Wind, Batteries, Green Hydrogen	Manufacturing-based, near-zero marginal costs, high CAPEX/low OPEX, learning curve cost declines, abundance-driven economics.	Solar PV, wind turbines, batteries, smart grids.	Energy independence, decentralized markets, reduced fossil fuel trade reliance.	Intermittency costs, critical mineral supply risks, high initial capital needs.

Source: author

3.1 Key properties of the new paradigm

One of the most fundamental features of new energy systems, and a key departure from the fossil fuel paradigm, is the near-zero marginal cost of generation. Unlike fossil fuels, where each unit of energy produced requires the consumption of a finite, priced fuel, the marginal cost of generating electricity from wind and solar is virtually zero. Once the infrastructure (solar panels or wind turbines) is in place, the "fuel" - sunlight and wind - is freely available. This fundamentally alters pricing dynamics in electricity markets, with renewables often displacing fossil fuels and driving down wholesale prices during periods of high renewable output (see Figure 5), inverting the traditional supply-demand relationship.

Figure 5: Merit order effect of renewables on electricity prices



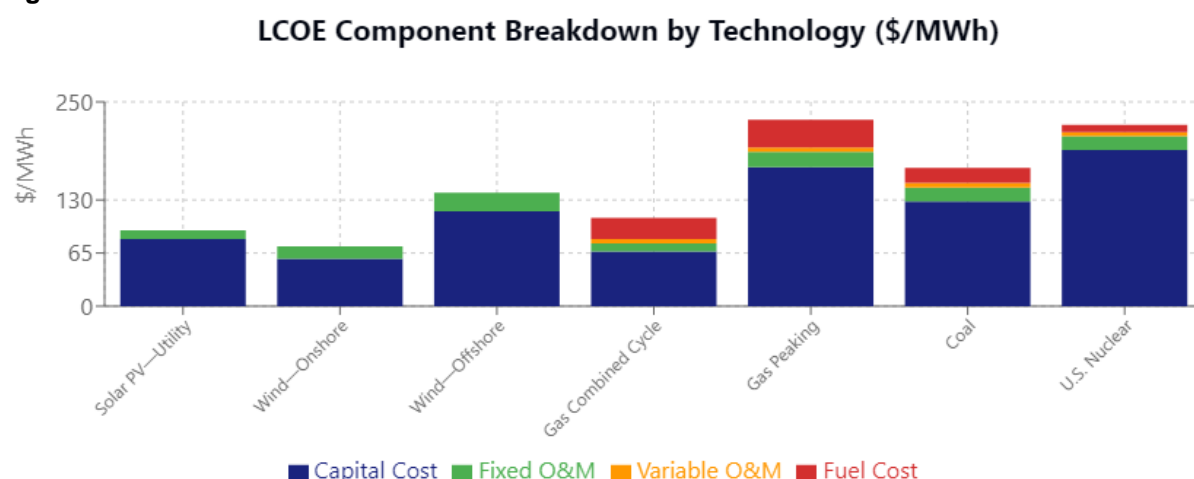
Source: author

This shift to near-zero marginal cost is intrinsically linked to another defining characteristic: the dominance of upfront capital costs. While the ongoing cost of "fuel" is negligible, the dominant cost in renewable energy is the initial capital expenditure (CAPEX) for manufacturing and installing the equipment. Operating expenses (OPEX), primarily maintenance, are comparatively low. This high CAPEX/low OPEX structure creates a need for substantial upfront financing, making the levelized cost of energy (LCOE) highly sensitive to the cost of capital (interest rates) and the equipment's lifespan. However, once operational, this structure also translates to relatively low-risk, long-term returns, attracting institutional investors seeking stable cash flows, a profile very different from the volatile returns of fossil fuel investments.

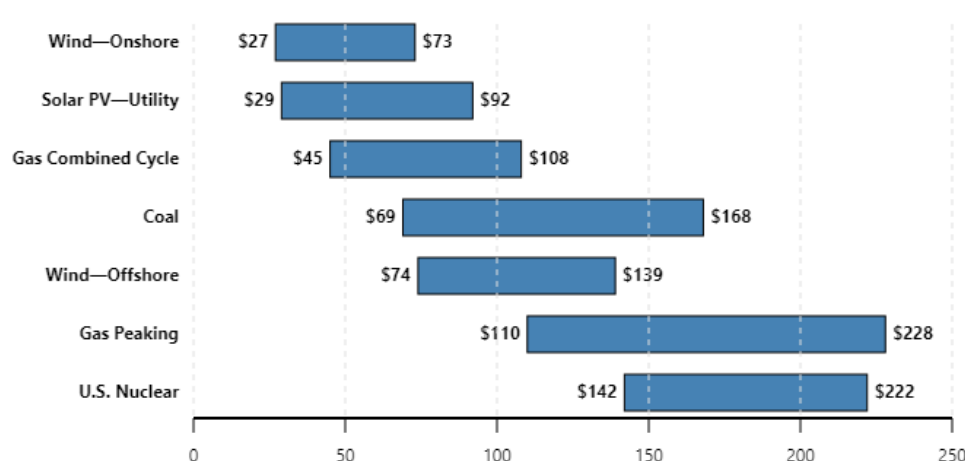


As shown in Figure 6, capital expenditures constitute 79–89% of total costs for renewable facilities—specifically 86–89% for utility-scale solar PV, 81–79% for onshore wind, and 84–83% for offshore wind—contrasting sharply with conventional generation, where capital costs represent a smaller proportion of the overall LCOE. Gas combined cycle facilities exhibit the most balanced cost profile, with capital expenditures accounting for 40–62% of costs and fuel expenses representing 24–51%, while coal and nuclear plants demonstrate intermediate profiles with capital costs constituting 70–76% and 80–86% of total expenses, respectively. This structural difference illustrates a fundamental economic reality: renewable energy technologies transform traditionally variable electricity costs into fixed costs, effectively frontloading expenditures and eliminating exposure to fuel price volatility.

Figure 6: The cost breakdown of LCOE of renewables versus conventional resources

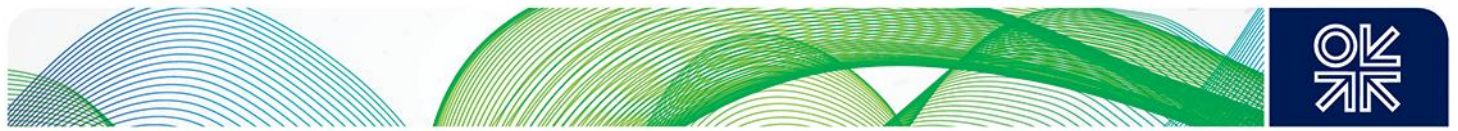


LCOE Ranges by Technology (\$/MWh)



Source of data: Lazard (2024)

Furthermore, the geographical constraints that define fossil fuel production are largely absent in the renewable energy landscape (IRENA, 2019). Renewable energy can be generated wherever suitable climatic conditions exist, drastically reducing the geopolitical risks and transportation costs associated with geographically concentrated fossil fuel reserves. While renewable resources are more widely distributed than fossil fuels, it is important to recognise that solar irradiation and wind resources are still unevenly distributed across regions. Some areas benefit from exceptional solar irradiation (such as the Sahara, Arabian Peninsula, and Australian Outback), consistent wind patterns (coastal regions, the



North Sea, and certain mountain passes), or both. These natural endowment disparities create varying potential for renewable generation and can influence capacity factors, which directly impact project economics and competitiveness. However, unlike fossil fuels where resource absence means complete dependency, even less-endowed regions typically have sufficient renewable resources to meet a significant portion of their energy needs, especially when combining multiple renewable sources and interconnection strategies. Furthermore, these geographic variations in resource quality do not recreate the stark geopolitical vulnerabilities associated with fossil fuel dependency, as they represent differences in economic efficiency rather than binary access to the resource itself.

This distributed nature of renewable resources, in turn, feeds into the increasing value of interconnected systems. The value of renewable energy systems increases with geographic diversity and interconnection, as this diversification smooths out the intermittency inherent in wind and solar resources. This creates positive network externalities, driving investment in transmission infrastructure and smart grid technologies, fostering a more resilient and integrated energy system.

Crucially, the locus of economic advantage shifts dramatically in this new paradigm. Unlike fossil fuels, where economies of scale are traditionally found in extraction, transportation, and refining, renewable energy exhibits economies of scale in the manufacturing of equipment. Larger factories producing solar panels or wind turbines achieve lower per-unit costs. This drives a trend towards larger manufacturing facilities, consolidation in the manufacturing sector, and, most importantly, rapid cost reductions as production volumes increase. This enables rapid international technology transfer and competition, a stark contrast to the location-bound, resource-extraction-based model of fossil fuels.

This manufacturing-driven cost reduction is further amplified by the phenomenon of learning curves. The cost of renewable energy technologies has declined dramatically over time, following predictable "learning curves." For every doubling of cumulative production, costs tend to fall by a consistent percentage. This represents a fundamental departure from the traditional Hotelling model of resource economics, where resource depletion is expected to increase costs over time. These cost reductions (albeit not unboundedly), which apply not just to core technologies like solar cells and wind turbine blades but also to "balance of system" components and installation processes, are a key driver of renewables' increasing competitiveness.

Overall, the new energy economics is characterised by deflationary cost trajectories, spatial democratisation, and manufacturing-driven scalability - a stark departure from the volatile, extraction-based model of fossil fuels. While challenges like intermittency, securing supply chains for critical minerals, and adapting market design persist, the structural advantages of renewables suggest an irreversible shift. This paradigm rewards innovation, manufacturing and tech leadership, rather than resource control, ushering in an era of energy abundance and fundamentally reshaping the global energy landscape.

3.2 The learning curve model

The concept of the learning curve (sometimes called the "Wright's curve") is most often traced back to T. P. Wright's 1936 paper, "Factors Affecting the Cost of Airplanes". Wright noticed that as the total number of airplanes produced doubled, the labour hours required per airplane declined at a relatively constant rate (see Wright, 1936). This relationship was formalized in what he called the "progress function" or "learning curve."⁷

In the 1960s and 1970s, the Boston Consulting Group (BCG) popularised a related concept they called the experience curve (BCG, 1973). While Wright had focused primarily on labour costs, BCG extended the idea to include all costs—labour, materials, overhead, etc.—observing that the total unit cost often

⁷ It's important to note that the idea of learning by doing predates Wright. Observations of improved efficiency with repetition existed in various industries. However, Wright was the first to quantify this relationship in a systematic and mathematical way within a specific industrial context.



drops by a constant percentage for every cumulative doubling of output. Over time, economists and management theorists have generalised these findings into “learning-by-doing” models, emphasizing that incremental improvements, process streamlining, and knowledge spillovers result in systematic cost declines as production expands.

The learning curve model captures how cumulative installed capacity (a proxy for “experience”) drives down costs through technological innovation, manufacturing efficiency, and supply-chain optimization. While called a “learning” curve, the model implicitly includes economies of scale, R &D breakthroughs, process innovations, and supply chain efficiencies, all of which help drive costs lower as production grows. This holistic perspective is especially useful for capturing the complexity in emerging technologies like solar PV modules, wind turbine, electrolyzers or battery storage.

While powerful, the learning curve model has limitations. It’s a simplified model that doesn’t capture all factors affecting cost reduction such as raw material price fluctuations or policy changes. Also, there may be limits to learning. At some point, cost reductions may slow down as the technology matures and further improvements become more difficult and expensive to achieve. Despite its limitations (e.g., ignoring external factors like material price volatility), the model’s empirical simplicity makes it a robust heuristic for analysing renewable energy technologies economics.

To show the way learning curve explains the cost evolution of the renewable energy technologies and analyse its implications, we use the following simple model:

Let $p(Q)$ be the (inverse) demand function for the technology (e.g., solar panels, wind turbines, batteries) at quantity Q . For simplicity we can assume p is constant or downward sloping.

Let $X(t)$ be the cumulative production of this technology up to time t . The per-unit manufacturing cost $c(X(t))$ declines as $X(t)$ increases, reflecting learning effects and economies of scale. We assume the learning has the following functional form:

$$c(X(t)) = c_0 \left(\frac{X(t)}{X_0} \right)^{-\alpha}$$

where $\alpha > 0$ measures the strength of learning, c_0 is an initial cost level, and X_0 a reference scale.

Let’s assume the dynamics of production are as follows:

$$\dot{X}(t) = Q(t), \quad X(0) = X_0$$

That is, cumulative production grows at the rate you produce new units.

A representative firm (or a group of competitive firms) maximises the present value of profit:

$$\max_{\{Q(t)\}} \int_0^{\infty} e^{-rt} [p(Q(t)) - c(X(t))] Q(t) dt$$

subject to

$$\dot{X}(t) = Q(t)$$

Here, $r > 0$ is the discount rate.

Using the Pontryagin Maximum Principle, we can define the current-value Hamiltonian:

$$\mathcal{H} = \underbrace{[p(Q) - c(X)]Q}_{\text{instant profit}} + \lambda(t) \underbrace{Q}_{\dot{X}}$$

where $\lambda(t)$ is the shadow price of increasing $X(t)$ (i.e., the value of experience or know-how).

Costate Equation

In a learning-by-doing framework:



$$\dot{\lambda}(t) = r\lambda(t) - \frac{\partial \mathcal{H}}{\partial X} = r\lambda(t) + \underbrace{\frac{C'(X)Q(t)}{\text{since } C'(X) < 0,}}_{\text{this term is typically negative}}$$

First-Order Optimality (w.r.t. $Q(t)$)

If the firm faces a competitive market with price $p(Q)$ as given, we get:

$$p(Q(t)) - c(X(t)) + \lambda(t) = 0$$

That is, the firm sets net revenue + shadow price of learning = 0, balancing immediate profit and the "externality" of accelerating cost declines.

