# The Economics of Clean Power in Africa

Technologies, Transition Pathways, and Business Impact

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# Executive Summary

The global transition toward net-zero emissions is redefining industrial competitiveness, energy systems, and the economic models of nations. For Africa, this transformation presents both a challenge and an opportunity to leapfrog traditional, carbon-intensive development pathways and build sustainable economies powered by clean, resilient, and inclusive technologies.

This paper explores the alternative technologies driving decarbonisation in renewable electricity generation, mobility, industry, and building sectors, while analysing how Platform Capital and other financial institutions are pioneering financial, technological, and advisory strategies that make this transition both commercially viable and socially transformative across the continent.

Through its Sustainable Green Energy Product leveraging solar solutions, Platform Capital along with its partners enables clients to pay only for the energy they consume, translating into 60–75% reductions in fuel expenditure, or annual savings of US$500,000–1,000,000 million for medium-sized facilities. Investments in innovators such as Koko Networks and Sannivation as examples further demonstrate the Platform's ecosystem-based approach supporting clean cooking, waste-to-energy, and distributed energy solutions that collectively reduce carbon footprints while expanding access to affordable energy.

This paper examines the wide array of emerging and established technologies that are accelerating global decarbonisation efforts across electrification and renewable energy transition, sustainable mobility and transport electrification, industrial decarbonisation and process innovation, and decarbonising buildings and energy efficiency. It highlights how these innovations collectively reduce dependence on fossil fuels, enhance energy efficiency, and enable the transition to low-carbon systems, while also analysing their regional adoption patterns, investment trends, and overall contribution to emissions reduction.

### Electrification and Renewable Energy Transition

Electricity lies at the heart of decarbonisation. The continent's vast solar, wind, hydro, and geothermal potential positions Africa as a future global hub for renewable energy production and export. Yet, high upfront costs remain a significant barrier to adoption. At Platform Capital, we address this through Zero Capex and Power-as-a-Service models, allowing adopters industries, hospitals, universities, and communities to access renewable energy infrastructure without bearing the initial capital burden. We are also introducing new hydro solutions that will leverage the vast pool of ponds, rivers and lagoons deploying cutting edge hydro solutions at significantly low capex to ensure the electricity demon hindering our country and continent is slayed once and for all

### Sustainable Mobility and Transport Electrification

The transport sector remains one of Africa's largest and fastest-growing sources of emissions. Platform Capital has been at the forefront of driving transport electrification, leveraging innovative financing and strategic advisory to accelerate the shift to electric vehicles (EVs). The Metropolitan Electric initiative, alongside other visionary entrepreneurs, seeks to establish SKD and CKD electric vehicle assembly plants in Nigeria positioning the country as a manufacturing hub at a time when many others remain focused solely on vehicle importation.

Through Zero Capex mobility models, fleet operators can now pay per kilometre or per kilowatt-hour consumed, avoiding up to 70% of initial capital outlays and achieving fuel and maintenance savings of US$3,000–4,000 per vehicle annually. Moreover, investments in EV charging networks and smart grid integration are laying the foundation for a continent-wide electric mobility ecosystem.

### Industrial Decarbonisation and Process Innovation

Industrial processes especially in steel, cement, and petrochemical sectors represent some of the hardest-to-abate emissions sources. Platform Capital's approach integrates renewable electrification, green hydrogen, and circular process design to help industries decouple growth from carbon intensity. For instance, switching from diesel to industrial solar or hybrid hydrogen power reduces energy costs from US$0.25/kWh (diesel) to US$0.10–0.12/kWh, yielding annual savings exceeding US$1 million for a 1 MW facility consuming 8 GWh annually.

By financing and aggregating industrial energy demand through joint-venture frameworks, Platform Capital lowers financing costs and enables economies of scale transforming heavy industry from carbon liabilities to engines of clean growth.

### Decarbonising Buildings and Energy Efficiency

Buildings account for nearly 40% of global energy use, driven by inefficient lighting, cooling, and heating systems. Platform Capital supports innovative retrofitting programs that integrate solar rooftops, efficient cooling technologies, and smart energy management systems into commercial and institutional buildings. By financing these upgrades under energy-as-a-service contracts, users can reduce operational costs by 30–50%, improve grid resilience, and enhance long-term asset value.

Underlying all these interventions is Platform Capital's financial innovation ecosystem a fusion of blended finance, carbon monetisation, and capacity development. Through hybrid financing structures, combining equity, concessional loans, and green bonds, the firm reduces project risk and financing costs by up to 30%, accelerating capital deployment. Its carbon credit monetisation programs enable adopters to generate new revenue streams from verified emission reductions, while local capacity-building initiatives lower maintenance costs and foster skilled employment. Together, these measures deliver net-positive returns within 3–6 years, a crucial horizon for investor confidence and scalability.

Africa's decarbonisation pathway is not solely a technological challenge it is a financial, infrastructural, and institutional transformation. Through strategic investments, innovative financing, and deep partnerships across renewable energy, transport, industry, and buildings, Platform Capital and other financial institutions are redefining how clean energy transitions are financed and scaled on the continent. By turning capital into climate impact and innovation into inclusion, we demonstrate that decarbonisation can be both profitable and transformative, positioning Africa not as a passive recipient of the global energy transition but as an active architect of a sustainable, low-carbon future.

This paper provides a detailed examination of each of the key themes driving the decarbonisation conversation that demonstrates attractive financial investment thesis enabling renewable energy to gain significant traction. It will highlight the key players driving innovation and adoption, from startups to established industry leaders, and explore the range of technologies and solutions being deployed.

In addition, the discussion will outline practical pathways for investors, entrepreneurs, and stakeholders to engage with these sectors, demonstrating how participation can yield both financial returns and contribute to broader decarbonisation and sustainability goals.

| Region | Sector | Emissions Reduced/Avoided ($MtCO_2$/yr) | Carbon Finance Attracted ($B/yr) | Carbon Infra. Framework (1-10) | Adoption Rate (%) |
|---|---|---|---|---|---|
| Asia Pacific | Electrification & RE Transition | ~3,000 (avoided) | 550 - 650 | 7 | RE Share: 30% of electricity |
| | Sustainable Mobility | ~135 (avoided) | 100 - 150 | 7 | EV Sales: ~20% (33% in China) |
| | Industrial Decarbonisation | Net Increase (+1,800) | 30 - 50 | 7 | Low-Carbon Steel: ~2% |
| | Building Decarbonisation | Net Increase | 300 - 400 | 6 | NZEB New Builds: ~5% |

| | | | | | |
|---|---|---|---|---|---|
| Europe | Electrification & RE Transition | ~850 (avoided) | 250 - 320 | 10 | RE Share: 44% of electricity |
| | Sustainable Mobility | ~80 (absolute reduction) | 80 - 100 | 10 | EV Sales: 24.4% |
| | Industrial Decarbonisation | -475 (absolute reduction) | 20 - 35 | 9.5 | Low-Carbon Steel: ~5% |
| | Building Decarbonisation | -475 (absolute reduction) | 150 - 200 | 10 | Heat Pump Sales: ~40% |
| North America | Electrification & RE Transition | ~750 (avoided) | 300 - 380 | 9 | RE Share: 26% of electricity |
| | Sustainable Mobility | ~60 (avoided) | 70 - 90 | 8 | EV Sales: 11.6% |
| | Industrial | -175 (absolute | 25 - 40 | 8 | Low-Carbon |

| | | | | | |
|---|---|---|---|---|---|
| | Decarbonisation | reduction) | | | Steel: ~4% |
| | Building Decarbonisation | -175 (absolute reduction) | 120 - 180 | 7 | Heat Pump Sales: ~45% |
| | Electrification & RE Transition | ~450 (avoided) | 30 - 50 | 6 | RE Share: 65% of electricity |
| | Sustainable Mobility | ~30 (avoided) | 5 - 15 | 5 | EV Sales: ~2.5% |
| | Industrial Decarbonisation | Net Increase (+50) | 1 - 3 | 5 | Low-Carbon Steel: ~10% (biomass) |
| | Building Decarbonisation | Net Increase | 10 - 25 | 4 | NZEB New Builds: <2% |
| Africa | Electrification & RE | ~125 (avoided) | 40 - 55 | 3 | RE Share: 24% of electricity |

| | | | | | |
|---|---|---|---|---|---|
| | Transition | | | | |
| | Sustainable Mobility | ~3 (avoided) | 3 - 8 | 2 | EV Sales: <0.5% |
| | | Net Increase (+100) | 0.5 - 2 | 3 | Low-Carbon Steel: ~0% |
| Middle East & Eurasia | Building Decarbonisation | Net Increase | 5 - 15 | 1 | NZEB New Builds: <1% |
| | Electrification & RE Transition | ~75 (avoided) | 40 - 60 | 5 | RE Share: 7% of electricity |
| | Sustainable Mobility | ~2 (avoided) | 5 - 10 | 4 | EV Sales: ~1.5% |
| | Industrial Decarbonisation | Net Increase (+125) | 5 - 15 | 4 | Low-Carbon Steel: ~0% |

| | | | | |
|---|---|---|---|---|
| Building Decarbonisation | Net Increase | 15 - 30 | 3 | NZEB New Builds: ~3% |

Matrix Table: Regional & Sectoral Climate Progress Metrics

Key Data Notes:

1. **Emissions:** "Avoided" = lower than a business-as-usual baseline. "Absolute Reduction" = lower than a historical peak.
2. **Finance:** Represents annual capital flows (investment, climate finance, VCM). Rounded to major bands.
3. **Framework:** Composite score based on strength of carbon pricing, binding laws, and regulatory maturity.
4. **Adoption:** Chosen as the most representative single KPI for sector transition in each region.
5. **Industrial & Building Sectors:** "Net Increase" in emissions denotes that efficiency gains are overwhelmed by activity growth.