Interpreting $\lambda(t)$

$\lambda(t)$ represents the marginal long-run benefit (present value) of having produced one more unit at time t —because it lowers future production costs by increasing cumulative experience. If $\lambda(t)$ is large (in absolute value), it means there's significant future cost-reduction gain from ramping production now.

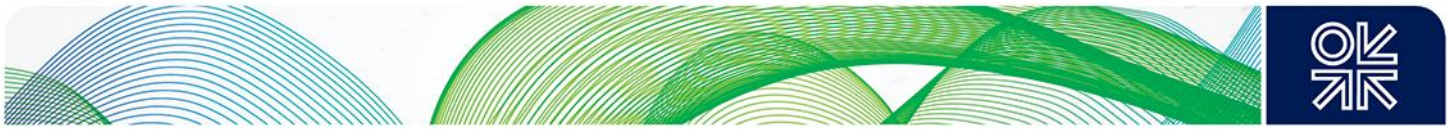
Both the Hotelling model and the learning curve model address dynamic, intertemporal decision-making, where producers choose how to allocate production across time to maximize the present value of profits (see Table 2). In the Hotelling framework, scarcity of a finite resource governs production rates: the resource owner trades off extracting today versus waiting for higher future net prices, subject to depletion constraints. In the learning curve model, the driver is technological improvement: producing more today lowers future costs by accumulating manufacturing experience. Despite these different mechanisms, both models share an optimal control structure in which agents balance current versus future payoffs while facing a state variable that evolves over time (the stock of resources in Hotelling, the cumulative production in the learning curve).

Table 2: Comparison of Hotelling's rule and the learning curve model

Aspect	Hotelling's Rule	Learning-Curve Model
Resource	Finite, exhaustible (oil, gas, etc.)	Essentially infinite, "fuel is free" (sun, wind)
Key Driver	Scarcity rent \uparrow	Learning-by-doing cost \downarrow
Net Price / Cost	$p - c$ rises at rate r	$c(X)$ falls with cumulative output
Shadow Value	$\lambda(t)$ of the in-ground unit	$\lambda(t)$ of "experience" gained
Intuition	Balance extraction now vs. leaving it in the ground for future higher prices	Balance producing now (to reduce future costs) vs. waiting until costs are naturally lower anyway

The crucial difference is the direction of pressure on net margins. In Hotelling's model, the net price ($p - c$) rises at the rate of interest because of increasing scarcity rents. This incentivizes owners to stagger extraction, so they capture the highest possible price in the future. By contrast, the learning curve model features falling costs with greater cumulative production, encouraging firms to ramp up output early in order to realize faster cost declines. Thus, while Hotelling's Rule reflects a growing scarcity rent for non-renewable resources, the learning curve model highlights a self-reinforcing cost advantage for those who invest rapidly.

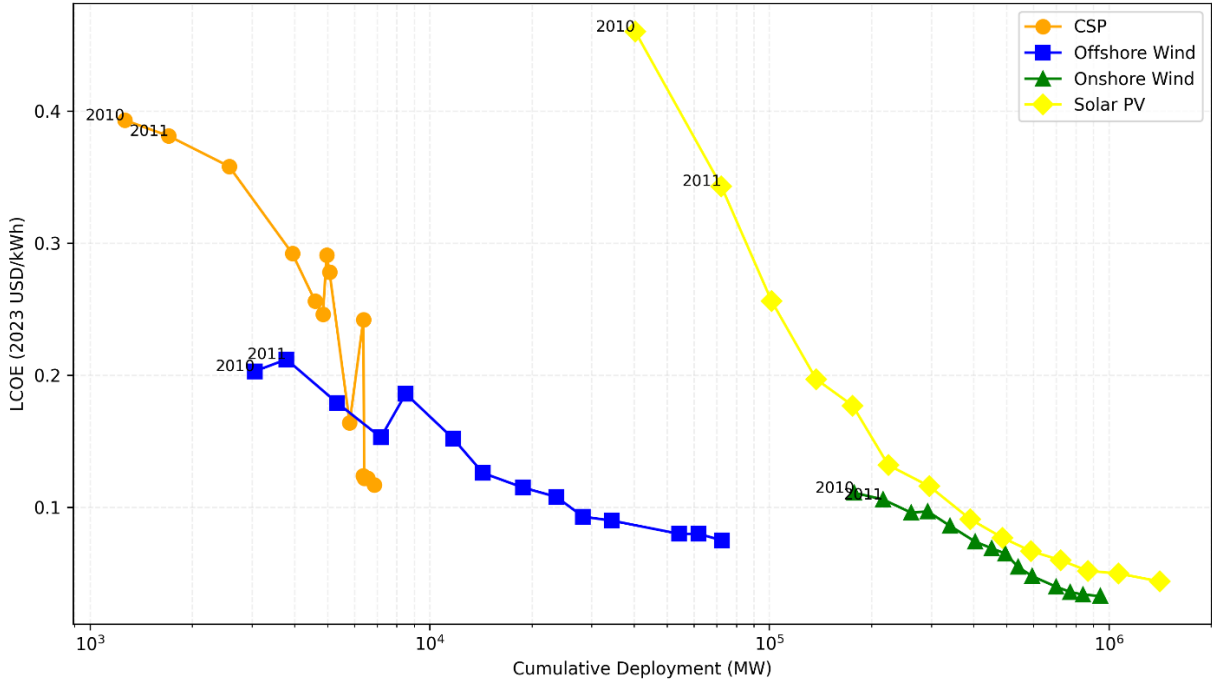
This provides insights into the contrasting economic logics of resource-based markets versus technology-based ones. In a resource-extraction setting, the location and finiteness of reserves confer long-run pricing power to those who defer extraction for higher rents. In technology manufacturing, continuous cost reductions via learning-by-doing push producers to scale aggressively, as early investment secures a persistent cost lead. From a policy perspective, this underscores why carbon-constrained economies shift from fossil scarcity models to clean-tech industrial strategies, where mastering the learning curve—often aided by subsidies or other support—becomes the key to long-term competitiveness.



3.2.1 Empirical evidence of the learning curve

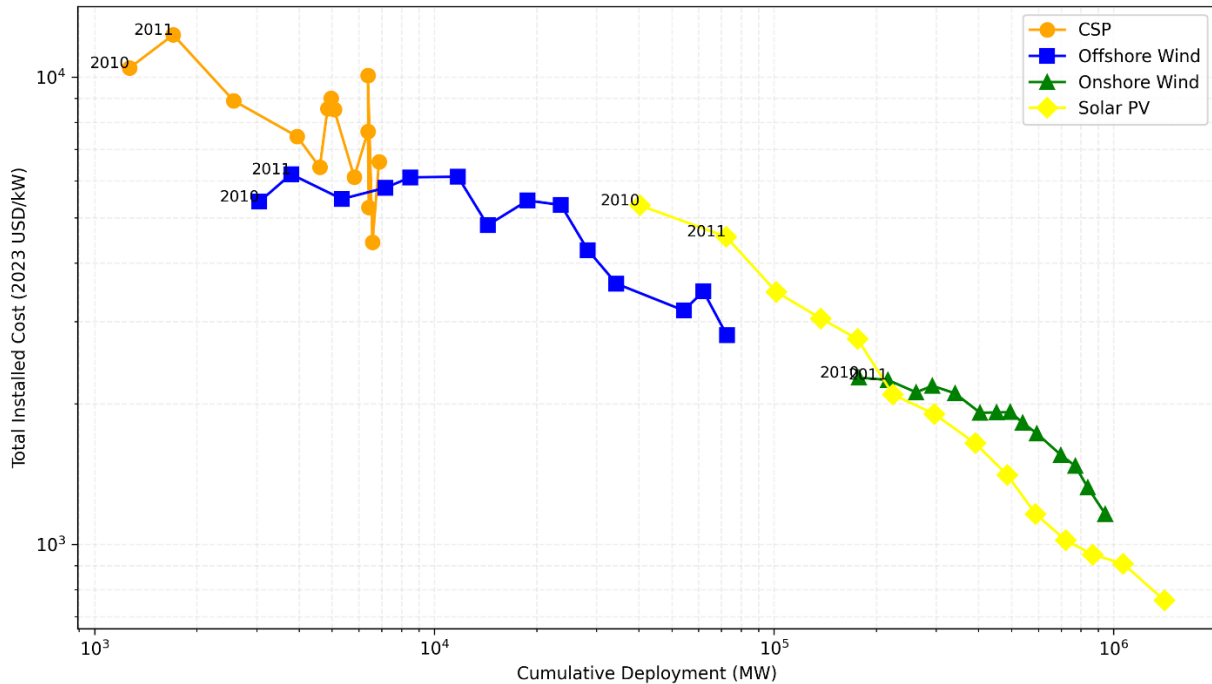
Empirical data on the cost and performance of solar, onshore wind, and offshore wind attests to the presence of technological learning curves in the renewable energy sector. The technological progress and market expansion of solar and wind have driven a remarkable decline in both capital expenditures and levelised cost of electricity (LCOE) (see Figures 7 and 8).

Figure 7: LCOE Learning Curve (2010–2023)



Source of data: IRENA (2024)

Figure 8: Total Installed Cost Learning Curve (2010–2023)



Source of data: IRENA (2024)



We use data in IRENA (2014)⁸ and the model presented in the previous section to estimate the learning parameters and learning rates for offshore wind, onshore wind, solar PV and concentrated solar power (CSP). These were estimated using a log-linear regression model based on the learning curve framework developed above (for details of approach see Appendix B). For each technology, we regressed the natural logarithm of cost, $\ln c(t)$, on the natural logarithm of cumulative deployment, $\ln X(t)$, with the slope providing the estimate for $-\alpha$.

The learning rate was calculated using the formula:

$$LR = 1 - 2^{-\alpha}$$

The results are provided in Table 3.

Table 3: Learning Parameters and Learning Rates for Different Technologies

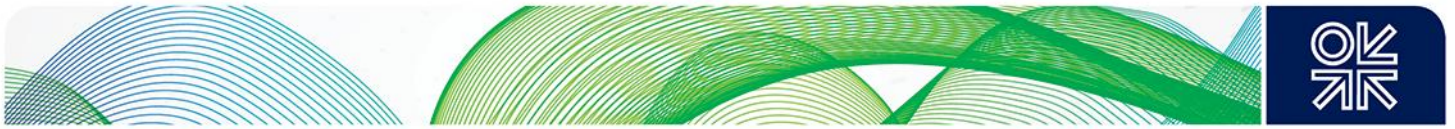
Technology	Learning Parameter (α)	Learning Rate (LR)
Concentrated Solar Power (CSP)	0.15	10.0%
Offshore Wind	0.22	14.9%
Onshore Wind	0.18	12.0%
Solar Photovoltaic (PV)	0.32	20.9%

Solar PV exhibits the strongest learning effect among the technologies analysed. For every doubling of cumulative deployment, the cost decreases by approximately 20.9%. This high learning rate is driven by modular technology, global manufacturing scale, and continuous innovation. The rapid cost reductions (from 5,310 USD/kW in 2010 to 757 USD/kW in 2023) reflect the significant benefits of cumulative experience in this sector. The rationale for aggressive deployment lies in these outsized future benefits: even if initial investments are costly, the rapid decline in expenses over time outweighs upfront expenditures. Policymakers and investors are thus incentivized to prioritize early and large-scale adoption, leveraging subsidies or incentives to overcome financial barriers, as the economic payoff from sustained deployment is both substantial and strategically critical for the renewable energy transition.

Offshore wind shows a moderate learning effect, with a 14.9% cost reduction for each doubling of cumulative deployment. Although the learning rate is lower than that of solar PV, it indicates accelerating cost declines as deployment increases. This suggests that offshore wind is an emerging technology with growing potential for cost competitiveness, especially as global deployment ramps up. The learning curve model suggests that increased production drives iterative improvements—such as optimized panel designs in Solar PV or larger, more efficient turbines in Offshore Wind—shrinking per-unit costs with each capacity milestone. This virtuous cycle means that the faster these technologies are rolled out, the sooner they reach price parity with fossil fuels, a pivotal factor in displacing carbon-intensive energy systems.

Onshore wind, a more mature technology, has a learning rate of 12.0%. While lower than solar PV and offshore wind, this still reflects steady cost reductions due to significant cumulative deployment. The technology benefits from economies of scale and incremental innovations, but its learning rate suggests diminishing returns as it approaches maturity. This suggests that further large-scale deployment is unlikely to unlock significant savings, as the technology has already reaped much of its learning curve benefits. Instead, efforts should centre on enhancing existing installations—through improved maintenance, turbine upgrades, or integration with storage solutions—to maximize efficiency and output. Incremental innovations, such as advanced materials or refined aerodynamics, can also sustain competitiveness without relying on the sheer volume of deployment.