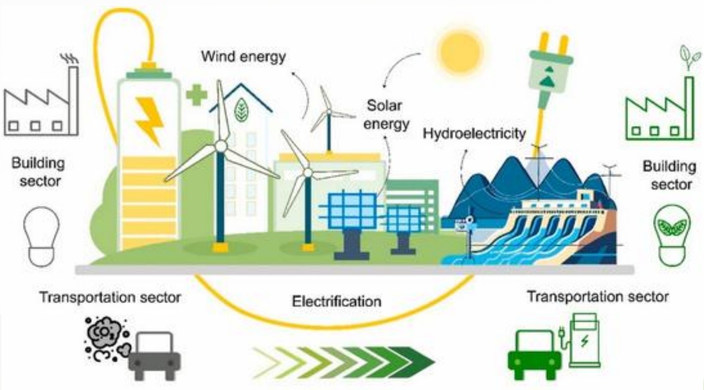
# Section 1

# Introduction

## Introduction

The central energy challenge of the 21st century has shifted. It is no longer sufficient merely to expand energy supply; the imperative now is to grow energy supply without carbon emissions. In other words, the world must decouple energy access, economic development, and social progress from fossil-fuel dependency. This is the heart of the decarbonisation agenda.

Decarbonisation refers to the transformation of energy systems, infrastructure, industrial processes, and consumption patterns so as to reduce net greenhouse-gas (GHG) emissions (typically expressed in $CO_2$-equivalent). It is not a minor tweak to existing systems, but a systemic overhaul a reconfiguration of how we generate, store, transmit, and consume energy; a reimagining of mobility, buildings, industry, and the underlying infrastructure that supports them. Since existing energy systems are deeply intertwined with economic, institutional, and social structures, decarbonisation is as much about governance, finance, and behaviour as it is about engineering (Giotitsas et al., 2022).



Clean energy in the decarbonization transition of multiple sectors

When one says "decarbonisation," it is often shorthand for energy-sector decarbonisation that is, reducing emissions arising from the generation, distribution, and consumption of energy. But energy consumption happens across varied end-use sectors; in particular, decarbonisation efforts often focus on power (electricity & heat), transport, industry, and buildings.

- **Power / electricity & heat generation** is foundational: many decarbonisation strategies rely on shifting generation away from fossil fuels (coal, natural gas, oil) and instead toward zero- or low-carbon generation sources (solar, wind, hydro, geothermal, bioenergy, nuclear). Because electricity is a universal vector, its decarbonisation underpins decarbonising other sectors via electrification.
- **Transport** is a major direct consumer of liquid fuels (gasoline, diesel, jet fuel), and today remains heavily dependent on fossil fuels. Decarbonisation in transport entails electrification (battery electric vehicles), fuel switching (hydrogen fuel cells, synthetic fuels, biofuels), modal shifts (public transit, non-motorized), and logistics redesign. According to the IPCC, the transport sector accounts for ~ 15–16 % of global greenhouse gas emissions, primarily from road vehicles, but aviation and shipping are also significant and particularly challenging to decarbonize (Bach, 2023).
- **Industry** covers energy-intensive processes (e.g. steel, cement, chemicals), plus furnaces, high-temperature heat, and chemical feedstocks. Some emissions are from fuel combustion; others are process emissions (e.g. $CO_2$ liberated when carbonate inputs are calcined in cement). Because of this dual nature, industrial decarbonisation is complex some of it can be addressed by electrification and renewable energy, but some will require hydrogen, carbon capture/utilization and storage (CCUS), or material substitution. Globally, industry accounts for ~ 24 % of emissions (excluding electricity usage), per U.S. EPA breakdowns (EPA, 2025).
- **Buildings** (residential, commercial, institutional) consume energy for heating, cooling, lighting, appliances, and sometimes on-site fuel combustion (e.g. gas, oil, biomass). The emissions from buildings are often counted partly under "energy" or "electricity" sectors, depending on who does the accounting, but regardless, buildings are a major locus of demand-side decarbonisation. The "operational" emissions (from buildings' energy use) are well studied, but increasingly the embodied emissions (from materials, construction, renovation, demolition) are being recognized as crucial to include. For example, the building

sector is estimated to account for ~ 33–37 % of global energy consumption and close to that proportion of emissions when embodied carbon is included (Zhang et al., 2024).

By concentrating on these four sectors power generation, mobility, industrial processes, and buildings, this paper addresses the primary sources of global energy-related emissions, which collectively account for over 70% of total greenhouse gas outputs. These areas represent the most critical levers for advancing deep decarbonisation, driving systemic transformation, and achieving sustainable, low-carbon economic growth.

### Geography & Regional Differentiation: Global + Regional Examples

Climatic warming, rising sea levels, extreme weather events, and environmental feedbacks do not respect national borders. To meet internationally agreed goals such as limiting global warming to 1.5 °C or 2 °C above pre-industrial levels countries must collectively reduce greenhouse gas emissions. Yet although the target is global, the pathways to reach it must be intensely local or regional in design, because resource availability, economic structures, institutional capacity, grid infrastructure, finance costs, and social preferences differ markedly from place to place. Any serious decarbonisation analysis must therefore balance a global framing (to understand cumulative emissions, technology learning curves, shared global challenges) with regional differentiation (to uncover realistic, cost-effective, locally feasible pathways).

### Key Factors Driving Renewable Energy Adoption and Feasibility

1. **Resource endowments**: The natural availability of renewable resources (solar irradiation, wind speed, hydropower potential, geothermal) is highly uneven. Regions with high solar insolation (deserts, tropical and sub-tropical zones) can leverage solar PV and concentrating solar power (CSP) more cost-effectively. Regions with long and windy coastlines can exploit offshore wind; regions with mountainous terrain and rivers may have hydropower advantage.
2. **Grid architecture and existing infrastructure**: The configuration of transmission networks, whether grids are centralized or decentralized, the existing generation mix (how much fossil vs low-carbon), and whether interconnection to neighbouring regions is feasible influence which technologies are practical. Regions with weak grids or isolated systems may find

distributed technologies (solar mini-grids, micro-hydro) more feasible in short-term than large centralized ones.

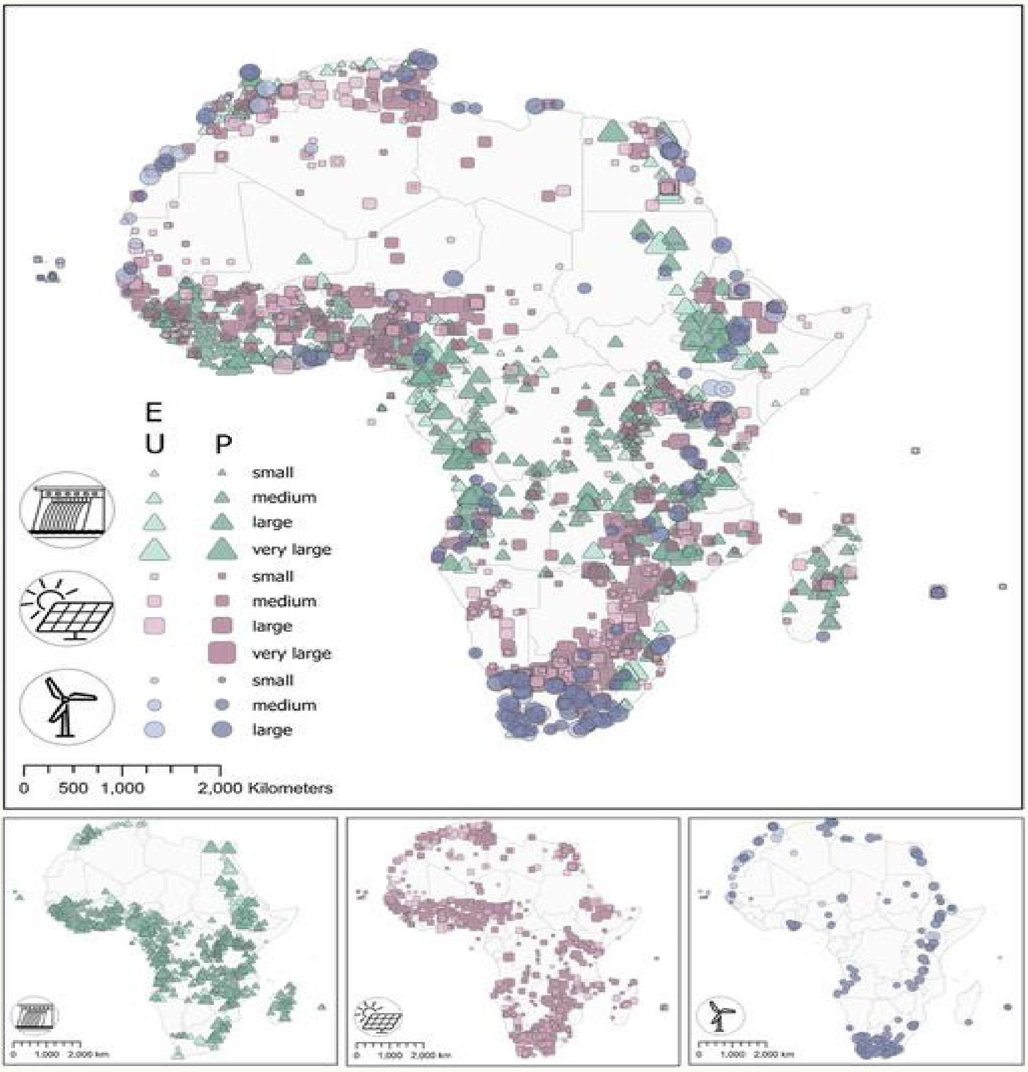
3. **Institutional and regulatory capacity**: Permitting, land rights, environmental regulation, policy stability, local supply chain capacity, investor confidence all of these shape cost and risk. A region may have excellent resource potential but weak institutional frameworks, high political or regulatory risk, which raises cost of capital and slows deployment.
4. **Economic structure and industrial profile**: If a region has heavy industrial activity (steel, cement, chemicals) then hard-to-abate sectors will dominate emissions and require specialized technologies (CCUS, hydrogen, process electrification). On the other hand, regions with largely service-oriented economies might focus more on building efficiency, transport electrification, renewables for power supply.
5. **Capital costs / cost of financing**: Regions differ in how expensive capital is for example, interest rates, risk premiums, debt availability. High cost of capital in many developing countries means that technologies with high upfront capital requirements are more expensive in local currency terms. Differences in financing can shift the comparative advantage between technologies requiring high CAPEX vs those with higher operational costs but lower upfront investment.
6. **Social, land, environmental constraints**: Land availability or suitability, competing land uses (agriculture, conservation), water availability (for cooling or hydropower), environmental impact concerns differ across regions and may limit or raise costs of certain technologies.
7. **Demography**: Population size, density, age structure, and urbanization rates significantly affect energy demand patterns and technology suitability. Rapid urbanization, common in Africa and Asia, increases demand for reliable electricity, public transport, and energy-efficient buildings, thereby accelerating electrification and clean energy adoption. Meanwhile, regions with dispersed rural populations may prioritize off-grid or mini-grid solutions to ensure equitable energy access. Youthful populations also tend to drive innovation and technology adoption, while aging societies may face slower transition rates due to lower workforce flexibility and investment appetite.
8. **Natural Disasters and Climate Vulnerability**: The frequency and severity of natural disasters such as floods, droughts, cyclones, earthquakes, and wildfires are critical determinants of infrastructure resilience and technology choice. These events directly influence where and how energy systems can be deployed and maintained. For instance, coastal or cyclone-

prone regions must design wind and solar installations with enhanced structural durability, while drought-prone regions may find water-intensive technologies, such as certain thermal or hydropower systems, less feasible due to competing water demands.