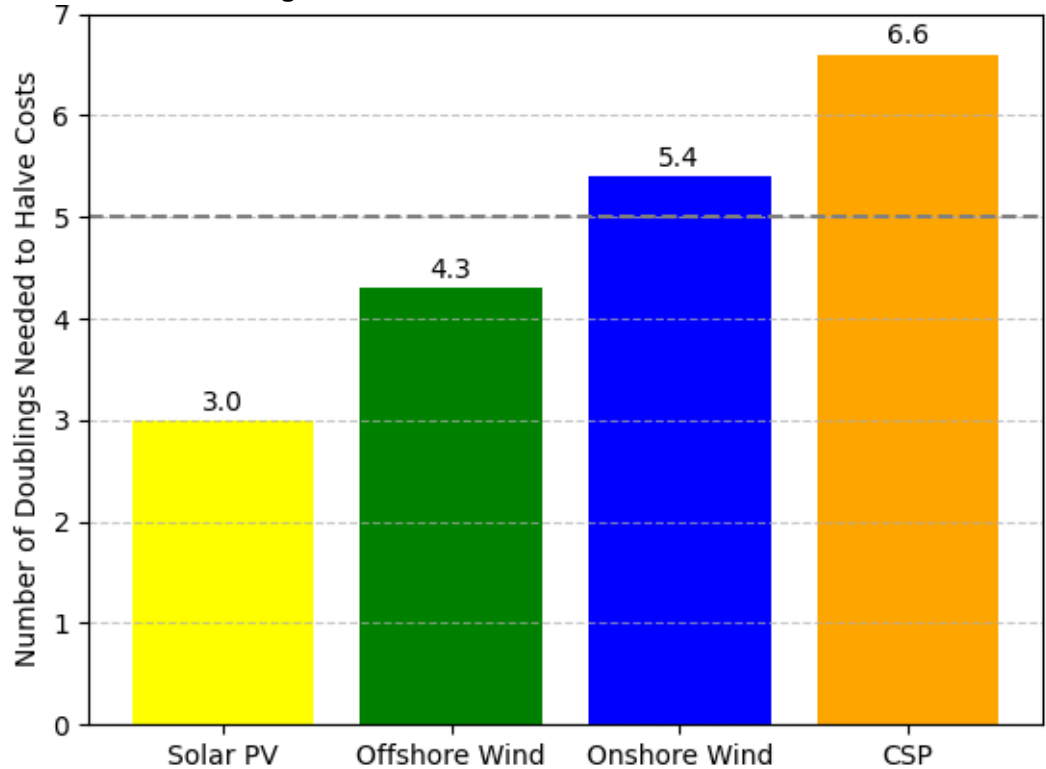
⁸ Data from IRENA (2024) capture annual, global weighted-average metrics for key renewable power technologies—specifically solar PV, onshore wind, and offshore wind—over the 2010–2023 period. They include total installed costs, measured in USD per kilowatt (USD/kW); levelised cost of electricity (LCOE), measured in USD per kilowatt-hour (USD/kWh); and capacity factors, expressed in percentage terms for newly commissioned capacity in each year.



CSP has the weakest learning effect, with only a 10.0% cost reduction per doubling of cumulative deployment. The volatile cost data (e.g., peaks in 2011 and 2021) and limited deployment suggest that CSP faces challenges such as technological complexity, project-specific factors, and lack of scale. This weak learning effect indicates that cost reductions may be harder to achieve without targeted interventions. CSP’s shallow learning curve stems from its complexity, limited scalability, and site-specific requirements, which hinder the rapid cost declines seen in Solar PV or Offshore Wind. Simply increasing installed capacity is unlikely to bridge the cost gap with other renewables or fossil fuels, as each project yields only marginal learning benefits. Instead, targeted R&D investments—aimed at improving thermal storage, mirror efficiency, or reducing construction costs—offer a pathway to unlock breakthroughs that deployment alone cannot achieve.

Figure 9 illustrates the efficiency of cost reduction per deployment increase. Solar PV emerges as the most responsive, requiring only 3.0 doublings of cumulative deployment to halve its costs, a testament to its steep learning curve and responsiveness to economies of scale. In contrast, CSP lags significantly, needing 6.6 doublings to achieve the same 50% cost reduction, indicating a shallower trajectory that limits its ability to translate increased deployment into substantial savings. Offshore Wind and Onshore Wind fall in between, with 4.3 and 5.4 doublings, respectively, reflecting moderate scalability.

Figure 9: Number of Doublings Needed to Halve Costs



Source: Author’s own analysis

The contrasting learning rates of renewable energy technologies demand tailored deployment strategies to optimize cost reductions and competitiveness. High-learning-rate technologies like Solar PV and Offshore Wind thrive under aggressive deployment, where rapid scaling accelerates cost declines and delivers substantial long-term gains, justifying initial investments. Conversely, low-learning-rate technologies such as Onshore Wind and CSP require a shift away from volume-driven approaches: Onshore Wind benefits from optimization of existing assets, while CSP demands innovative R&D.

3.2.2 The role of government subsidies

Government incentives, such as subsidies, tax credits, or guaranteed markets (e.g., feed-in tariffs), play a pivotal role in a learning-curve model for technology and manufacturing. A key question is that why governments subsidise new technologies. There are at least two important reasons.

First, the government aims to correct for positive externalities. The core idea is that learning-by-doing in new technologies (e.g., solar, batteries, wind) often generates positive externalities: as one firm scales up production, it lowers costs not just for itself, but often for other firms and future market entrants via knowledge spillovers, supply-chain efficiencies, and shared R&D breakthroughs. In a pure market setting, a single firm captures only the private benefits of its learning. But in reality, some of that knowledge or supply-chain improvement “spills over” to other producers or the broader industry. Because each firm thus under-invests in scaling up (they can’t capture all the returns), government incentives internalize part of that “public” benefit—effectively rewarding firms for accelerating industry-wide cost declines. Similarly, early-stage R&D often yields widely shared insights. Public funding or tax credits can encourage a higher level of R&D than firms would invest in on their own.

Second, by subsidizing production or deployment (e.g., solar feed-in tariffs, EV tax credits), governments create demand that speeds up cumulative output $X(t)$. As $X(t)$ ramps up faster, learning-by-doing occurs more quickly, pushing down the cost curve earlier than it might have in a purely private market. This helps the technology cross the “valley of death” (where costs are high and volumes are low) and reach a scale at which it becomes competitive without subsidies. When new technologies are initially expensive, someone must buy them to get the production learning started. Governments can act as first movers (public procurement) or stimulate private demand via subsidies.

To see how subsidies affect production and learning we use a simple model. Suppose the firm receives a constant price p per unit from the market (for simplicity). On top of that, the government provides a per-unit subsidy s . Therefore, total revenue per unit is $[p + s]$.

The firm chooses $Q(t)$ to maximize the present value of profits:

$$\max_{Q(t)} \int_0^{\infty} e^{-rt} \left[\underbrace{p + s}_{\text{revenue per unit}} - \underbrace{c(X(t))}_{\text{cost per unit}} \right] Q(t) dt$$

subject to $\dot{X}(t) = Q(t)$ and $X(0) = X_0$.

In current-value form, we write the Hamiltonian:

$$\mathcal{H}(Q, X, \lambda) = [(p + s) - c(X)] Q + \lambda(t) Q$$

where:

$[(p + s) - c(X)] Q$ is the instant (current-value) profit at time t ,

$\lambda(t)$ is the shadow price (costate) associated with $X(t)$,

$\dot{X}(t) = Q(t)$ appears as $\lambda(t) Q$ in the Hamiltonian (the “plus” sign is used because $\dot{X} = +Q$).

First-Order Condition (Optimality wrt Q)

We take the partial derivative of \mathcal{H} with respect to Q and set it to zero:

$$\frac{\partial \mathcal{H}}{\partial Q} = [(p + s) - c(X)] + \lambda(t) = 0$$

Hence,

$$\lambda(t) = c(X(t)) - [p + s]$$



This means in equilibrium, the shadow price of increasing cumulative production ($\lambda(t)$) equals (the negative of) the firm's net margin (price plus subsidy minus cost). If the margin is large, $\lambda(t)$ becomes negative, meaning the firm finds it profitable to expand $X(t)$ (since we will see in the costate equation how $\lambda(t)$ evolves)⁹.

Costate Equation

In current-value form, the costate equation is:

$$\dot{\lambda}(t) = r \lambda(t) - \frac{\partial \mathcal{H}}{\partial X}$$

We have:

$$\frac{\partial \mathcal{H}}{\partial X} = \frac{\partial}{\partial X} [(p + s) - c(X)] Q + \lambda(t) \frac{\partial Q}{\partial X}$$

Since Q is the control variable (independent of X in the partial-derivative sense), $\frac{\partial Q}{\partial X} = 0$. Also, $\frac{\partial}{\partial X} [(p + s) - c(X)] = -c'(X)$. Thus,

$$\frac{\partial \mathcal{H}}{\partial X} = -c'(X) Q(t)$$

So,

$$\dot{\lambda}(t) = r \lambda(t) + c'(X) Q(t)$$

(Recall $c'(X)$ is typically negative because c is a decreasing function of X .)

From an economic perspective, because the firm's instantaneous profit is $[p + s - c(X)]Q$ instead of $[p - c(X)]Q$, which is the case without subsidy, it has a higher net margin. This incentivises larger $Q(t)$ earlier to accumulate experience (increase $X(t)$) and push down costs more rapidly.

We have $\lambda(t) = c(X) - [p + s]$ from the first-order condition. If $p + s > c(X)$, the net margin is positive, implying $\lambda(t) < 0$. This typically indicates strong incentives to expand production quickly (the "learning externality" can be beneficial in a broader sense).

Although real-world subsidies (e.g., FiTs, CfDs) typically go to the energy producer (the wind/solar farm operator), the economic mechanism still spurs manufacturing scale and accelerates cost declines. In the simplified learning-curve model (where we wrote $[p + s - c(X)]Q$), we can think of $p + s$ as the effective price perceived by manufacturer. The way this works is as follows. The incentives provided to generators elevate the effective demand for solar panels or wind turbines, because project developers can more profitably deploy them. This higher and more secure demand, in turn, spurs manufacturers to scale up production, thereby reaping the same cost reductions posited in the theoretical model. From the manufacturer's perspective, it's almost as if they face a higher effective market price—because the generator's willingness to pay for turbines or panels is higher when they can secure guaranteed revenue streams from feed-in tariffs or CfDs¹⁰.

⁹ In the learning curve model, a large margin (price plus subsidy minus cost) implies high immediate profitability, and since producing more today increases cumulative output $X(t)$, it reduces future unit costs through learning-by-doing. The shadow price $\lambda(t)$, which reflects the marginal value of expanding $X(t)$, becomes negative—signalling that ramping up production yields long-term benefits by lowering future costs. This contrasts with the Hotelling model of exhaustible resources, where the shadow price $\lambda(t)$ is positive and rising over time, reflecting increasing scarcity. In Hotelling, extracting today carries an opportunity cost (forfeiting higher future value), whereas in the learning model, producing today creates an opportunity benefit (accelerating cost decline), hence the negative $\lambda(t)$.

¹⁰ It is important to note that we do not claim that all of the generator's subsidy automatically translates to higher manufacturer profits. The portion that flows upstream depends on factors such as negotiating power of turbine/solar manufacturers vs. project



Furthermore, as learning effects depend on total cumulative output rather than on who formally receives the subsidy, labelling the term $p + s$ as “revenue to the manufacturer” highlights the essential idea: anytime net proceeds from producing additional units rise, the firm is motivated to produce more, thus accelerating the descent along the learning curve.

For illustration purposes, in Figure 10, we compare actual and counterfactual solar PV cost reductions assuming no government subsidies. The actual scenario is built using cumulative deployment and cost data from IRENA (2024) (see descriptive statistics in Table 4), which provides a detailed record of solar PV installations and their associated costs from 2010 to 2023. For the counterfactual scenario, representing a no-subsidy case, we use Bloomberg NEF corporate Power Purchase Agreement (PPA) data¹¹ as a proxy for market-driven growth, capturing cumulative corporate PPA additions from 2015 to 2023¹² (see Table 4).

Table 4: Descriptive statistics of data

Statistic	Installed Cost (\$/kW)	LCOE (\$/kWh)	Cumulative deployment (MW) (with subsidies)	Cumulative market-driven deployment (MW)
Count	14	14	14	9
Mean	2211.264	0.151685	470256.8	87877.7
std	1431.887	0.125004	416174.9	69286.7
Min	757.6878	0.044247	40311.14	20000
25%	1054.76	0.061931	147142	30600
50%	1772.401	0.103554	343729.8	65300
75%	2969.096	0.191834	688770.4	12700
Max	5310.488	0.460012	1412093	214300

To analyse cost trends, a learning parameter (α) was derived from the IRENA data for 2010 and 2023 and applied to both scenarios using the learning curve model $c(X) = c_0 \left(\frac{X}{X_0}\right)^{-\alpha}$ to estimate costs based on their respective cumulative deployments.

The graphic reveals significant insights into the role of subsidies in driving solar PV cost reductions. In the actual scenario, fuelled by subsidies, cumulative deployment surged to 1,412,092.54 MW by 2023, reducing costs by 85.7% from 5,310.49 USD/kW in 2010 to 757.69 USD/kW. Conversely, the counterfactual scenario, limited to market-driven growth without subsidies from 2015, achieves a cumulative deployment of only 390,459.033 MW by 2023, with costs dropping by 71.2% to approximately 1,529.52 USD/kW.

developers, global manufacturing overcapacity or competition, and policy design (local content rules, auctions, etc.). If demand is extremely elastic (many potential wind/solar projects are waiting in the wings), most of the subsidy might get passed on to the manufacturer in the form of higher order volumes (not necessarily higher per-unit price but a higher quantity of orders). In this case, because the manufacturer doesn't directly see “+s” in their revenue line, the effect is indirect: it spurs more orders today. Over time, that additional volume accumulates into the learning curve. Despite these nuances, the aggregate outcome—faster scale-up and reduced costs—mirrors what we see if the manufacturer were subsidized directly. The main difference is who initially pockets the subsidy and how competition and supply-chain relationships distribute that value.

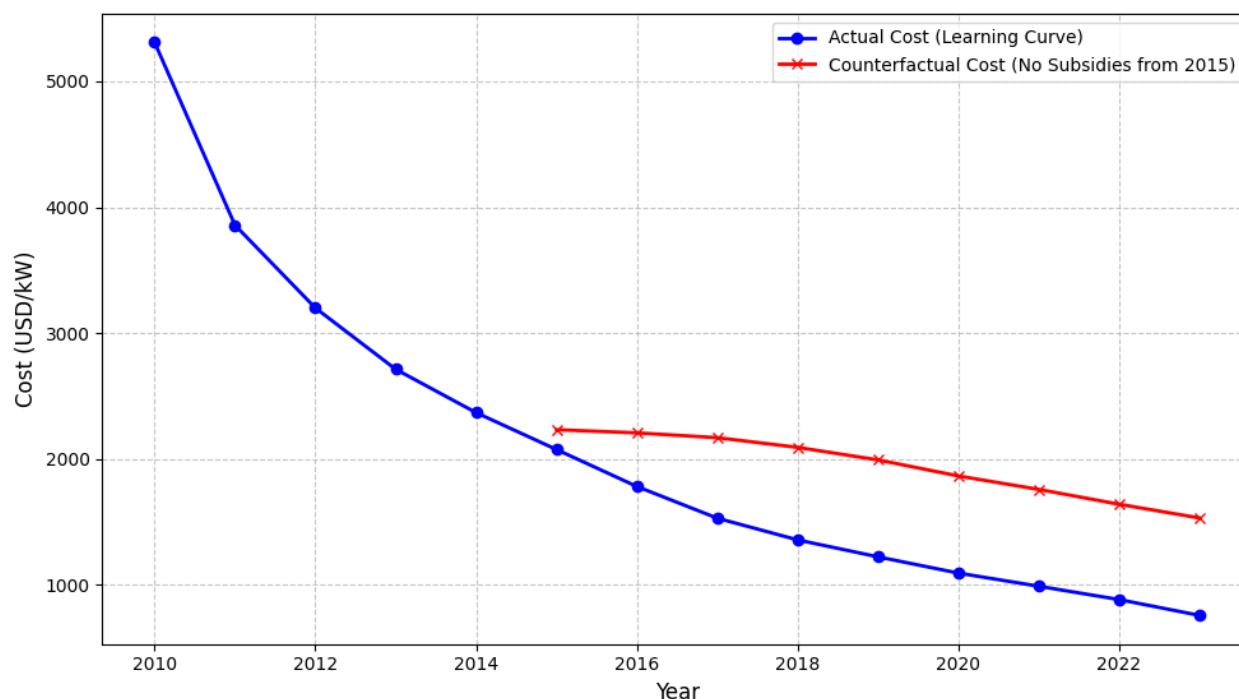
¹¹ Please see <https://about.bnef.com/blog/corporate-clean-power-buying-grew-12-to-new-record-in-2023-according-to-bloombergnef/>

¹² We acknowledge that this is not an accurate estimate as PPAs have significantly benefited from wider industry level subsidies for technologies such as solar PV.



The marked divergence in costs from 2015 onward highlights how subsidies accelerated deployment and amplified cost declines. This contrast underscores the pivotal role of policy support in enhancing the affordability and widespread adoption of solar PV technology over the period.

Figure 10: Solar PV Cost Reduction: Actual vs. Counterfactual (2010–2023)



Source: Author's own analysis

While we acknowledge that the counterfactual estimate is not entirely accurate- since PPAs for solar PV have benefited from years of industry-wide subsidies- the analysis still sheds light on the technology's trajectory. Subsidies have historically played a key role in reducing costs and driving the rapid deployment of solar PV, especially in its early, less competitive phases. By 2015, however, solar PV had surpassed a critical point of market penetration, where factors like economies of scale, technological advancements, and market demand began to sustain its momentum. If subsidies had been removed at that stage, the growth rate of solar PV would likely have declined, and the pace of cost reduction would have slowed. Yet, growth would not have stopped entirely; the technology's increasing cost-competitiveness and the global shift toward decarbonisation would have ensured continued, albeit slower, expansion. At this point, subsidies primarily accelerate deployment rather than being essential to the industry's survival.

This resilience, however, does not extend to all renewable technologies. For example, offshore wind, which remains in a less mature stage of development, still heavily depends on subsidies to manage its higher costs and technological challenges. Unlike solar PV, offshore wind has not yet achieved the same level of market penetration or cost reduction. If subsidies were removed, the sector could face a significant setback, with deployment slowing considerably and progress toward cost competitiveness stalling. Innovation in offshore wind might also suffer without the policy support needed to drive learning effects and economies of scale.



4. The implications of technology-based energy economics

The transition to a manufacturing-based, near-zero marginal cost energy system driven by renewables is a fundamental shift with wide-ranging consequences. In this section, we discuss some of the major implications of this transition.

4.1 The rise of new dominant players

One of the most important implications of new energy economics based on manufacturing and learning curve is the so called “winner-takes-most” dynamic where early movers become dominant exporters of cheaper, higher-quality technology. A firm (or a country) that aggressively ramps up production early, even at low or negative margins, reaps the benefits of rapidly accumulating manufacturing experience. This experience in turn drives down costs via learning-by-doing effects, allowing the early mover to undercut late entrants on price or invest more in quality improvements. As it expands market share, its cost advantage snowballs—larger volumes further reinforce its position on the learning curve, thereby widening the gap between it and less-established competitors. Once a certain lead is achieved, it becomes very difficult for newcomers to overcome, since they would need to produce at sufficiently large scales and for long enough to catch up on cost reductions. In this way, an initial willingness to sacrifice near-term profits in exchange for higher output can lock in a self-reinforcing cost advantage that, in equilibrium, results in one or a few dominant firms.

This effect can be directly deduced from the learning curve model. To see this consider two firms, $i = 1, 2$. Each firm i has a state variable $X_i(t)$ denoting its cumulative production up to time t . Production rates are $Q_i(t)$. Thus,

$$\dot{X}_i(t) = Q_i(t), \quad X_i(0) = X_{i0}$$

Each firm's per-unit cost declines with its own cumulative output:

$$c_i(X_i(t)) = c_0 \left(\frac{X_i(t)}{X_{i0}} \right)^{-\alpha}, \quad \alpha > 0$$

or any other decreasing function of $X_i(t)$. If firm 1 accumulates more total production than firm 2, it maintains a cost advantage.

Suppose there is a total demand $D(p(t))$ for the product (e.g., solar panels), which both firms serve, splitting the quantity $Q_1(t) + Q_2(t)$. Each firm maximizes its own discounted profit over time:

$$\max_{\{Q_i(t)\}} \int_0^{\infty} e^{-rt} [p_i(Q_1(t), Q_2(t)) - c_i(X_i(t))] Q_i(t) dt$$

subject to $\dot{X}_i(t) = Q_i(t)$.

Under some competition models, the price p_i each firm receives depends on how total supply meets demand. In a more stylised model, if the firms produce homogeneous products, the firm with lower cost wins most of the market.

The lower cost can happen through industrial strategy because there is a positive feedback: early investment lowers future costs. To see this suppose firm 1 chooses a larger $Q_1(t)$ early on, accepting temporary low or even negative margins to build its cumulative output $X_1(t)$. As $X_1(t)$ grows, $c_1(X_1(t))$ declines faster than $c_2(X_2(t))$. A small initial advantage can snowball:

$$c_1(X_1(t)) < c_2(X_2(t)) \Rightarrow \text{Firm 1 can charge a lower price or enjoy higher margins.}$$

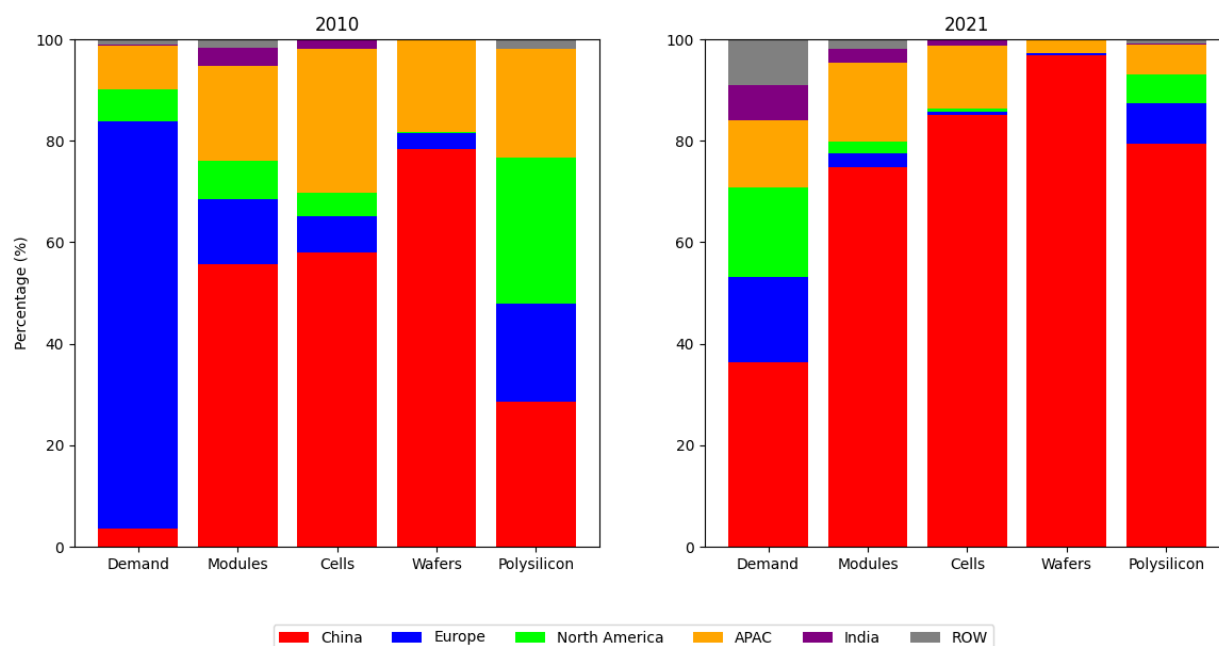
In many competition models (e.g., Bertrand competition with identical products), the lower-cost firm can price just slightly below the rival and grab most (if not all) of the demand $D(p)$. As firm 1 sells more, it further increases X_1 , further lowering $c_1(X_1)$. Meanwhile, firm 2's lower sales keep X_2 small, so $c_2(X_2)$ does not decline as quickly. This feedback loop can produce a single dominant producer.



Over time, $X_1(t)$ keeps rising while $X_2(t)$ stagnates, thereby locking in or widening the cost gap $c_1(X_1) < c_2(X_2)$. A small lead becomes a permanent cost advantage. This is the basic “tipping” or “path dependence” phenomenon: once a firm is far enough down the learning curve, it’s very hard for latecomers to catch up because the leading firm enjoys enduring cost superiority.

This pattern is evident in the global solar PV industry, where countries such as China aggressively scaled up manufacturing capacity and captured the benefits of steep learning curves. Supported by proactive industrial policies, they were able to flood the market with inexpensive yet increasingly efficient panels, driving down costs at a pace that made it prohibitively difficult for latecomers in Europe or North America to remain price-competitive. Even as technology improvements occur worldwide, China’s entrenched cost leadership and established supply-chain networks protect its dominant position. As seen from Figure 11, In 2010, Europe held the largest share of solar PV demand at 80.4%, while China already had substantial manufacturing capacity, with 55.7% of modules, 57.9% of cells, and 78.3% of wafers. By 2021, China’s influence had grown dramatically, commanding 96.8% of wafer production and over 74% of modules, cells, and polysilicon. At the same time, China’s demand for solar PV surged from 3.5% to 36.4%, establishing it as both the leading producer and a major consumer. This transformation underscores China’s strategic consolidation of the solar PV industry, while other regions, including Europe and North America, saw their manufacturing shares shrink considerably. The result is a market structure in which the lion’s share of global solar panel production is concentrated among a handful of early-mover firms that can sustainably maintain lower costs, having already accrued the productivity and efficiency gains of large-scale, prolonged manufacturing.

Figure 11: Solar PV manufacturing capacity by country and region in 2010 and 2021



Source of data: IEA (2022)

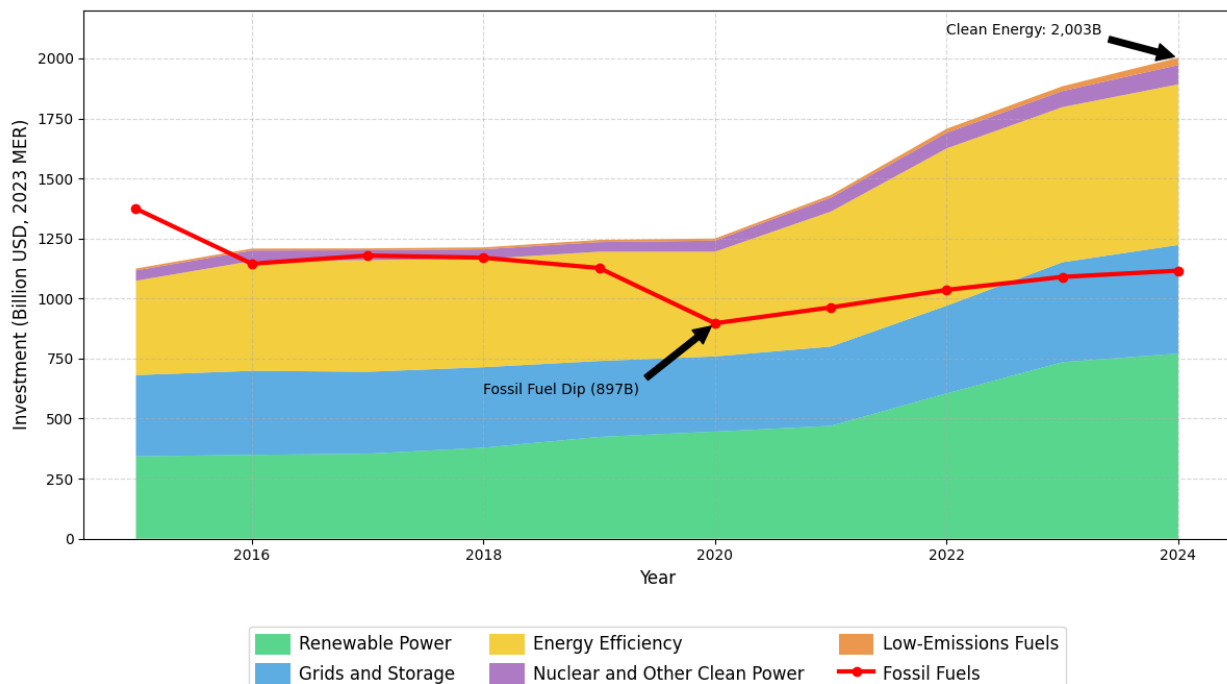
4.2 Re-definition of energy security

In the evolving global energy landscape, traditional notions of energy security centred around securing access to fossil fuel reserves are becoming increasingly obsolete. For decades, countries focused their energy security strategies on maintaining reliable access to oil and gas resources, building strategic petroleum reserves, and cultivating diplomatic relationships with fossil fuel-producing nations. However, this paradigm is fundamentally shifting as renewable energy technologies become the dominant force in the global energy system.