Moreover, regions that experience recurring natural disasters often develop stronger policy and public awareness toward clean energy adoption. For example, cities like California, which frequently endure devastating wildfires, are increasingly motivated to accelerate their transition to renewable and decentralized clean energy systems. The first-hand impact of climate change ranging from rising temperatures to prolonged droughts and wildfire-induced power outages have made resilience and sustainability central to California's energy policy. As a result, the state is investing heavily in solar microgrids, battery storage, and wildfire-resistant transmission infrastructure to enhance grid reliability while reducing emissions. These examples underscore those natural disasters not only pose risks to existing infrastructure but also serve as catalysts for change pushing governments, industries, and communities to adopt cleaner, more resilient energy solutions. Incorporating climate-resilient design principles, redundancy, and diversification into energy infrastructure is therefore essential to sustaining long-term decarbonisation goals amid escalating climate risks and environmental uncertainties.

### Sub-Saharan Africa: Solar and decentralized renewables

Sub-Saharan Africa possesses abundant solar irradiation and many sunny days, making solar energy one of the region's most promising low-carbon energy sources; yet many rural areas remain under-electrified, with weak or non-existent grid infrastructure, high dependency on diesel or kerosene for backup, and frequent outages. In response, decentralized and off-grid solutions solar home systems, mini-grids, and even small-scale concentrating solar power (CSP) hold particular appeal. Pilot CSP installations, for example the micro-CSP projects in northern Ghana under the TBHEC-CSP4Africa initiative, have demonstrated that locally sourced materials, simpler designs, and high community involvement can lower local power costs and build technical capacity, though they also reveal challenges: misaligned solar tracking and heliostat focus issues reduce operational efficiency, and high capital and maintenance costs (especially for tracking, mirror alignment, and control systems) remain barriers to scaling. (Ramde et al., 2020).



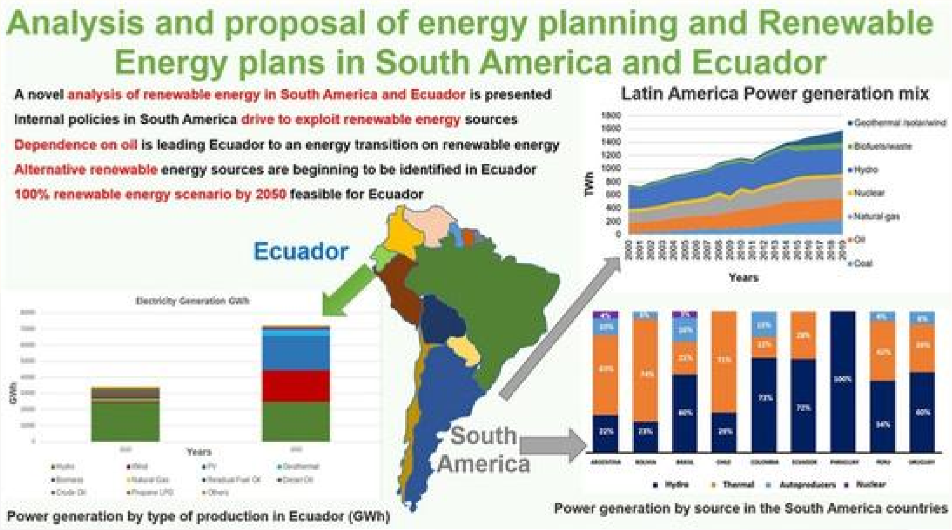

*Map of all hydropower, solar power and wind power plants as compiled in the African Renewable Power Plant database (RePP Africa). Symbol colour and shape indicate renewable energy type; colour intensity indicates status (E - existing and U - under construction, P - proposed); symbol size indicates capacity in megawatts [MW] with small 1–10 MW, medium >10–100 MW, large >100–1000 MW, and very large >1000 MW. No plants are located on open water; all facilities not located on the mainland are located on islands. Image Credit: University of Tübingen*

Meanwhile, in Kenya, solar mini-grids have brought tangible socioeconomic gains: after connection, households reported healthier indoor environments owing to reduced kerosene lamp use; income among many increased; productivity rose; communities gained access to electrical appliances, lighting and clean water; and emissions dropped relative to fossil-fuel-based backups. (Carabajal et al., 2024). For Nigeria, an increasing number of companies, factories, and industrial facilities are actively transitioning to renewable energy sources such as solar and hybrid systems to reduce dependence on diesel generators, lower operational costs, and align with global sustainability and decarbonisation goals.

Nonetheless, the cost of capital in Sub-Saharan Africa tends to be high, institutional and regulatory risks are often elevated, and financing large-scale centralized storage or long transmission lines is difficult. These constraints imply that while decentralized solar systems are economically promising, assessing return on investment must account for local financing costs, system reliability, operations & maintenance challenges, and policy/regulatory uncertainty. Solar mini-grids and CSP pilots thus offer both a roadmap and a warning: promising potential for clean energy access and emissions reduction, but only if the design, financing, regulatory framework and local capacity are robust.

### Latin America & Hydropower base + Renewables growth

Latin America has long built its low-carbon electricity backbone on hydropower, with countries like Brazil, Colombia, Peru, and Ecuador relying heavily on large dams to supply a major slice of their renewable electricity. Brazil, for instance, gets much of its electricity from hydropower, giving it a “low-carbon baseline” that reduces the urgency of constructing gigawatts of zero-carbon generation from scratch.




However, hydropower growth especially from large dams is slowing in many Latin American nations as the region runs into environmental, social, and resource constraints. Issues such as land inundation, displacement, ecological disruption, and opposition from local communities are increasingly prominent. Also, the number of viable dam sites with favourable hydrology and acceptable environmental trade-offs is diminishing; climatic changes like reduced rainfall or altered river flow are increasing risks for hydropower reliability. BP, in its Energy Outlook, projects that hydropower output growth in South and Central America will peak before 2030 and then taper off thereafter even under its evolving-transition scenario, while non-conventional renewables (solar, wind) continue more rapid expansion (Factor This, 2019).

In light of this, Latin American countries are turning more aggressively to solar PV and wind (onshore and in some coastal cases offshore). Countries such as Chile, Brazil, Mexico, and Argentina are expanding their solar and wind capacity markedly. The International Energy Agency (IEA) notes that Latin America will likely see the share of electricity from solar PV and wind double by 2030 and continue growing through 2050, especially under more ambitious policy settings (IEA, 2023).

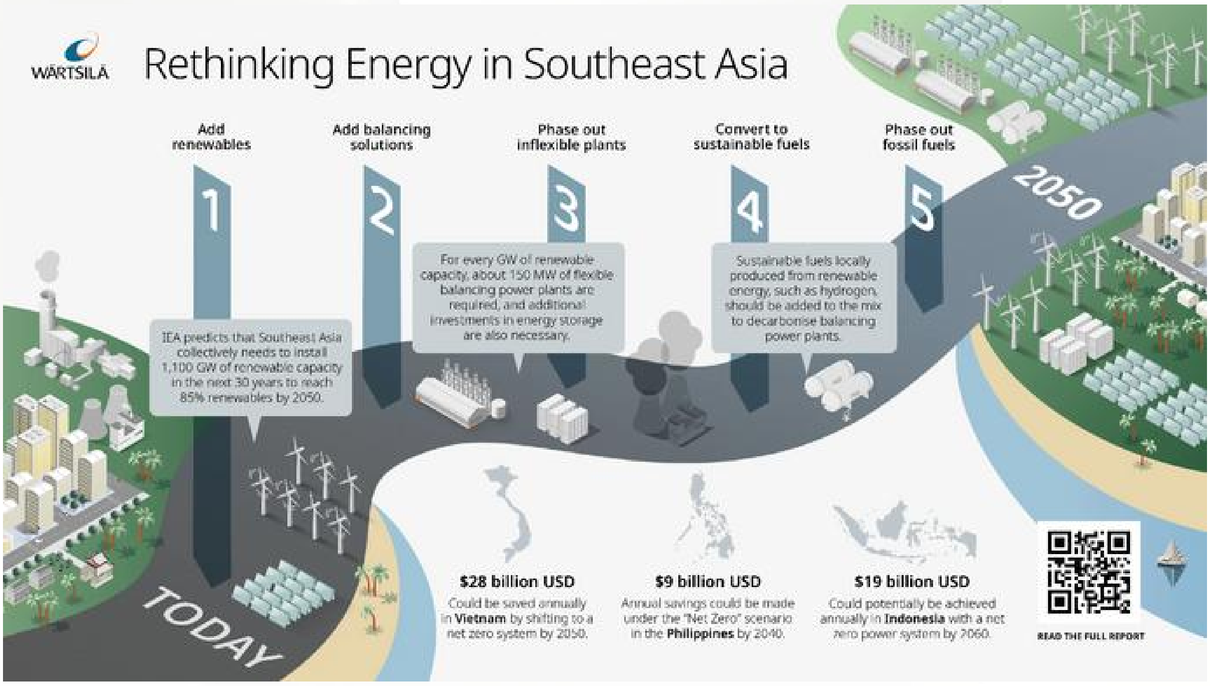
A striking example is Chile's national clean hydrogen push. Leveraging its abundant renewable energy resources (solar and wind), Chile is aiming to build electrolysis capacity to produce green hydrogen, both for domestic decarbonisation and for export. In its "National Green Hydrogen Strategy" (fully adopted in 2022), the country targets 5 GW of electrolyzer capacity by 2025 and 25 GW by 2030, while setting ambitious cost targets (around USD 0.8-1.1 per kilogram) that would make its hydrogen globally competitive. Mexico, Colombia, and others are also exploring similar paths, but Chile's strategy has stood out in terms of scale and planning (Day, 2024).