As shown in Figure 12, clean energy investment—comprising renewable power, grids and storage, energy efficiency, nuclear and other clean power, and low-emission fuels—has steadily increased from 1,125 billion USD in 2015 to 2,003 billion USD in 2024, nearly doubling over the decade. This growth is driven primarily by renewable power (rising from 343 to 771 billion USD) and energy efficiency (393 to 669 billion USD), reflecting a strong global push toward sustainable energy solutions. In contrast, fossil fuel investment shows a volatile trajectory, peaking at 1,374 billion USD in 2015, dropping sharply to 897 billion USD in 2020—likely due to economic condition in the Covid era—and then partially recovering to 1,116 billion USD by 2024. A key milestone occurs around 2020–2021, when clean energy investment surpasses fossil fuels, highlighting a pivotal transition in global energy priorities toward cleaner, more sustainable sources by 2024.

Figure 12: Global investment in clean energy and fossil fuels, 2015-2024

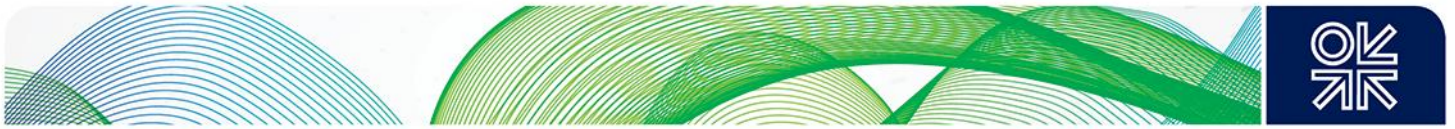


Source of data: IEA (2024b)

The core of this new energy security paradigm lies in the ability to manufacture the key components of renewable energy systems: solar panels, wind turbines, batteries, and electrolyzers. These are not naturally occurring resources, but manufactured goods, subject to the principles of learning curves and economies of scale. As a result, the question of “how to ensure energy security” now focuses more on capabilities and technology than on physical access to fuel deposits.

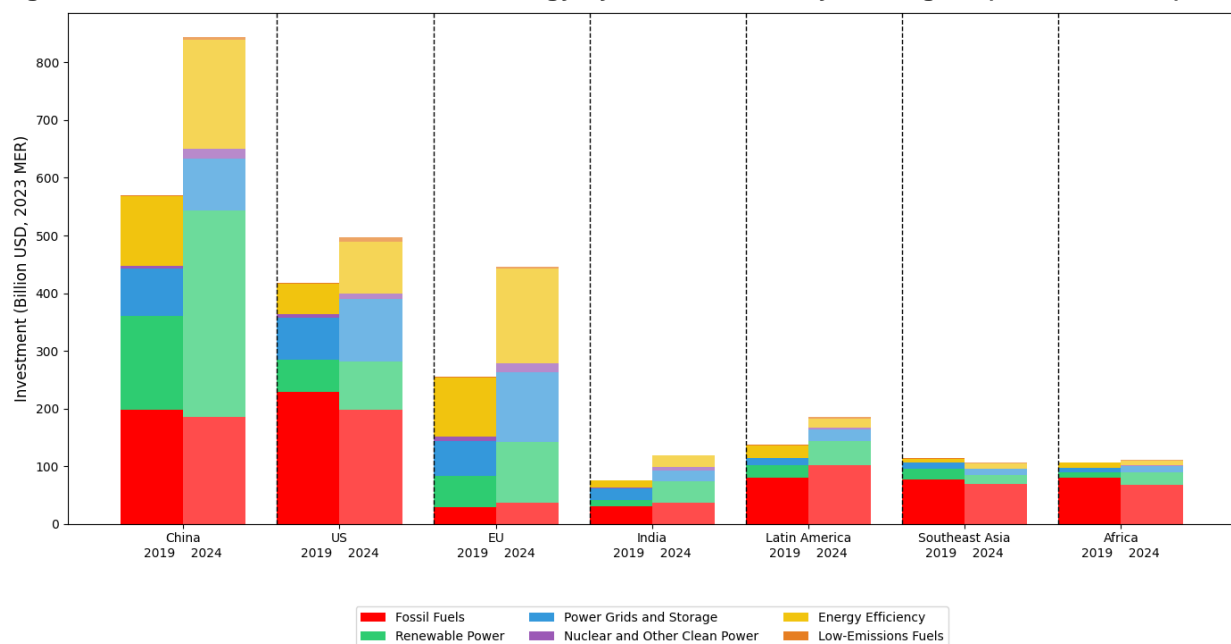
Consequently, a nation’s ability to produce these technologies domestically becomes a paramount strategic concern. Dependence on imports for these critical components creates vulnerabilities analogous to the historical reliance on foreign oil – potential supply disruptions, price volatility dictated by exporting nations, and susceptibility to geopolitical pressures. Developing robust domestic manufacturing capabilities mitigates these risks and offers significant advantages. It fosters economic growth, creates high-skilled jobs, and drives innovation within the country. Furthermore, a strong domestic manufacturing base allows for greater control over the technology’s evolution, enabling nations to tailor renewable energy systems to their specific needs and environmental conditions. This independence is crucial for achieving true energy independence, moving beyond simply replacing one form of import dependence with another.

However, building domestic manufacturing capabilities requires significant investment in infrastructure, skilled labour, and research and development. As Figure 13 shows, China’s investment surge underscores its dominant position in clean tech manufacturing, reflecting robust industrial capacity for



solar panels, wind turbines, and battery systems. The EU investment levels signals advanced manufacturing capabilities in wind and energy storage technologies, supported by strong policy frameworks. The US, with a modest shift from 418 to 497 billion USD and growth in grids (74 to 108), suggests solid but less aggressive expansion in clean tech production, possibly constrained by a lingering fossil fuel focus (228 to 197). India's rise from 75 to 118 billion USD, driven by renewable power (12 to 37), hints at emerging manufacturing potential, though still nascent compared to leaders. In contrast, Latin America (137 to 186), Southeast Asia (114 to 107), and Africa (106 to 111) show limited growth in clean tech investment—renewables and efficiency remain low (e.g., Africa's 9 to 22 for renewables)—indicating weaker manufacturing bases, reliance on imported technologies and insufficient industrial infrastructure. This disparity highlights a global divide where China and the EU lead in clean tech manufacturing scalability, while developing regions lag, constrained by capital, technology access, and industrial capacity as of 2024.

Figure 13: Annual investment in clean energy by selected country and region (2019 and 2024)



Source of data: IEA (2024b)

Countries must also address challenges such as securing access to critical minerals (e.g., lithium, cobalt, and rare earths) needed for renewable technologies (will be discussed in more details in subsequent sections). This has led to a new dimension of energy security: mineral diplomacy. Nations are forming alliances and partnerships to secure stable supplies of these materials, while also investing in recycling technologies to reduce dependence on primary extraction. These efforts aimed to complement domestic manufacturing strategies and help countries to create a more resilient and sustainable energy system.

4.3 The rise of green industrial policy

Recognizing the strategic importance of renewable energy and the shift towards a manufacturing-based energy system, governments worldwide are increasingly employing industrial policy as a key lever for growth and security (IEA, 2022). This represents a departure from purely market-driven approaches, acknowledging the need for targeted government intervention to accelerate the development and deployment of clean energy technologies (IRENA, 2022). A central pillar of this strategy is robust R&D funding, aimed at fostering innovation across the entire renewable energy value chain. This includes basic research into new materials, improved cell efficiencies for solar panels, more efficient wind turbine designs, advanced battery chemistries, and grid management technologies (Niskanen Center, 2021). The goal is to maintain a technological edge, driving down costs and improving the performance of renewable energy systems, ensuring long-term competitiveness (REN21, 2023).



Beyond basic research, industrial policy extends to direct support for manufacturing. Governments are implementing a range of incentives to encourage domestic production of renewable energy equipment. Since 2020, governments worldwide have allocated roughly 90 billion in direct incentives to bolster domestic clean energy manufacturing (IEA, 2023). This has also been accompanied by major legislation. For instance, the European Union, which traditionally had stricter limits on state aid, is moving to directly support clean tech manufacturing in member states (European Commission, 2023). The EU's Net-Zero Industry Act (2023) and related Green Deal initiatives identify homegrown manufacturing as key to energy security. The EU is pursuing targets to onshore a significant share of its renewable hardware production. The Net-Zero Industry Act and Carbon Border Adjustment Mechanism incentivise local renewable energy manufacturing and penalize high-carbon imports, explicitly to reduce dependency on foreign supply (REN21, 2023). Likewise, the United States' Inflation Reduction Act devotes billions of dollars to expanding domestic factories for batteries, solar modules, wind towers, etc., framing it as both a climate and energy security effort (World Economic Forum, 2023). In Asia, India's Production-Linked Incentive schemes for solar manufacturing and EV batteries are driven by a desire to cut import reliance and gain strategic autonomy in energy (MNRE, 2023). Also, China famously leveraged state-owned banks to provide low-interest loans and credit lines to solar and battery companies – a form of support that allowed rapid scale-up of production. After 2009, the Chinese central government gave solar PV manufacturers access to cheap capital and other aid, which, combined with a huge domestic market, enabled China to dominate global solar supply (Niskanen Center, 2021).

Trade policies constitute a more controversial, yet frequently employed, aspect of industrial policy in the renewable energy sector. Governments often use tariffs, import quotas, and local content requirements to protect nascent domestic industries from international competition, particularly from countries with lower labour costs or established manufacturing dominance (IRENA, 2022). The rationale is to provide a “breathing space” for domestic manufacturers to scale up, achieve economies of scale, and become globally competitive (Columbia Law, 2016). Proponents argue that such measures are necessary to level the playing field and prevent unfair trade practices, such as dumping (selling goods below cost). They are often seen as essential for securing a place in the strategic global supply chain of these crucial technologies (Columbia SIPA, 2022).

There are many cases of these trade policies. The United States imposed tariffs on imported solar cells and modules multiple times – first under anti-dumping/countervailing duty (AD/CVD) investigations in 2012–2015, and later broad safeguard tariffs in 2018 (SEIA, 2021). President Trump's Section 201 tariffs started at 30% in 2018, stepping down to 15% by 2021 (SEIA, 2021). These were aimed chiefly at Chinese-made panels (though applied globally with some exemptions) to shield U.S. manufacturers. The EU likewise introduced anti-dumping and anti-subsidy duties in 2013 on Chinese solar imports, citing that Chinese companies were selling below cost thanks to subsidies. Those EU measures required Chinese firms to respect a minimum price or face duties up to 64.9% on panels, cells, and wafers (Reuters, 2018a; Reuters, 2018b). India has also turned to tariffs – in April 2022, India began levying a 40% basic customs duty on imported solar modules and 25% on solar cells to discourage cheap imports (mostly from China) and boost domestic production (Reuters, 2022). This marked a sharp increase from a prior 15% safeguard duty. Other countries from Canada to Turkey have similarly taxed imported solar equipment to protect local industry (World Economic Forum, 2023).

Trade protectionism in the renewable sector has sparked debate because of its mixed impacts. On one hand, advocates argue they are necessary to develop domestic industries and prevent over-reliance on imports; on the other hand, tariffs and local content rules can raise costs and slow clean energy deployment, at least in the short term (SEIA, 2021). For example, U.S. solar panel prices became among the highest in the world after tariffs were imposed. By 2020, prices in the U.S. were 43–57% higher than the global average, largely due to the import tariffs on cells and modules (SEIA, 2021). The Solar Energy Industries Association estimates that the Section 201 solar tariffs (2018–2021) significantly slowed U.S. solar installations, causing a loss of about 10.5 GW of potential capacity (SEIA, 2021). In the EU, installers similarly argued that anti-dumping duties on Chinese panels stifled solar growth. When Europe decided to end its trade controls on Chinese solar panels in 2018, SolarPower Europe hailed it as removing the biggest barrier to growth for solar and a watershed moment for the industry (Reuters,



2018b). These outcomes highlight the core trade-off: protection can inflate prices for clean energy hardware, which in turn slows down installations and the pace of decarbonization (Cato Institute, 2021).

Protectionist moves have led to tit-for-tat trade disputes that add uncertainty. The US–China solar trade war is a prime example. After the U.S. imposed anti-dumping duties on Chinese panels in 2012 (ranging roughly 30–250% on various firms), China retaliated with its own duties on U.S. polysilicon exports (used in making panels), cutting off U.S. polysilicon makers from the China market and forcing some into bankruptcy (SEIA, 2021). There have also been WTO challenges: China, the EU, and others contested each other's solar tariffs through the WTO in the 2010s. Similarly, India's and Canada's use of local content requirements (LCRs) for renewables were challenged by the U.S. and EU at the WTO and found inconsistent with trade rules (Columbia Law, 2016). While these disputes are about legal principles, their practical effect was to force policy changes (Ontario dropped its LCR, India modified its programs) and at times impose retaliatory tariffs elsewhere (Columbia SIPA, 2022). The result can be market uncertainty, with companies unsure of tariff costs or eligibility rules year to year – which itself can slow investment. For instance, during a 2022 U.S. investigation into tariff circumvention by Southeast Asian solar suppliers, project developers paused purchases, fearing retroactive duties, which the industry said put many gigawatts on hold (Columbia SIPA, 2022). Thus, protectionism can trigger trade conflicts that disrupt supply chains and delay projects until resolved (IMF, 2023).