These shifts carry significant implications. First, the strong hydropower base provides Latin America with operational flexibility and a firm foundation for integrating intermittent renewables hydro dams with storage or regulation capacity can buffer solar and wind variability. Second, as solar and wind grow, there will be increasing demands on grid infrastructure, transmission lines, and interconnection, especially to connect remote solar or windy zones to load centres. Third, for clean hydrogen to truly scale, substantial infrastructure investments are needed not just electrolysis, but desalination (in some cases), renewable power generation dedicated to hydrogen, logistics, and ports (where exports are concerned). Chile's H2 Magallanes project, for example, involves a 10 GW wind farm, electrolysis plants, a desalination plant, an ammonia facility, and export infrastructure (Reuters, 2025).

But challenges remain. Environmental and social concerns over dam construction continue to slow or block new hydropower projects; climate variability threatens hydropower reliability; regulatory hurdles, permitting delays, and difficulties securing finance add friction; and exporting green hydrogen raises issues of scale, cost, and global competition. Moreover, while many Latin American countries are seeing increases in renewable investment, the cost of capital, policy stability, and infrastructure readiness vary markedly among nations, influencing how fast and how deeply they can shift their energy mixes. In sum, Latin America's energy transition is moving from being hydropower-led toward a more diversified renewables base including solar, wind, and emerging clean fuels. Hydropower remains a critical pillar, but its expansion is constrained; the new growth comes from those technologies that complement hydropower and enable decarbonisation beyond what dams alone can provide. This mixed pathway seems not only more sustainable socially and environmentally, but increasingly inevitable under both policy and climate pressures.

### East Asia & Southeast Asia: Offshore wind expansion, regulatory maturity, coastal constraints

Across East Asia and Southeast Asia, the push toward offshore wind expansion is gaining momentum, driven by a combination of rising onshore constraints, coastal geography, and increasing maturity in regulatory and industrial capacity. Coastal East Asian countries such as China, Japan, South Korea, Taiwan, and Vietnam find themselves at the forefront: as land becomes scarcer or more contested for development, offshore wind offers a compelling alternative. In fact, Asia-Pacific offshore wind capacity is projected to grow about twentyfold by 2027, reaching roughly 43 GW, with China leading and Taiwan accelerating in its deployment (Wood Mackenzie, 2018).




In Southeast Asia, too, many nations boast extensive coastlines but limited viable land for large-scale solar farms, making offshore wind particularly attractive. The Philippines, for example, is estimated to possess some 178 GW of technical offshore wind potential; under high-growth scenarios, it could deploy about 21 GW by 2040. In Vietnam, early pilot projects are underway, and some studies project that offshore wind could contribute around 12 % of the country's electricity by 2035 (Societe Generale, 2023).

Yet significant challenges lie beneath the promise. Many prospective offshore sites are in deep waters, which necessitates floating foundations rather than fixed-bottom platforms technology that is more complex and costly. Grid interconnection infrastructure (subsea cables, offshore-to-onshore transmission) must be expanded and strengthened. Investor confidence depends heavily on stable regulatory regimes and predictable policies over decades, including permitting, environmental oversight, and maritime spatial planning. In Japan, for example, the target of 45 GW by 2040 is ambitious, but geographic constraints deep coastal waters, typhoon risk, and complex approval processes temper expectations and raise costs (Global Wind Energy Council, 2025).

Thus, while East and Southeast Asia are among the most promising regions for offshore wind deployment, the transition requires overcoming technical, regulatory, financial, and infrastructural hurdles. Success will depend not only on resource potential, but on building robust supply chains, regulatory certainty, grid integration, and technological innovation (especially in floating wind systems).

### Regions with abundant hydropower & existing renewable infrastructure

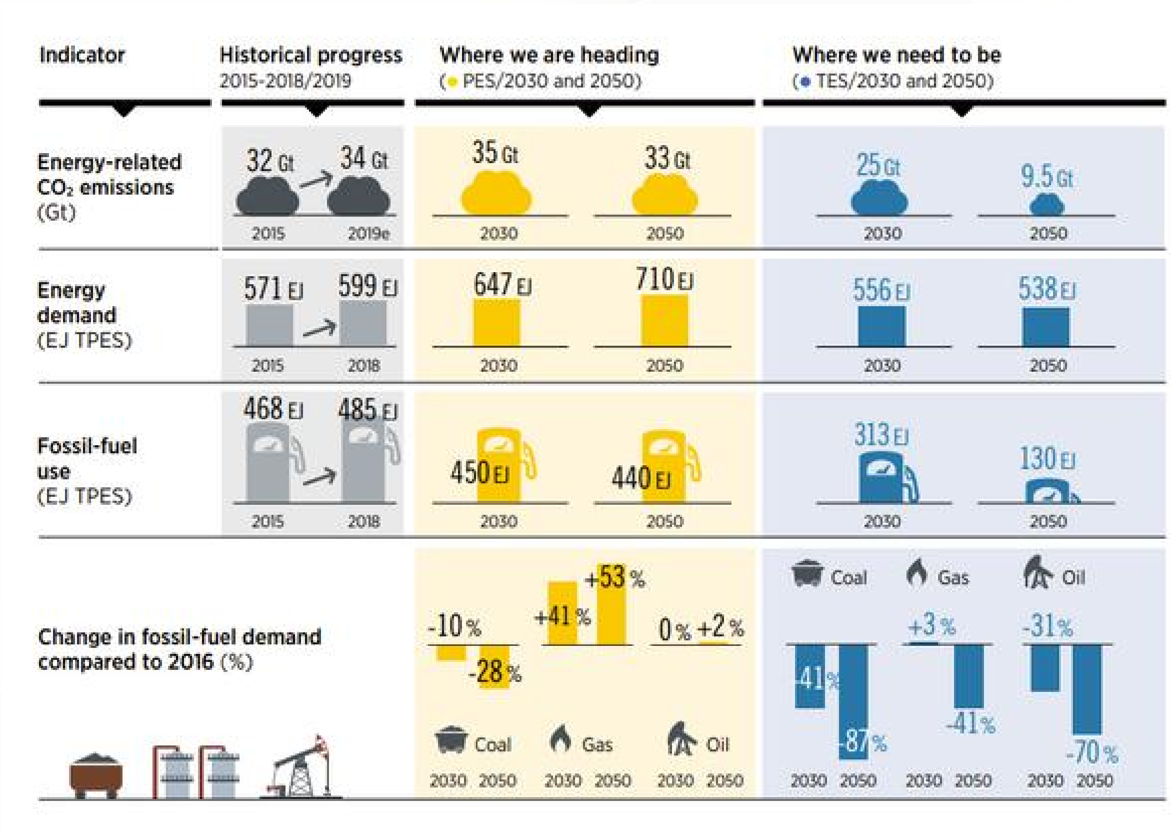
Regions endowed with abundant hydropower and established renewable infrastructure such as Southeast Asia (notably Indonesia, Laos, and Malaysia), Latin America, and other mountainous or river-rich areas enjoy a natural advantage in the global energy transition. Their existing hydropower capacity provides a source of dispatchable low-carbon electricity, which enhances grid stability and can serve as a reliable backbone for integrating variable renewable sources such as solar and wind. Hydropower's ability to ramp generation up or down in response to fluctuations in renewable output makes it a crucial enabler of decarbonisation, offering system flexibility and supporting baseload power needs. However, hydropower is not without risks. Climate change is altering regional hydrological cycles affecting rainfall patterns, glacial melt, and river flow which in turn undermines the predictability and reliability of hydropower output. In recent years, severe droughts in parts of Latin America have exposed these vulnerabilities; for example, Ecuador and Brazil have faced electricity shortages and rising prices when droughts sharply curtailed hydropower generation, prompting governments to activate fossil-fuel backup plants and import power to stabilize grids (WIRED, 2024). Such events underscore that while hydropower is low-carbon, it is not climate-proof. Moreover, new hydropower developments frequently encounter environmental, social, and regulatory hurdles, including concerns over ecosystem disruption, biodiversity loss, displacement of local communities, and contentious water-use rights. These challenges not only delay project approvals but also reduce public support and increase financial risks, leading many countries to reconsider large-scale dam construction in favour of smaller, more sustainable alternatives or hybrid systems that combine hydropower with solar and storage. Consequently, while regions with strong hydropower foundations hold a comparative advantage in achieving deep decarbonisation, their future energy resilience depends on diversifying renewable sources and implementing adaptive water and energy management strategies that can withstand climatic variability.

### Time Horizon: 2030, 2050 and Intermediate Milestones

One cannot talk meaningfully about decarbonisation without specifying a temporal horizon. Because the climate stakes are tied to cumulative emissions, and because technology transitions take decades, choosing time markers is critical.

A meaningful discussion of decarbonisation must begin with the selection of time horizons, because climate outcomes depend on cumulative emissions and energy transitions inherently unfold over decades.

Without clearly defined temporal benchmarks, comparisons of pathways or policy proposals risk being ambiguous or misleading. In much of the climate modelling and policy literature, two anchor points stand out: **2030** and **2050**, with intermediate milestones (such as 2040) frequently used to interpolate progress.