This convergence on industrial policy reflects a political reality: leaders want the economic benefits (jobs, factories, supply security) of the energy transition to accrue at home (IEA, 2023). As the IMF notes, “the political incentives that shaped the IRA are not unique to the United States” – many countries are finding that ambitious climate action is more palatable when tied to domestic industry promotion, even if that clashes with free-trade principles (IMF, 2023). In other words, subsidies, local requirements, and trade measures are becoming a normalized part of clean energy policy, driven by voters' and industries' demands to secure local gains from global decarbonization (WTO, 2022).

A truly multilateral approach – where countries agree not to erect new trade barriers and perhaps coordinate investments – could, in theory, accelerate the energy transition by spreading technology at the lowest cost. Institutions like the WTO have been discussing win-win options, such as reviving the Environmental Goods Agreement to cut tariffs on clean tech globally, or developing new rules to govern green subsidies (TESS, 2021; WTO, 2022). However, progress is limited. The WTO's rules were not crafted with climate subsidies in mind and are struggling to adapt; WTO talks on an Environmental Goods Agreement collapsed in 2016 over disagreements, and no revival is in sight (Cato Institute, 2021). Meanwhile, climate-focused trade initiatives (like the EU's Carbon Border Adjustment Mechanism, which will put tariffs on carbon-intensive imports) are causing diplomatic frictions – the EU CBAM has already provoked negative responses from many countries, including the U.S. and developing economies, who fear it as a protectionist tool in green guise (IMF, 2023).

Economic nationalism is on the rise globally, and clean energy is seen as a strategic sector – meaning trade will be used as a tool of statecraft (IEA, 2023). Geopolitics strongly suggests trade measures will persist. Therefore, unless a new consensus emerges, we should expect more trade tensions in clean energy (e.g. disputes over subsidy programs, carbon tariffs, export controls on minerals) as the world races to decarbonize (WTO, 2022). Each government is positioning itself to win in the new energy economy, and that almost certainly entails using trade levers to nurture its own industry (IMF, 2023).

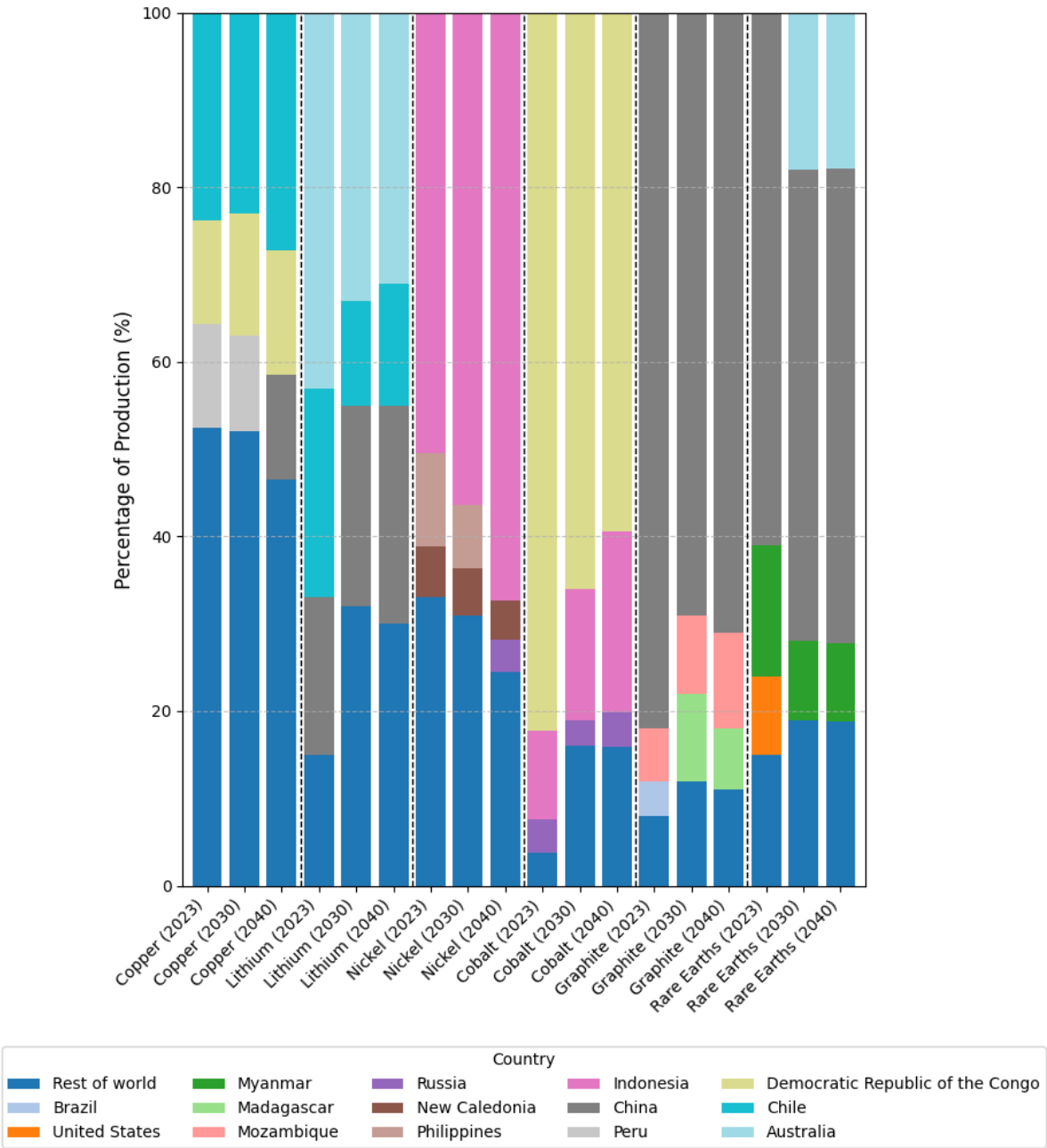
4.4 New scarcity: critical materials and supply chains

The transition to a renewable energy system, while addressing the finite nature of fossil fuel resources, introduces a new form of scarcity: the scarcity of critical materials and control over their associated supply chains. This scarcity centres around minerals like lithium, cobalt, nickel, rare earth elements (REEs), copper, and others, all essential for manufacturing solar panels, wind turbines, batteries, and electrolyzers. Unlike the readily available and geographically distributed nature of sunlight and wind, these materials are geographically concentrated, often found in politically unstable regions, or controlled by a limited number of companies and countries. This creates a new landscape of resource dependence, bringing with it a distinct set of geopolitical and economic implications.



As seen in Figure 14, Copper extraction involves a mix of players like Chile, Australia, and a broad "Rest of World" category, suggesting a somewhat balanced but shifting landscape. Lithium relies heavily on Australia and Chile, pointing to a dependence on specific regions with significant deposits. Nickel production is increasingly dominated by Indonesia, with smaller roles for places like the Philippines, while cobalt is almost entirely centred in the Democratic Republic of Congo, highlighting a risky reliance on a single, potentially unstable source. Graphite and rare earth minerals show China as the leading force, with emerging contributions from countries like Mozambique and Australia, underscoring how control over these materials is concentrated in a few hands. This pattern paints a picture of vulnerability, where geopolitical tensions or regional instability could disrupt the flow of materials essential for renewable energy technologies.

Figure 14: Geographical distribution of mined or raw material production for key energy transition minerals

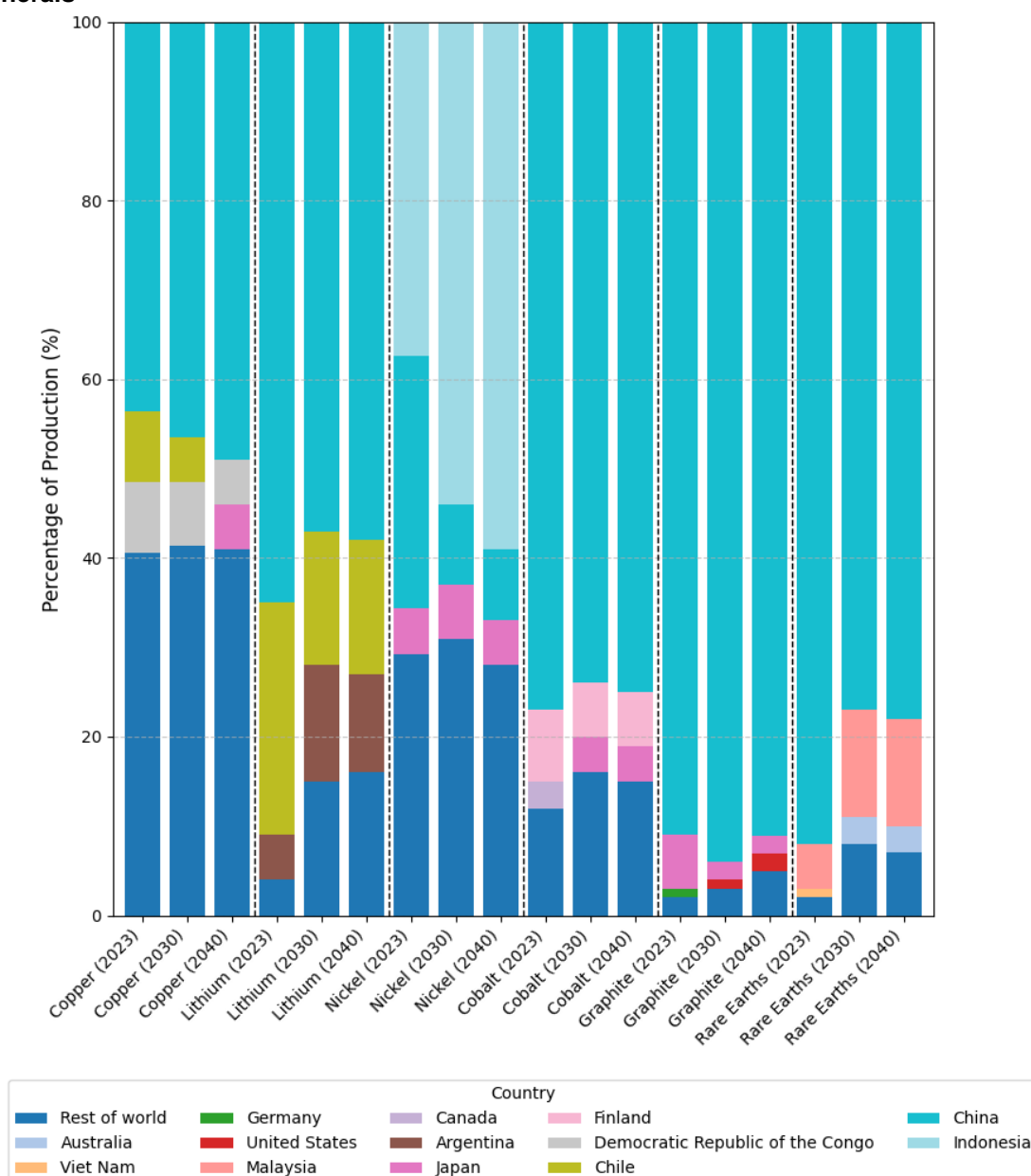


Source of data: IEA (2024c)

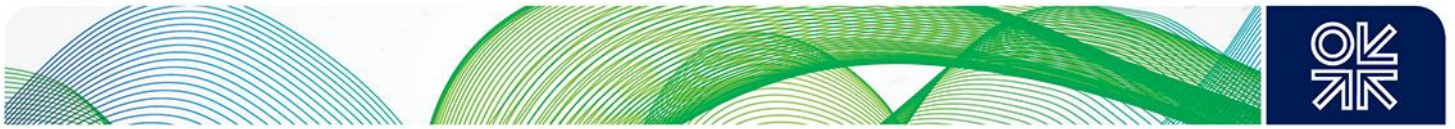


The chart for refined material production tells a story of stark concentration, with China emerging as the linchpin in processing key energy transition minerals from 2023 to 2040 (see Figure 15). Copper refining involves China alongside a diverse "Rest of World" group, but the balance tips heavily toward China over time, showing its growing influence. Lithium refining leans on China too, with Argentina and Chile playing supporting roles, suggesting that raw materials from South America are funnelled through Chinese facilities. Nickel and cobalt refining further amplify this trend, with China overshadowing partners like Indonesia and Finland, creating a near-monopoly in these critical steps. Graphite and rare earths refining take this to an extreme, where China's dominance leaves little room for others, dwarfing contributions from places like Japan or Malaysia.

Figure 15: Geographical distribution of refined material production for key energy transition minerals



Source of data: IEA (2024c)



This new resource landscape shares similarities with the fossil fuel era. Just as with oil and natural gas, the concentration of critical minerals in specific regions creates opportunities for geopolitical leverage. Countries controlling these resources, or their processing, can exert influence on the global energy transition. We might see resource nationalism, export restrictions, and strategic alliances forming around these materials, mirroring historical patterns observed with oil. Furthermore, both fossil fuels and critical minerals are characterized by complex, global supply chains. Disruptions – whether from political instability, natural disasters, trade disputes, or pandemics – can lead to price volatility and shortages, impacting energy security and economic stability. These price fluctuations are driven by the familiar forces of supply and demand, speculation, and geopolitical events, mirroring the volatility seen in fossil fuel markets.