The changing nature of energy and fossil-fuel useEnergy-related CO2 emissions, energy demand and fossil-fuel outlook

The near-term horizon of 2030 is commonly employed to represent a transitional phase: it marks the period over which early deployment of mature technologies must scale, cost reductions (via learning curves) must be realized, and “lock-in” of carbon-intensive infrastructure must be forestalled. Many countries set their Nationally Determined Contributions (NDCs) for 2030, and global emission reduction pledges typically aim for substantial cuts by that year (UNFCCC, 2021). The 2030 marker thus acts as both a political and technical checkpoint, indicating which technologies must already be deployed and where momentum must be built.

By contrast, **2050** is often adopted as the long-term target by which many nations and organizations aim to reach net-zero emissions, encompassing the full transformation of energy systems, end-use sectors, and industrial processes. The 2050 horizon allows for deep integration of novel technologies such as hydrogen, advanced carbon removal, long-duration storage as well as the retirement or repurposing of legacy fossil infrastructure. Framing ambition relative to 2050 helps align with climate goals (e.g. pathways consistent with limiting warming to 1.5 °C) (IEA, 2021; UNFCCC, 2021).

Including intermediate milestones, such as 2040 or 2035, enriches the analysis by adding granularity to the transition trajectory. These midpoints help to expose the pace and sequencing of deployment, reveal whether certain technologies or sectors are lagging, and make visible the emergence of constraints or stranded assets. In practice, adopting both 2030 and 2050 as target points and anchoring scenarios around them enables analysts to trace transitional pathways: for example, to delineate which investments must begin early (say, in the 2020s) if 2050 outcomes are to remain feasible, how cost curves might evolve over time, and under what conditions stranded capital or technological “lock-in” risks may materialize (Eitan et al., 2023; Mercure et al., 2013).

This dual-horizon orientation yields several advantages. First, it highlights a tension between near-term pragmatism and long-term ambition: in the near term, priority might lie in deploying proven, scalable technologies and building enabling infrastructure (e.g. transmission, manufacturing capacity), while in the longer term, more experimental or capital-intensive solutions may become viable. Second, it surfaces timing constraints: delay beyond certain tipping points for example, postponing investment until 2035 may foreclose lower-cost trajectories or force more drastic shifts later, increasing system cost or risk. Third, comparing performance across the two horizons allows one to assess whether early actions generate durable momentum or risk dead ends.

Indeed, cumulative emissions to 2030 help determine how much carbon “headroom” remains. Because the remaining carbon budget compatible with 1.5 °C is already constrained, delays in the 2020s compound into steeper required rates of decarbonisation later (IPCC, 2018). Thus, defining and consistently applying these temporal anchors strengthens comparison across technologies, regions, and scenarios, and ensures decisions are grounded in the physics of the climate system as well as in technological realities.

Going forward, this paper will therefore undertake an in-depth exploration of the key sectors driving Africa's decarbonisation journey, namely power and electricity generation, mobility, industrial processes, and buildings.

For each sector, the discussion will highlight the major players ranging from innovative startups to established corporations who are pioneering the adoption of renewable energy and low-carbon technologies. Furthermore, the paper will examine the opportunities for participation, outlining how investors, entrepreneurs, and other stakeholders can engage with these sectors. By detailing technological, financial, and policy pathways, it aims to provide actionable insights into how participation can generate both economic returns and environmental impact.

# Section 2 —

# Renewable Electricity Generation Technologies

### Renewable electricity generation technologies

Renewable electricity generation technologies are central to global efforts to lower greenhouse gas emissions and transition towards sustainable energy systems. Broadly speaking, renewable generation includes solar, wind, hydropower, geothermal, and bioenergy (including biomass, biogas) technologies as well as emerging marine sources such as tidal and wave energy. Each of these technologies has distinct characteristics, maturity levels, advantages, and limitations, and each plays different roles in different geographies depending on resource availability, cost, grid infrastructure, and policy support (National Academies of Sciences, Engineering, and Medicine [NASEM], 2010; Hemeida, Hemeida, Senjyu, & Osheba, 2022).

Solar photovoltaics (PV) and concentrated solar power (CSP) convert sunlight directly into electricity (PV) or use concentrated sunlight to drive thermal conversion (CSP). Over the past decade, solar PV has experienced steep cost declines, making it among the lowest-cost options for new electricity in many regions. CSP, while less widespread, offers advantages where thermal storage is used, enabling solar power to generate electricity beyond daylight hours. However, solar technologies face challenges such as intermittency, land use (for utility-scale plants), and dependence on local solar irradiance (Hemeida et al., 2022). Wind energy is already a mature technology in many countries. Onshore wind turbines are widely deployed; offshore wind is rapidly growing, especially where coastal or offshore wind speeds are high and land is constrained. Wind's intermittency (variation with weather) and the need for grid flexibility and storage are key integration challenges. Still, wind's high-capacity factors in favourable sites make it highly competitive under many scenarios (NASEM, 2010).

Hydropower both large-scale dams and smaller run-of-river installations provides dispatchable renewable electricity. Its ability to ramp generation up and down quickly makes it valuable for balancing grids, especially with variable sources like solar and wind. In some regions, hydropower constitutes a large share of existing renewable capacity, offering a low-carbon baseline. Nevertheless, hydropower is subject to environmental, social, and hydrological constraints: reservoir impoundment can disrupt ecosystems and communities; droughts or changing rainfall patterns can undermine reliability; and many of the most viable large dam sites are already developed or contentious (Hemeida et al., 2022; NASEM, 2010).

Geothermal energy uses heat from the Earth's interior for electricity generation (as well as direct use heat). It is highly reliable and provides baseload power where geological conditions are favourable. However, upfront exploration risk, high drilling costs, and site specificity limit its deployment in many regions. Bioenergy (including biomass combustion, biogas, or waste-to-energy) offers potential both for electricity generation and for coupling with carbon capture in some models (i.e., BECCS – bioenergy with carbon capture and storage). Bioenergy's advantages include its dispatchability and potential for using waste streams. But there are concerns: competition for land (food vs fuel), sustainability of feedstock, life-cycle emissions, and the risk of deforestation or other negative environmental impacts (Hemeida et al., 2022). Emerging and marine renewables such as tidal, wave, and ocean thermal energy conversion are less mature but potentially promising particularly for coastal regions. Their consistency is often better than solar or wind in some contexts, but technological, environmental, and economic challenges remain, including high capital costs, maintenance in marine environments, and limited commercial scale deployments.

From a systems perspective, the integration of these renewable technologies requires grid flexibility (storage, demand management, transmission enhancements), policies that support stable investment, and infrastructure to match generation with load. Complementarity among sources (e.g., solar + wind + hydropower) can mitigate variability and ensure reliability (Jurasz, Canales, Kies, Guezgouz, & Beluco, 2019). The relative cost competitiveness of renewables has improved markedly; many new renewable projects are now cheaper than new fossil-fuel generation when full cost including environmental externalities is considered (IRENA, as reported in recent news).

These renewable generation technologies offer a diverse portfolio of options. Solar PV and wind are leading in cost reduction and deployment scale; hydropower provides dispatchability and a long-standing renewable base; geothermal and bioenergy fill niches in reliable or flexible supply; and marine renewables offer future promise. The trade-offs between cost, reliability, environmental and social impacts, geographic suitability, and integration challenges mean that no single technology is sufficient combinations and systems approaches are essential for robust decarbonization pathways.

### Solar Photovoltaics (PV) and Concentrating Solar Power (CSP)

Solar technologies principally photovoltaic (PV) systems and concentrating solar power (CSP) are central to contemporary decarbonisation strategies because they convert abundant solar energy into electricity with little or no operational greenhouse-gas (GHG) emissions. Although both convert sunlight to electricity, they do so via different physical principles, component sets, and system designs, which produce distinct performance characteristics, environmental footprints, supply-chain requirements, and deployment pathways. The following essay provides an integrated, evidence-based discussion of technical variants, maturity and deployment status, performance metrics, environmental and social impacts, supply-chain and critical-mineral risks, innovation frontiers, comparative analysis, and scaling challenges for utility and distributed PV and for CSP.

### Technical description and variants

Solar power technologies are broadly divided into two main categories photovoltaic (PV) systems and concentrating solar power (CSP) systems each employing distinct scientific and engineering principles to harness the sun’s energy for electricity generation. These technologies are continuously evolving, characterized by advances in materials science, system design, and energy conversion efficiency. Understanding their technical configurations and variants is essential to evaluate their suitability across geographical, economic, and policy contexts.

### Photovoltaic (PV) Systems

Photovoltaic (PV) systems directly convert sunlight into electricity through the *photovoltaic effect*, which occurs in semiconductor materials when absorbed photons excite electrons, generating an electric current. The basic unit of a PV system is the solar cell, which is typically connected in series and parallel combinations to form modules and arrays. The dominant commercial PV technology today is *crystalline silicon* (c-Si), which accounts for over 90% of global production due to its balance of efficiency, cost, and reliability (IEA, 2024). Crystalline silicon modules are subdivided into *monocrystalline* and *multicrystalline* (polycrystalline) types. Monocrystalline silicon cells are made from single-crystal ingots, offering higher efficiencies (typically 20–23%) but higher production costs, while multicrystalline cells, produced from multiple crystal grains, have slightly lower efficiencies (17–20%) but are cheaper to manufacture (NASEM, 2010; IEA-PVPS, 2024).

Beyond crystalline silicon, *thin-film* technologies represent another major class of PV systems. These include cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si). Thin-film modules deposit active semiconductor layers onto substrates such as glass or metal, reducing material use and enabling flexible, lightweight configurations. CdTe modules have achieved commercial efficiencies exceeding 19%, with lower manufacturing costs and shorter energy payback times than silicon modules (NREL, 2024). However, they rely on scarce elements such as tellurium and indium, which raises supply-chain and sustainability concerns (OECD, 2022). CIGS modules also demonstrate high performance in diffuse light conditions and can be integrated into building façades or curved surfaces, contributing to the diversification of solar applications (IEA-PVPS, 2024).

At the system level, PV installations are typically classified as *utility-scale*, *commercial rooftop*, or *distributed (residential)* systems. Utility-scale syste100ms involve large ground-mounted arrays connected to the grid, often located in high-solar-irradiance regions, with capacities ranging from tens to hundreds of megawatts. Rooftop and distributed systems, on the other hand, cater to end-users directly, reducing transmission losses and enhancing energy autonomy. To maximize solar energy capture, modules can be fixed at an optimal tilt or installed on *single-axis* or *dual-axis trackers*, which follow the sun's path throughout the day, improving annual energy yield by 15–30% depending on location (IEA, 2024).