Despite these parallels, crucial differences distinguish the scarcity of critical minerals from that of fossil fuels. Fossil fuel scarcity is fundamentally about absolute scarcity – a finite amount of oil, gas, and coal within the Earth's crust. While critical mineral scarcity also has an element of absolute scarcity (limited known deposits), it is more acutely a problem of economic and geopolitical scarcity. The challenge is not necessarily that we will completely exhaust these minerals, but rather that accessing them affordably and reliably becomes increasingly difficult. This is further complicated because, unlike the relatively mature fossil fuel market, the market for many of these minerals is relatively new and experiences rapid growth in demand. This can outpace the development of mining and refining capacities, leading to bottlenecks and price spikes. This situation is often without the stabilising influence of mature logistics or financial hedging instruments. This difference highlights a key temporal distinction: fossil fuel scarcity is a long-term depletion concern, whereas critical mineral scarcity is an immediate bottleneck stemming from the rapid acceleration of the energy transition.

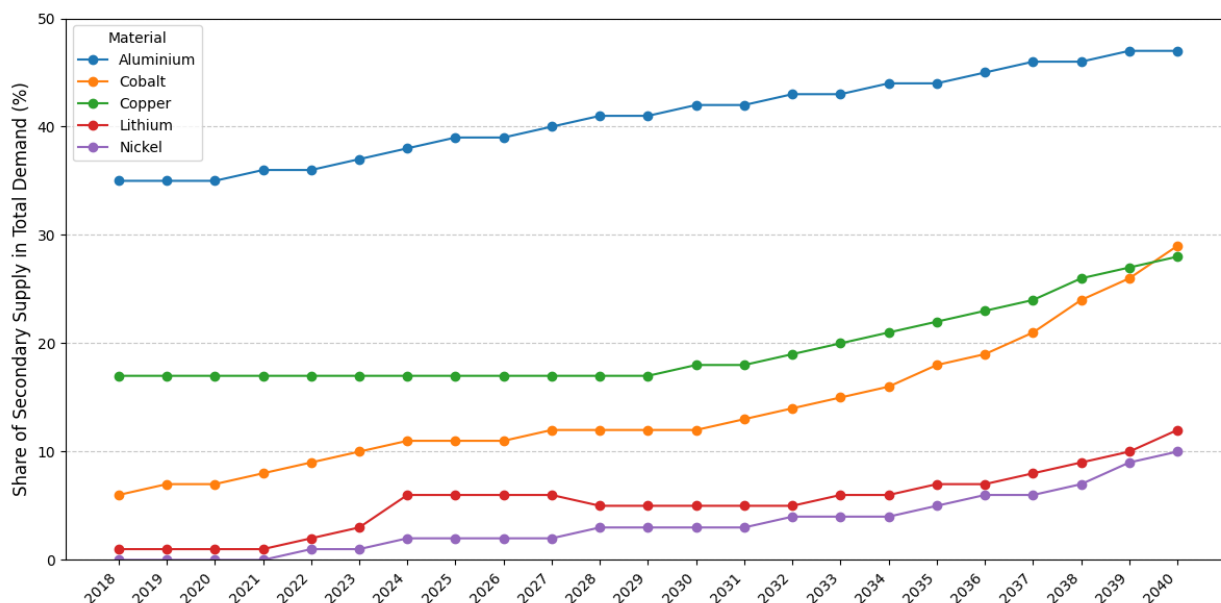
Another significant difference lies in the potential for substitution. While replacing one fossil fuel with another (e.g., coal for oil) offers limited flexibility, there is significantly greater potential for substitution among critical minerals. Ongoing research is exploring alternative battery chemistries (like sodium-ion instead of lithium-ion), different magnet materials, and more efficient designs that minimize the use of scarce materials. This offers a viable pathway to mitigating scarcity, an option less readily available with fossil fuels.

Besides all, a fundamental distinction exists in the inherent nature of these resources. Fossil fuels are one-time-use resources, combusted for energy and releasing carbon into the atmosphere. While some secondary products exist, their primary energy value is irreversibly consumed. In contrast, metals and minerals can, in principle, be recovered and recycled. Once extracted and refined, they can circulate through multiple lifecycles – for example, from electric vehicle batteries to stationary storage. This opens the possibility of a circular economy model, substantially reducing the long-term reliance on virgin mineral extraction and marking a significant departure from the linear consumption model of fossil fuels.

Figure 16 tracking the share of secondary supply in total demand for key energy transition minerals from 2018 to 2040 reveals a growing reliance on recycling to meet future needs, though the pace and extent vary across materials. Aluminium starts with a substantial share and climbs steadily, suggesting a mature recycling system that could ease pressure on primary sources. Cobalt and Copper also show consistent increases, with Cobalt's sharper rise hinting at efforts to recover this critical battery material amid supply constraints, while Copper's gradual growth reflects its widespread use and established recycling infrastructure. Lithium and Nickel, however, begin with negligible shares and only see modest gains by 2040, indicating that recycling for these materials remains underdeveloped, likely due to technological challenges or lower historical stockpiles. Overall, the chart implies that while secondary supply will play an increasingly vital role in the energy transition—potentially reducing dependence on mined resources—there is an uneven progress across materials.



Figure 16: Share of secondary supply in total demand for selected materials, 2010-2040



Source of data: IEA (2024c)

Finally, the relevance of the Hotelling model to the emerging scarcity of critical minerals warrants examination. While it provides a useful conceptual framework for understanding how resource owners balance present extraction against future scarcity value, critical minerals challenge its core assumptions. Unlike fossil fuels, their recyclability and reusability diminish the “exhaustibility” paradigm central to the Hotelling model. Furthermore, rapid technological advancements, such as new battery chemistries and improved recycling processes, lead to significant demand fluctuations for individual minerals, making accurate price path predictions difficult.

Moreover, real-world market dynamics for critical minerals diverge from the model’s idealized competitive, profit-maximizing producers with perfect foresight. Political, strategic, and corporate factors often supersede pure economic logic, with a few dominant players controlling production and refining. Consequently, while the Hotelling model offers valuable insights into resource economics, its applicability to critical minerals is limited and requires significant caveats.

4.5 The changing nature of risks

Fossil-based systems typically concentrate risks around volatile commodity prices, geopolitical resource control, and the environmental impacts of extraction and combustion. By contrast, a renewables-focused framework shifts the emphasis toward issues of technological integration, infrastructure reliability, and effective resource deployment. Although supply chain considerations—particularly concerning critical minerals—remain significant (as discussed in Section 4.4), other salient challenges arise from the inherent intermittency of renewable resources, the need for adequate flexibility solutions, and the importance of land-use planning.

Intermittency in the context of a renewables-dominant energy system fundamentally redefines how energy supply and demand must be managed. While fossil fuel systems manage predictable supply to meet variable demand, renewable-dominated systems must manage variable supply alongside variable demand. The fundamental challenge is to maintain reliability not through fuel stockpiles but through a portfolio of flexibility solutions: geographic interconnection, diversified generation, storage at multiple timescales, demand-side management, sector coupling, and advanced forecasting. While this creates significant complexity, it also offers opportunities for system optimisation, democratisation, and decarbonisation that were not possible in traditional fossil fuel systems.



For example, the variability of wind and solar generation in any single location can be smoothed, to some degrees, by connecting resources across diverse weather systems. This evolution demands not just technical solutions but new institutional frameworks that transcend traditional jurisdictional boundaries, creating multinational electricity markets and coordinated planning processes. Beyond spatial integration, intermittency introduces a complex temporal dimension, requiring flexibility solutions across multiple timescales. For brief fluctuations (seconds to minutes), grid-forming inverters and synthetic inertia can maintain system stability. For hourly and daily variations, battery storage and demand response provide efficient balancing. Weekly patterns might leverage pumped hydro storage, while seasonal variations require longer-duration solutions like hydrogen production, carbon-neutral fuels, or deep geothermal resources.

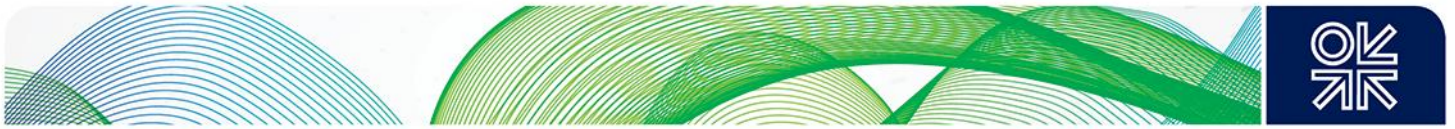
As this temporal complexity unfolds, the provision of stability services—once the exclusive domain of large generators—becomes increasingly democratised. Distributed energy resources like rooftop solar, electric vehicles, and smart appliances can collectively provide frequency regulation, voltage support, and emergency reserves. This transformation turns millions of small-scale resources into participants in system management, provided the right market mechanisms and coordination tools exist. This also challenges traditional concepts of “baseload” and “peaking” resources, requiring a more sophisticated approach to resource adequacy. Instead of simply meeting peak demand, planners must now consider the statistical characteristics of both renewable generation and demand across all hours, identifying potential shortfall periods that may occur during extended low-wind or solar conditions rather than traditional peak hours.

Another aspect is the increasing linkage between electricity and heating, transportation, and industrial processes which expand flexibility toolkit for system planners exponentially. Electric vehicles can serve as distributed storage resources, hydrogen production can absorb surplus renewable generation, and district heating systems with thermal storage can shift electricity demand across days. As a result, grid operators must evolve from direct controllers of dozens of large generators to orchestrators of millions of distributed assets. This requires sophisticated forecasting tools to predict generation patterns, automated market platforms that can optimise resources in near-real-time, and new approaches to system operations.

Beyond flexibility, there is the issue of land-use planning which fundamentally shapes the risk landscape of renewable energy systems. Siting wind farms, solar arrays, and related infrastructure often brings local environmental considerations—such as ecosystem impacts, habitat disturbance, and aesthetic concerns—to the forefront of the policy-making process. Unlike fossil fuel extraction, which is typically concentrated in fewer locations, renewable installations can be more widely distributed, requiring local community engagement and stakeholder consensus. Although this dispersal can reduce certain systemic vulnerabilities—by diluting geopolitical risk and spreading generation assets across multiple regions—it necessitates more complex governance structures and regulatory frameworks capable of addressing varied local concerns.

At the heart of this challenge lies what might be called an “energy density paradox”. While fossil fuels offer high energy density—requiring relatively small land footprints for extraction—they create dispersed environmental impacts through emissions. Conversely, renewables produce minimal operational emissions but require substantially larger land areas to capture diffuse energy resources. These shifting spatial dynamics generate tension between democratisation and resistance. The distributed nature of renewable energy creates potential for community-owned energy projects that distribute economic benefits locally, creating stronger constituencies for clean energy. Nonetheless, this same visibility and proximity to population centres can simultaneously amplify opposition through “not-in-my-backyard” movements. The resulting tension creates uneven development patterns where projects advance more readily in communities with supportive governance structures, potentially reinforcing existing socioeconomic disparities if not carefully managed.

The temporal dimension of renewable energy land use further differentiates it from fossil systems and reshapes risk profiles. While extraction sites might operate for decades before requiring extensive reclamation, renewable installations offer greater reversibility—solar panels and wind turbines can be removed with relatively minimal long-term impact. Moreover, technological improvements continually



increase energy yield per unit of land, allowing for “repowering” of existing sites with more efficient equipment. This inherently changes risk profiles for long-term land stewardship and reclamation compared to extractive industries, potentially reducing intergenerational conflicts over land degradation.

Overall, the systemic risks in a renewables-based framework tend to be more dispersed and less tied to fuel-related price volatility, but they demand careful, ongoing coordination among policymakers, industry stakeholders, and communities. These risks are mitigated through measures such as adaptive grid management, strategic infrastructure investment, and prudent resource allocation. If appropriately managed, the transition to renewables can ultimately deliver more resilient and sustainable energy systems—ones less prone to sharp price shocks and less burdened by long-term environmental harm. Yet success depends on recognising and addressing the new challenges posed by intermittency, storage, and land use planning, ensuring that the benefits of clean energy are matched by equally robust governance and risk mitigation strategies.

4.6 The importance of system aspects

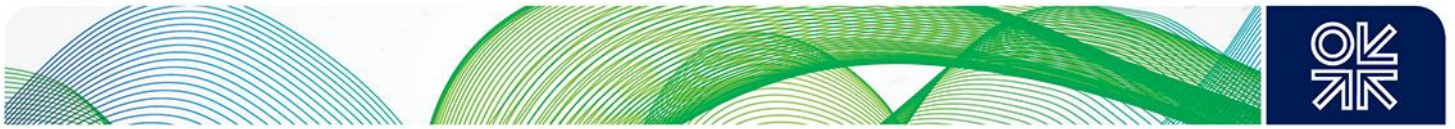
The transition from fossil fuel to renewable energy systems represents a comprehensive transformation across all system properties: elements (the fundamental components like generation technologies and physical resources), interconnections (the relationships and flows between system components), boundaries (the definitions of what is included within the system), purpose (the fundamental goals and functions being served), and emergence (the higher-order behaviours that arise from system interactions). While all these properties undergo significant change, three aspects demand particular attention as they have huge implications for the economics and regulation of the system: boundaries, interconnections, and emergence.

First, the fossil fuel era established clear, well-defined boundaries across multiple dimensions. Ownership of energy resources followed concrete physical and legal demarcations, with underground deposits mapped, claimed, and defended through established legal frameworks. Sectoral boundaries remained equally distinct, with energy companies operating in clearly defined industry classifications separate from other economic sectors. These clear boundaries simplified governance, investment decisions, and regulatory frameworks.

In contrast, renewable energy systems dissolve these traditional boundaries, most notably between production and consumption. With technologies like rooftop solar, home batteries, and grid-connected electric vehicles, households and businesses simultaneously participate on both sides of the energy transaction. This fundamentally alters market relationships and requires new regulatory approaches to accommodate entities that sometimes buy and sometimes sell energy. The once-clear boundary between producer and consumer becomes permeable and context-dependent.