Recent advances in PV cell architecture have further improved conversion efficiency and reliability. The *passivated emitter rear contact* (PERC) design enhances light absorption and reduces electron recombination, enabling higher output without significant cost increases. *Tunnelling oxide passivated contact* (TOPCon) and *heterojunction* (HJT) cells integrate advanced passivation and low-temperature deposition techniques, achieving efficiencies above 24% in mass production (IEA-PVPS, 2024). *Bifacial modules* which capture sunlight from both the front and rear surfaces offer additional performance gains, especially over reflective surfaces such as snow or sand.

The next frontier in PV development involves *tandem* and *multi-junction* devices, particularly *perovskite–silicon* tandems.

Perovskites are a family of materials with tuneable bandgaps and strong light absorption properties, allowing better utilization of the solar spectrum when layered atop silicon cells. Laboratory efficiencies exceeding 30% have been achieved, far surpassing the theoretical limit of single-junction silicon cells (Huang et al., 2025). Despite challenges with stability, scalability, and toxicity (involving lead-based compounds), research continues toward commercializing stable, high-efficiency tandem modules that could redefine solar energy economics.

**Example**

**First Solar:**

Founded in 1999, First Solar stands as the United States' foremost photovoltaic (PV) technology and manufacturing company, distinguishing itself as the only U.S.-headquartered firm among the world's leading solar manufacturers. Through its advanced thin film PV technology, developed in R&D centres located in California and Ohio, the company delivers a next-generation solar power solution that is both competitively priced and responsibly produced. Unlike conventional crystalline silicon (c-Si) modules, First Solar's cadmium telluride (CdTe) thin film technology provides a high-performance, scalable, and lower-cost alternative that is designed to enable reliable, sustainable power generation.

With a robust manufacturing presence, First Solar maintains five operational factories across Ohio, Alabama, and Louisiana, representing the Western Hemisphere's largest solar manufacturing footprint. By 2026, it is projected to reach a global production capacity of 25 GW annually, supported by facilities in the United States, India, Malaysia, and Vietnam. Its vertically integrated process transforms sheets of glass into fully functioning solar panels in approximately four hours, employing advanced Industry 4.0 systems artificial intelligence, machine-to-machine communication, and IoT connectivity to ensure efficiency and precision without reliance on Chinese c-Si supply chains.

First Solar’s Series 7 Series 7 *TR1*

Technologically, First Solar’s CdTe modules outperform traditional silicon-based panels in key areas such as degradation rate, temperature coefficient, and spectral response. They require only 1–2% of the semiconductor material needed by c-Si modules to produce comparable power, offering faster production cycles, greater traceability, and higher transparency.

First Solar’s commitment to “Responsible Solar” extends across the full life cycle from raw material sourcing to end-of-life recycling. Its technology achieves up to four times lower carbon and water footprints than conventional panels, underscoring its dedication to sustainability. As a platinum-rated member of the Responsible Business Alliance, the company aims to power all operations with renewable energy by 2028 and achieve net-zero emissions by 2050, positioning it as a global benchmark for responsible, high-performance solar manufacturing.

Jinko Solar

Jinko Solar Co., Ltd. stands at the forefront of global renewable electricity generation technologies, serving as a key player driving decarbonization through advanced photovoltaic (PV) innovation. As a vertically integrated PV module manufacturer and energy storage system integrator, JinkoSolar has built its leadership on end-to-end control of the solar value chain from silicon wafer production to complete module assembly. This integration allows the company to maximize efficiency, reduce production costs, and deliver high-performance, sustainable energy solutions.

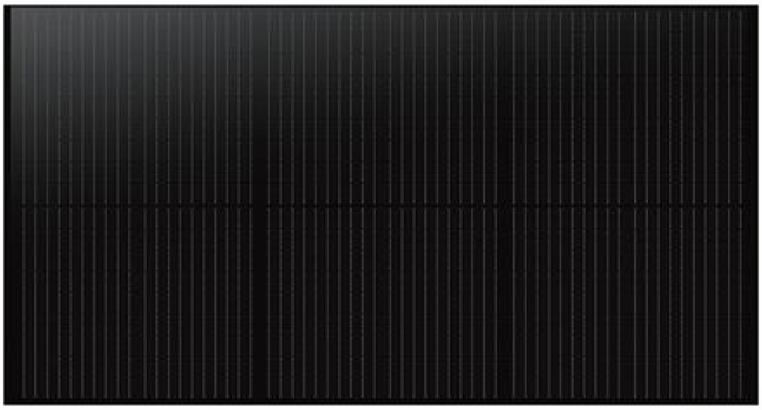
With operations spanning over 10 manufacturing bases across China, the United States, Southeast Asia, and the Middle East, JinkoSolar maintains a vast global footprint. As of mid-2025, it has shipped approximately 350 GW of modules worldwide, ranking first in global module shipments six times. The company's N-type Tiger Neo series, with cumulative shipments exceeding 200 GW by August 2025, represents the best-selling and most efficient PV module series globally. These modules leverage advanced N-type TOPCon cell technology, enhancing energy conversion efficiency and ensuring better performance under low-light conditions key factors in driving down the levelized cost of electricity (LCOE) for users.

Jinko Solar

JinkoSolar's technological edge is reinforced by its strong research and development base, comprising over 2,000 R&D professionals and a portfolio of 5,500 patents, including 731 related to TOPCon technology. As an active member of the RE100 initiative and participant in the G20's B20 framework, JinkoSolar underscores its commitment to sustainability and corporate responsibility. Through innovation and scale, the company not only advances solar efficiency but also contributes substantially to global carbon reduction and cost-effective renewable energy deployment.

### Longi

Founded in 2000, LONGi Green Energy Technology Co., Ltd. has become one of the world's foremost leaders in renewable electricity generation, pioneering alternative technologies that accelerate global decarbonization. Guided by its mission of "making the best of solar energy to build a green world," LONGi focuses on customer-centred innovation and sustainable energy transformation across diverse applications. The company's operations span five major business sectors: mono-crystalline silicon wafers, solar cells and modules, distributed photovoltaic (PV) solutions, utility-scale plant systems, and hydrogen energy equipment.



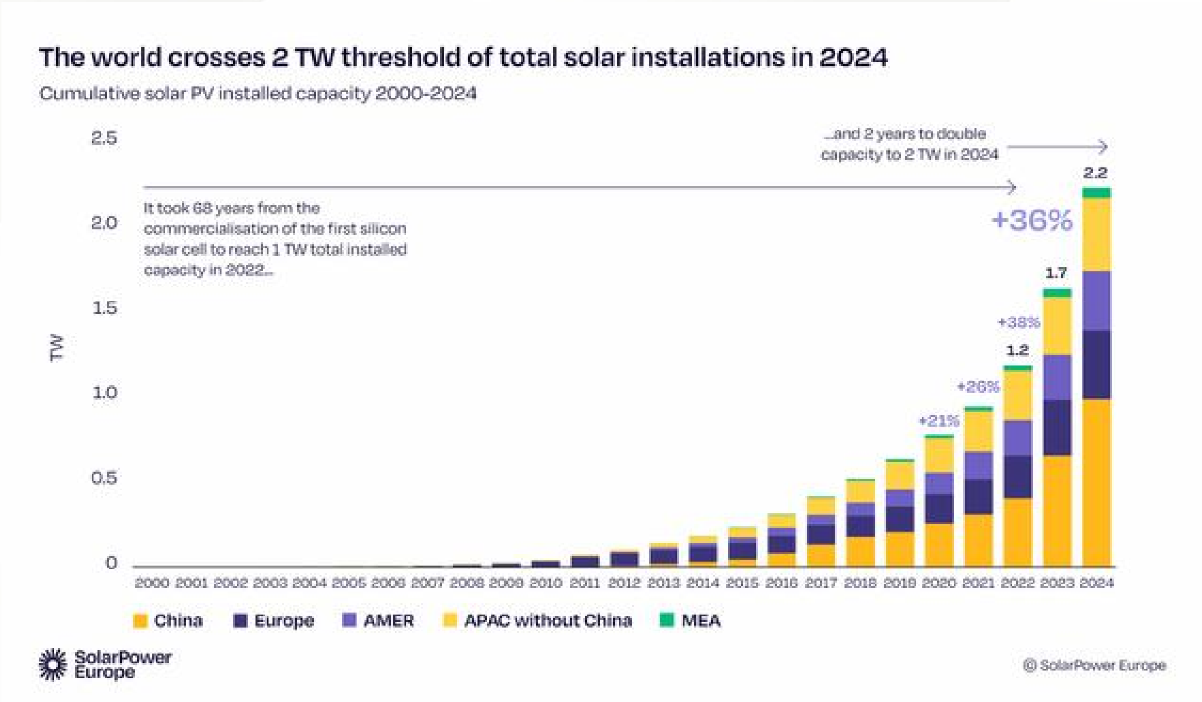
LONGi's core strength lies in its mastery of mono-crystalline silicon technology, which has set industry benchmarks for efficiency and durability. Its advancements in high-efficiency PERC and HJT cells have significantly reduced the cost per watt of solar energy, making clean power more affordable for both industrial and residential adopters. The company's expansion into green hydrogen production further positions it at the intersection of renewable electricity and next-generation energy storage, enabling deeper decarbonization across sectors. As the most trusted and reliable solar company in the global market, LONGi continues to blaze the trail for green technology, providing integrated energy solutions that optimize power generation, reduce emissions, and support a resilient, low-carbon future.

### Global Trends in Solar Energy Installations

By 2024, the world reached a historic milestone in renewable energy development surpassing 2.2 terawatts (TW) of installed solar power globally. This achievement marks a dramatic acceleration in solar adoption: while it took 68 years from the invention of the first commercial silicon solar cell to achieve the 1 TW milestone in 2022, it took only two additional years to double that capacity. The year 2024 alone saw the addition of approximately 597 gigawatts (GW) of new solar capacity, underscoring the exponential growth trend in the solar energy sector.