Furthermore, renewable systems drive integration across previously separate sectors through electrification and digitalization. Electric vehicles connect transportation with the power sector; heat pumps link building climate control to electricity markets; and digital technologies become core infrastructure rather than optional additions. Regulatory agencies can no longer treat energy, transport, and digital infrastructure as separate silos. Policy must integrate multiple domains, from grid codes for EV charging to building codes promoting heat pumps, resulting in cross-sector governance structures. This boundary dissolution sometimes extends geographically as well, with optimal renewable deployment requiring cross-border transmission systems and integrated markets that transcend national boundaries. This necessitates a long-term, systems-thinking perspective that transcends short-term political cycles and sectoral interests.

Moving beyond boundaries, the fossil fuel era operated through remarkably linear interconnections, characterised by a one-way flow from extraction to consumption. Resources moved predictably through well-defined stages—extraction, transportation, refinement, distribution, and final use—with minimal feedback loops. This linear structure created relatively manageable supply chains where each barrel of oil followed a straightforward path from well to end-user with no return journey, simplifying system management and stakeholder relationships.



By comparison, renewable energy fundamentally restructures these interconnections by enabling bidirectional energy flows. The emergence of prosumers—entities that both consume and produce energy—creates complex feedback loops throughout the system. A household might draw electricity from the grid at night while selling excess solar production during daylight hours, establishing new market relationships that didn't exist in the fossil paradigm. This bidirectionality transcends individual connections to reshape the entire network's operational logic.

Additionally, renewable systems create novel interconnections between previously separate domains. Energy systems become intricately linked with weather patterns, digital infrastructure, and time-sensitive market mechanisms. The value of electricity varies dramatically by hour and location based on generation availability, creating complex pricing mechanisms that reflect physical system constraints rather than simple commodity economics. These multidimensional interconnections require new market design and regulation. Existing regulations, designed for unidirectional energy flow and centralized generation, are ill-equipped to handle the complex bidirectional transactions inherent in distributed renewable energy systems. They also necessitate sophisticated management systems where data flows become as critical as energy flows—a relationship entirely foreign to fossil fuel operations.

Alongside these changing interconnections, the fossil fuel system generated powerful emergent properties, mostly unintended, that arose from the interaction between fixed resources, technological systems, and economic incentives. These emergent properties—from climate disruption to particular geopolitical arrangements—developed gradually over decades, often becoming apparent only after they were deeply entrenched. The relatively stable and predictable nature of fossil energy systems allowed these emergent properties to be observed and eventually managed, albeit imperfectly.

In stark contrast, renewable energy systems are creating fundamentally different emergent phenomena. Market behaviours in renewable-dominant systems increasingly resemble complex adaptive systems in nature, with prices fluctuating in response to weather patterns, demand shifts, storage levels, and participant strategies. These markets exhibit characteristic properties of complex systems: non-linear responses, sensitivity to initial conditions, pattern formation, and adaptation. The “emergent intelligence” of these markets transcends the understanding of any individual participant yet arises from their collective behaviour.

Finally, renewable systems create unprecedented integration between digital and physical infrastructure, generating novel emergent behaviours at this interface. Smart grid technologies, automated trading platforms, and AI-driven optimization create system behaviours that no single algorithm or device was programmed to produce. The resulting “cyber-physical system” exhibits emergent properties that can only be understood by analysing the interplay between information processing, physical constraints, and network structures. Non-linear market behaviours create volatility but also opportunities for innovation. Traditional economic models struggle to predict emergent outcomes, necessitating new tools to assess system value and risk. Regulators must ultimately shift from static rules to flexible, data-driven approaches that respond to evolving system behaviours if they are to successfully navigate the complex, dynamic landscape of renewable energy systems.

5. Conclusion

The global energy system is undergoing a fundamental transformation from a commodity-based, extractive model to a technology and manufacturing-driven paradigm. This shift has profound implications across economic, geopolitical, and systemic dimensions. The traditional fossil fuel paradigm operates under a fundamentally different economic model than renewable energy systems, creating a stark contrast in resource dynamics, cost structures, and market behaviours. While fossil fuels embody a quintessential scarcity-based economy—requiring continuous extraction of finite, geographically concentrated resources that become progressively more expensive to access—renewable energy represents an abundance-based model centred on technology manufacturing. Once renewable infrastructure is constructed, the “fuel” itself arrives freely and perpetually, transforming energy from an extractive industry into what is essentially a one-time manufacturing challenge followed by decades of near-zero-cost harvesting.



The collision between Hotelling's Rule and the learning curve model represents perhaps one of the most profound economic disruptions in energy markets since the industrial revolution. While fossil fuel economics, theoretically, operates under Hotelling's principle—where increasing resource scarcity drives inexorably rising extraction costs and prices over time—renewable technologies follow the manufacturing-based “learning curve” model, where each doubling of cumulative production yields predictable cost reductions. Our analysis reveals these cost declines are remarkably consistent, with solar PV demonstrating the most dramatic learning effect, creating a virtuous cycle where increased deployment simultaneously enhances affordability.

The transition from extraction to manufacturing fundamentally reorients the factors determining competitive advantage in global energy markets. In the fossil fuel era, advantage derived primarily from controlling physical access to geological resources, with geographic accidents of resource distribution determining national wealth and corporate power. The renewable paradigm shatters this connection to geography, creating a “footloose” production model where manufacturing prowess, technological innovation, and cumulative production experience become the primary determinants of market leadership. This has enabled China's strategic capture of critical renewable supply chains, securing 85% of global solar module production and 79% of EV battery manufacturing by leveraging early investments, manufacturing scale, and aggressive deployment.

The manufacturing-based renewable energy paradigm necessitates a comprehensive reconceptualization of energy security, shifting focus from resource access to technological capability and supply chain resilience. Traditionally, energy security centred on securing reliable access to fossil fuel deposits through geopolitical alliances, military projection, strategic reserves, and international trade relationships. The renewable transition fundamentally reframes these concerns, prioritising instead the ability to manufacture, deploy, and control critical energy technologies domestically. Forward-thinking nations are already developing new security frameworks emphasising technological sovereignty, domestic manufacturing capacity, diversified mineral supply chains, and advanced recycling capabilities.

This manufacturing orientation has catalysed a global resurgence of industrial policy as nations race to secure leadership positions in clean energy technology production. Programs like the U.S. Inflation Reduction Act, European Net-Zero Industry Act, China's strategic lending to solar and battery manufacturers, and India's Production-Linked Incentive schemes represent a watershed shift from market-driven approaches toward strategic state intervention. While such measures create trade tensions and economic nationalism, they reflect the new reality that renewable manufacturing capacity has become a strategic national asset directly linked to economic competitiveness, job creation, export potential, and energy independence.

While renewable energy eliminates traditional fuel scarcity, it introduces new, qualitatively different scarcity challenges centred around raw materials and manufacturing capabilities rather than the energy sources themselves. The transition requires substantial quantities of critical minerals which face supply constraints due to geographic concentration and processing bottlenecks. However, these materials exhibit fundamentally different economic properties than fossil fuels: they aren't consumed during energy production but rather embodied in long-lived equipment, creating the potential for circular economy approaches through recycling and recovery. Moreover, the reliance on intermittent renewable generation fundamentally reshapes the nature of energy security, shifting it away from traditional fuel storage towards diverse flexibility solutions. Managing variable supply alongside variable demand requires geographic interconnection, storage solutions operating at multiple timescales, demand-side management, and sector coupling. This creates significant operational complexity but also opens opportunities for optimised, decarbonised, and democratised energy systems that transcend the constraints of fossil-based infrastructure. Furthermore, unlike fossil fuels, renewable energy installations have a larger, more visible spatial footprint, often requiring careful local planning to mitigate ecosystem impacts, habitat disturbances, and aesthetic concerns. Hence, effective renewable energy deployment requires governance frameworks capable of balancing diverse local interests, ensuring that the broader societal benefits of clean energy are not undermined by localised conflicts.



Finally, the renewable energy transition triggers profound system-level transformations that extend far beyond simple technology substitution. Traditional fossil fuel systems operated through well-defined boundaries, clearly demarcated sectoral divisions, and linear, predictable flows from extraction to consumption. Renewable energy dissolves these comfortable boundaries by blurring the line between producers and consumers, driving integration across previously separate sectors, creating bidirectional networked energy flows, and generating complex emergent behaviours. The resulting system increasingly resembles a complex adaptive network more than a linear infrastructure, necessitating entirely new governance approaches, market designs, and operational paradigms.

In sum, this transition not only reshapes traditional energy markets but also redefines geopolitics, industrial strategy, and the global economy for the decades to come. The competitive advantages of the new energy paradigm will accrue to those nations and organisations that most effectively navigate these shifts—recognising that manufacturing prowess, technological innovation, and systems integration capabilities now determine energy leadership more than geological fortune or resource control.



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Appendix A

A simple solution to Hotelling model can be provided as follows.

$$\max_{Q(t)} \int_0^T e^{-rt} \left[\underbrace{p(Q(t)) Q(t)}_{\text{revenue}} - \underbrace{c Q(t)}_{\text{extraction cost}} \right] dt$$

subject to the stock constraint

$$\dot{S}(t) = -Q(t).$$

To solve this, one typically uses optimal control (Pontryagin's Maximum Principle). We define the current-value Hamiltonian (which factors out e^{-rt}) as:

$$\mathcal{H} = p(Q(t)) Q(t) - c Q(t) + \lambda(t) [-Q(t)]$$

where:

$\lambda(t)$ is the shadow price (costate variable) of the resource stock $S(t)$.

In economic terms, $\lambda(t)$ measures the value of an additional unit of the resource in the ground at time t (often called the scarcity rent).

Because we are using a current-value Hamiltonian, the costate equation is:

$$\dot{\lambda}(t) = r \lambda(t) - \frac{\partial \mathcal{H}}{\partial S(t)}.$$

However, \mathcal{H} does not explicitly depend on $S(t)$ (only on $Q(t)$ and λ). Thus,

$$\dot{\lambda}(t) = r \lambda(t).$$

This implies:

$$\lambda(t) = \lambda(0) e^{rt}.$$

To maximize \mathcal{H} with respect to $Q(t)$, we set its partial derivative to zero:

$$\frac{\partial \mathcal{H}}{\partial Q(t)} = p(Q(t)) + \frac{\partial p(Q(t))}{\partial Q(t)} Q(t) - c - \lambda(t) = 0.$$

In many simplified treatments, price is taken as exogenous (or we treat $\partial p / \partial Q \approx 0$), especially under perfect competition. The result is that:

$$p(Q(t)) - c = \lambda(t).$$

That is, the net price ($p - c$) equals the scarcity rent ($\lambda(t)$).

The Hotelling Rule provide multiple insights. The fundamental insights of Hotelling model is that under conditions of perfect competition and no technological change, the price of an exhaustible resource should increase at the rate of interest. To show this, from the Hamiltonian formulation, we obtained the costate equation:

$$\dot{\lambda}(t) = r \lambda(t)$$

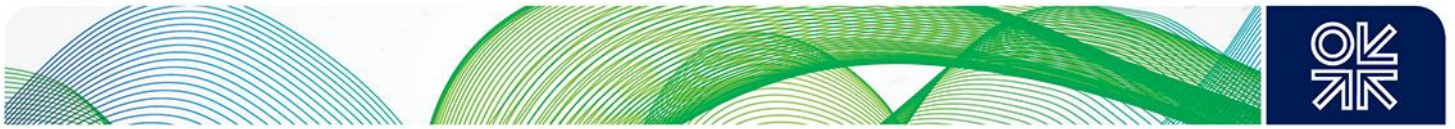
which solves to:

$$\lambda(t) = \lambda(0) e^{rt}$$

Since the optimality condition gives:

$$p(Q(t)) - c = \lambda(t)$$

we substitute the expression for $\lambda(t)$:



$$p(Q(t)) - c = \lambda(0)e^{rt}$$

Rearranging, we obtain the classic Hotelling Rule:

$$\frac{\dot{P}(t)}{P(t)} = r$$

where $P(t) = p(Q(t)) - c$ is the net price of the resource.



Appendix B

The learning curve model assumes that the cost of a technology decreases as its cumulative deployment increases, following the functional form:

$$c(X) = c_0 \left(\frac{X}{X_0} \right)^{-\alpha}$$

where:

- $c(X)$: Cost at cumulative deployment X (in 2023 USD per kilowatt, USD/kW),
- c_0 : Initial cost at the reference cumulative deployment X_0 (e.g., 2010),
- X : Cumulative deployment (in megawatts, MW),
- X_0 : Reference cumulative deployment (e.g., 2010),
- α : Learning parameter, capturing the strength of the learning effect.

The learning rate (LR) represents the percentage reduction in cost for each doubling of cumulative deployment and is calculated as:

$$LR = 1 - 2^{-\alpha}$$

Below, we outline the step-by-step methodology for estimating α and LR .

For each technology (CSP, Offshore Wind, Onshore Wind, and Solar PV), we used the following data from 2010 to 2023:

- **Cumulative Deployment** $X(t)$: Total installed capacity up to year t , in megawatts (MW).
- **Cost** $c(t)$: Capital cost of the technology in year t , in 2023 USD per kilowatt (USD/kW).

To estimate α , we transformed the learning curve equation into a linear form by taking the natural logarithm of both sides:

$$\ln c(X) = \ln c_0 - \alpha \ln \left(\frac{X}{X_0} \right)$$

Since X_0 is a constant, we can rewrite this as:

$$\ln c(X) = \ln c_0 - \alpha \ln X + \alpha \ln X_0$$

This equation can be expressed as a linear regression model:

$$y = \beta_0 + \beta_1 x$$

where:

$$\begin{aligned} y &= \ln c(X), \\ x &= \ln X, \\ \beta_0 &= \ln c_0 + \alpha \ln X_0, \\ \beta_1 &= -\alpha. \end{aligned}$$

Thus, the learning parameter α is obtained from the slope of the regression line as:

$$\alpha = -\beta_1$$