**Solar Installations by Region (Capacity in GW)**

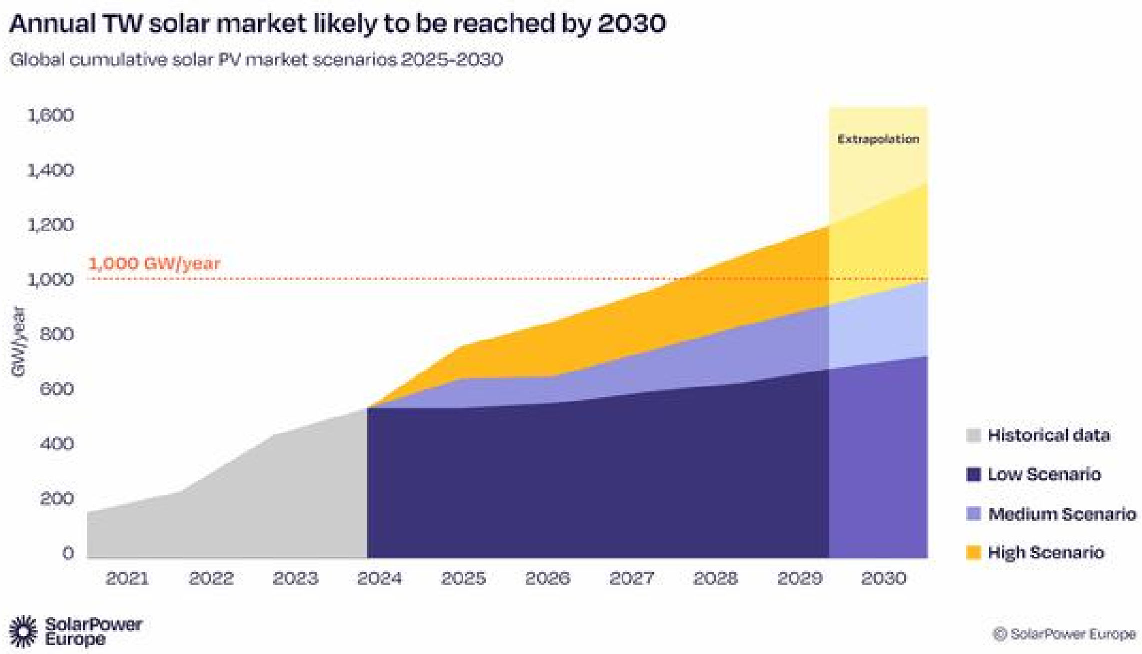
| Region | 2024 Annual Additions (GW) | 2024 Cumulative Capacity (TW/GW) | Share of Global Cumulative Capacity |
|---|---|---|---|
| **Asia-Pacific** | ~421.5 GW | ~1.4 TW (1,400 GW) | 63% |
| **Europe** | ~82.1 GW | ~480 GW (per capita) | 19.1% (total renewables) |
| **Americas** (North & South) | ~72.5 GW (approx.) | ~886 GW (approx.) | 17.1% (total renewables) |
| **Middle East & Africa** | ~17.8 GW (approx.) | ~107 GW (approx.) | 3.9% (total renewables) |
| **Oceania** | ~8.7 GW | ~74 GW (total renewables) | 1.7% (total renewables) |
| **Global Total** | **~597 GW** | **~2.2 TW (2,200 GW)** | **100%** |




Regionally, the Asia-Pacific region leads the global solar landscape, accounting for about 1.4 TW (63%) of total capacity, driven primarily by China, India, and Japan. Europe follows with approximately 480 GW, representing about 19.1% of total renewable capacity, as nations such as Germany, Spain, and the Netherlands continue to expand rooftop and utility-scale solar systems. The Americas collectively hold about 886 GW (17.1%), led by the United States and Brazil, both of which have made significant policy and investment commitments toward clean energy transition. The Middle East and Africa regions, though smaller contributors, are rapidly emerging with roughly 107 GW (3.9%), propelled by large-scale projects in Egypt, South Africa, and the United Arab Emirates. Oceania, particularly Australia, accounts for about 74 GW (1.7%) of total global renewables.

Looking ahead, solar energy deployment is set to accelerate even more rapidly. SolarPower Europe's annual report projects that by 2030, the world could be installing an astonishing 1

TW of solar capacity every year, positioning solar as the dominant driver of global renewable expansion.




By that time, solar power is expected to represent around 65% of the total renewable capacity required to meet global climate and decarbonisation targets, reinforcing its central role in the clean energy revolution.

A Q1 2025 report by the Africa Solar Industry Association (AFSIA) revealed that Nigeria ranked 4th in Africa for solar energy adoption in 2024, adding 63.5 megawatts peak (MWp) of new capacity and bringing its total installed solar capacity to approximately 385.7 MWp. While this marks a notable improvement from previous years, solar energy still represents only 1.6% of Nigeria's overall energy mix, underscoring the significant room for expansion in the renewable sector. Across Africa, total solar installations reached 2.5 gigawatts peak (GWp) in 2024, with Nigeria among the leading contributors to this continental growth.

In Nigeria, the ongoing transition to solar energy is being primarily driven by corporate organisations and industrial players rather than the government. Businesses have increasingly recognized solar power as a strategic tool for reducing operational costs, especially in light of fluctuating fuel prices, unstable electricity supply, and rising grid

tariffs. This trend is evident in the surge of private-sector–led solar projects, particularly within manufacturing, telecommunications, and commercial estates. Supporting this momentum, the

Nigerian Electricity Regulatory Commission (NERC) recently approved 55 new licenses for solar projects, most of which were initiated by companies seeking energy independence and financial sustainability. This corporate-led shift highlights the growing economic rationale behind solar adoption in Nigeria's energy landscape

### Concentrating Solar Power (CSP) Systems

Unlike PV systems that convert sunlight directly into electricity, *concentrating solar power* (CSP) systems use mirrors or lenses to concentrate sunlight onto a receiver, generating high temperatures that drive a thermodynamic cycle usually a steam turbine or Brayton cycle to produce electricity. CSP operates optimally in regions with high *direct normal irradiance* (DNI), such as deserts and arid zones, making it suitable for countries like Spain, Morocco, Chile, and parts of the Middle East and North Africa (Alami et al., 2023).

CSP technologies can be categorized into several variants based on optical configuration and heat-transfer mechanisms. The *parabolic trough* system, the most mature type, uses long, curved mirrors to focus sunlight onto a receiver tube filled with a heat-transfer fluid (typically synthetic oil or molten salt), which then generates steam to drive a turbine. *Linear Fresnel systems* use flat or slightly curved mirrors arranged in rows to focus light onto an elevated receiver; they are cheaper to build but less efficient due to lower concentration ratios. *Power tower* (central receiver) systems employ large arrays of *heliostats* flat mirrors that track the sun and reflect light onto a central receiver mounted on a tall tower achieving much higher operating temperatures (up to 565°C or more). Higher temperatures improve thermodynamic efficiency and facilitate *thermal energy storage* (TES), usually in molten salts, which allows CSP plants to store heat during the day and generate electricity at night (NREL, 2023).

A key differentiator for CSP is this inherent *dispatchability*. While PV generation ceases at sunset unless paired with batteries, CSP can deliver power for extended periods after daylight, contributing to grid stability and reliability. Depending on storage capacity (commonly 6–12 hours), CSP plants can achieve capacity factors of 40–60%, rivalling fossil-fuel plants under favourable conditions (NREL, 2023; Alami et al., 2023). However, CSP systems are more complex and capital-intensive than PV, requiring precise optical alignment, large land areas, and regular maintenance especially for mirror cleaning in dusty environments. They also have higher water requirements if equipped with wet cooling, though dry cooling technologies are increasingly adopted in arid zones to reduce consumption.

In recent years, hybrid systems that combine *PV and CSP* have emerged to exploit the strengths of both technologies. PV provides low-cost daytime electricity, while CSP with storage offers dispatchable evening power, thereby smoothing the intermittency of solar energy and enhancing overall grid flexibility. Moreover, innovations in *high-temperature CSP* such as supercritical $CO_2$ cycles and new ceramic or particle-based heat-transfer media promise higher efficiencies and reduced costs, expanding the future role of CSP within decarbonised power systems (NREL, 2023).

In all, PV and CSP represent complementary approaches to solar power conversion. PV dominates the global market due to modularity, scalability, and rapidly declining costs, while CSP contributes valuable dispatchable capacity in high-DNI regions. The technical diversity within these technologies from crystalline silicon to thin films, from parabolic troughs to power towers demonstrates the adaptability of solar systems to varied energy needs and geographies. As research continues to push the boundaries of efficiency, durability, and integration, solar technologies will remain central to the global energy transition and the pursuit of net-zero emissions by mid-century.

**Examples of Companies**

BrightSource Energy

BrightSource Energy stands at the forefront of solar thermal innovation, developing cutting-edge Concentrated Solar Power (CSP) technologies that deliver clean, dispatchable energy while minimizing environmental impact. The company's proprietary solar thermal systems use thousands of computer-controlled mirrors, or heliostats, to track the sun and focus its rays onto a central boiler atop a tower. This process generates superheated steam similar to conventional power plants but without burning fossil fuels. The steam can drive a turbine to produce electricity or be used for industrial applications such as thermal enhanced oil recovery (EOR).

By integrating proven components like turbines with its advanced solar field design, BrightSource produces reliable, cost-competitive power. The company also incorporates molten salt storage and hybridization with fossil fuels to increase efficiency and stability, significantly reducing overall energy costs. Beyond electricity generation, BrightSource's CSP technology supports multiple applications, including desalination, mining, and industrial heat supply.

Globally, BrightSource collaborates with partners across China, South Africa, and the Middle East to expand CSP deployment. Projects like the Huanghe Qinghai Delingha Solar Thermal Power Project in China demonstrate its leadership in scalable clean energy solutions. Through its innovation, environmental stewardship, and global partnerships, BrightSource Energy exemplifies how solar thermal power can shape a sustainable and flexible energy future.

Shangai Electricity

Shanghai Electric Group Company Limited is a global leader in the design, manufacture, and distribution of electric power and industrial equipment, with a strong focus on renewable energy technologies. Among its flagship innovations is its work in Concentrated Solar Power (CSP) systems, which harness sunlight through mirrors or lenses to generate high-temperature heat for steam turbines and electricity production.

At the core of Shanghai Electric's CSP innovation is its 700 MW solar power plant, featuring both tower and tube collectors. The plant's central tower standing at 267 meters, the tallest thermal tower in the world receives concentrated sunlight from 70,000 mirrors, reaching temperatures above 500°C to drive efficient steam generation. This large-scale renewable system exemplifies Shanghai Electric's commitment to sustainable power solutions, technological excellence, and the transition toward cleaner global energy systems.

### Examples of Companies Promoting Transition to Solar in Nigeria

Nigeria's transition to renewable energy is being driven not only by policy direction and climate imperatives, but increasingly by the actions of private-sector companies that are deploying capital, technology, and innovative business models at scale. Faced with rising energy costs, unreliable grid supply, and growing sustainability pressures, Nigerian industries, commercial enterprises, and service providers are turning to renewable solutions as a strategic response rather than a peripheral alternative. A new generation of indigenous and international firms is leading this shift by developing solar, storage, and hybrid energy systems tailored to local operating realities. These companies are accelerating decarbonisation, improving energy reliability, and demonstrating that renewable energy is now a commercially viable and competitive cornerstone of Nigeria's energy future.

### Rensource

Rensource is one of the companies at the forefront of accelerating Nigeria's transition to solar energy by providing practical, commercially viable alternatives to diesel-dependent power systems. As a leading West African provider of renewable energy solutions, Rensource focuses on the development and financing of solar-hybrid captive power systems tailored to the needs of commercial, industrial, and utility-scale customers. Its core value proposition is bridging the persistent gap between unreliable grid supply and the growing energy demand of Nigerian businesses. Rather than promoting solar as a standalone solution in all cases, Rensource adopts a hybrid approach, integrating solar photovoltaic systems with battery storage and, where required, gas or diesel generation. This design ensures reliability while progressively reducing fossil fuel dependence, enabling businesses to lower operating costs without compromising power quality or uptime. Importantly, Rensource also provides flexible financing structures that remove the burden of large upfront capital expenditure, allowing customers to pay for energy as a service.

To date, Rensource has delivered 12 major projects with approximately 10 MW of installed and projected capacity across Nigeria and the wider region. These deployments have generated tangible environmental and economic benefits, including the avoidance of approximately 5,588 metric tonnes of $CO_2$ emissions and the displacement of over 2 million litres of fossil fuel. These outcomes demonstrate that solar adoption in Nigeria is not merely aspirational but already delivering measurable impact.

Notable installations include a 717 kWp solar PV system at Valentine Chickens in Kwara State, a 5 MWp solar PV plant at Baze University in Abuja, and a 700 kWp solar-powered plant at Premium Poultry Farms in Kuje, Abuja. Smaller but strategically important projects—such as installations for Rubis Energie and additional Valentine Chicken facilities—highlight Rensource's ability to scale solutions across different load profiles and sectors. Through its project portfolio, Rensource exemplifies how private-sector innovation is driving Nigeria's solar transition—cutting fuel costs, improving energy security, and demonstrating that clean energy can be both reliable and economically superior to diesel-based power systems.

### Daystar Power Group

Daystar Power Group is one of the most influential companies driving Nigeria's transition to solar energy, particularly within the commercial and industrial (C&I) segment where diesel dependence has historically been most entrenched. Operating at the intersection of energy reliability, cost efficiency, and decarbonisation, Daystar Power has positioned itself as a critical solution provider in a region facing chronic grid instability and rising fuel costs. Its acquisition by Shell in 2022 further underscores the strategic importance of distributed solar solutions in Africa's energy transition.

Sub-Saharan Africa continues to experience a structural power crisis, marked by limited grid access and frequent outages that can last for hours or even days. In Nigeria, businesses that are connected to the grid still rely heavily on diesel generators to maintain operations, resulting in high operating costs and significant environmental pollution. Daystar Power directly addresses this challenge by delivering solar-hybrid power systems that integrate solar PV, battery storage, and grid or generator backup, ensuring stable and uninterrupted electricity supply. A defining feature of Daystar Power's model is its use of Power Purchase Agreements (PPAs), which eliminate upfront capital expenditure for clients. Under this arrangement, businesses pay a predictable monthly fee for clean power, making solar adoption financially accessible while immediately reducing energy costs. This approach has proven particularly attractive to banks, manufacturing firms, fast-moving consumer goods companies, and telecommunication

Over its eight years of operation, Daystar Power has deployed more than 400 installations across five African countries, achieving over 150 MW of installed capacity and a system reliability rate of 99% uptime. In Nigeria, flagship projects include the 12.1 MW solar deployment across eight Nigerian Bottling Company (Coca-Cola) factories, significantly reducing diesel consumption and emissions. Other deployments, such as Vivo Energy's solar installation powering 40% of facility load during daytime operations, demonstrate the scalability and commercial viability of solar for industrial users. By lowering energy costs, stabilizing power supply, and reducing pollution, Daystar Power is not only helping Nigerian companies decarbonise but also strengthening their competitiveness. Its success illustrates how private-sector-led solar deployment is becoming a cornerstone of Nigeria's clean energy transition.

**Eauxwell Nigeria Limited**

Founded in 1987, Eauxwell Nigeria Limited has evolved from a pioneering water engineering services firm into one of Nigeria's most significant drivers of large-scale solar deployment and energy infrastructure modernization. The company's early focus on water engineering established a strong technical foundation, which enabled a strategic expansion in 2005 into solar water pumping—an early and forward-looking response to Nigeria's energy access and infrastructure gaps. This transition marked the beginning of Eauxwell's transformation into a fully integrated solar engineering, procurement, and construction (EPC) provider. Today, Eauxwell is widely recognized as Nigeria's leading solar EPC, delivering rooftop, utility-scale solar photovoltaic (PV), and advanced battery energy storage systems (BESS) across industrial, commercial, and public-sector applications. With a workforce of over 200 highly skilled professionals, the company has successfully installed more than 120 MW of solar PV capacity across Africa, demonstrating both scale and technical depth. Its expertise spans grid-connected, hybrid, and off-grid systems, positioning Eauxwell at the forefront of Nigeria's clean energy transition.

Eauxwell's project portfolio reflects its capability to execute complex, large-scale installations. Notable deployments include the 11.8 MWp Kano grid-connected solar project, the 10.8 MWp solar PV plus 20 MWh BESS hybrid project in Port Harcourt, and multiple hybrid solar and storage systems in Abeokuta, Owerri, and Uyo. Beyond industrial and urban energy systems, Eauxwell has played a critical role in expanding rural electrification through solar-powered water pumping schemes and hybrid mini-grids, including projects in Toto, Atsawa, Ogegume, Ome, Binin, and Dakpan. Through its integrated approach and long-standing presence in Nigeria's energy landscape, Eauxwell exemplifies how indigenous engineering capacity is enabling reliable, scalable, and low-carbon power solutions nationwide.

### Rationale for Transition

Nigeria's electricity cost structure presents a compelling financial case for transitioning away from both grid power and diesel generation toward renewable energy, particularly solar photovoltaics.

### Cost of Grid Electricity (Public Supply)

Grid electricity tariffs in Nigeria vary by service band, reflecting the number of hours of supply. As of mid-2024, **Band A customers**—those receiving 20 or more hours of electricity per day—pay approximately **₦209.50 per kWh**. For a commercial or industrial consumer using **1,000 MWh (1,000,000 kWh) annually**, grid electricity costs would be:

- **₦209.50 × 1,000,000 kWh = ₦209.5 million per year**

While grid electricity is cheaper than diesel, it remains expensive relative to global benchmarks and is often unreliable, forcing most businesses to maintain diesel backup systems. This dual-power reality significantly raises total energy costs and operational risk.

### Cost of Diesel-Generated Electricity

Diesel generation remains the dominant power source for Nigerian industries due to grid unreliability. However, it is the most expensive option.

At a diesel price of **₦1,100 per litre**, the cost per kWh depends on generator efficiency:

- **Energy content of diesel:** ~10.7 kWh (thermal) per litre
- **Generator efficiency:** 30–40%
- **Usable electricity:** 2.7–3.7 kWh per litre

**Cost per kWh calculation:**

- High efficiency (3.7 kWh/litre): ₦1,100 ÷ 3.7 ≈ **₦297/kWh**
- Low efficiency (2.7 kWh/litre): ₦1,100 ÷ 2.7 ≈ **₦407/kWh**

For the same **1,000 MWh annual consumption**, diesel power costs range between:

- **₦297 million – ₦407 million per year**

This excludes maintenance, engine overhauls, downtime losses, and emissions-related health and environmental costs.

**Solar Power Cost Comparison**

According to IRENA (2024), the median global LCOE for newly commissioned utility-scale solar is **US$0.043 per kWh**. Using an exchange rate of **₦1,600/USD**, this equals approximately:

- **₦68.80 per kWh**

For a facility consuming **1,000 MWh annually**:

- **₦68.80 × 1,000,000 kWh = ₦68.8 million per year**

By switching from:

- **Grid power (₦209.5/kWh):** annual savings ≈ **₦140.7 million**
- **Diesel power (₦297–₦407/kWh):** annual savings ≈ **₦228–₦338 million**

These savings translate into **US$140,000–US$210,000 annually**, depending on the displaced power source. The implications are transformative. Lower energy costs free capital for expansion, innovation, and employment. Businesses reduce exposure to fuel price volatility, foreign exchange risk, and supply disruptions. When deployed through zero-capex or PPA models, solar adoption requires no upfront investment, delivering immediate cash-flow savings with typical payback periods of 1–4 years. In purely economic terms before even accounting for emissions, air quality, or ESG benefits renewable energy has become the most rational and competitive power choice for Nigerian businesses (IRENA, 2024).

**Onshore Wind**

Onshore wind energy has emerged as one of the most mature and rapidly expanding renewable electricity generation technologies globally. It converts the kinetic energy of moving air masses into mechanical energy through wind turbines, which is then transformed into electrical energy via generators. The technology's core principle capturing wind's natural motion to produce electricity has evolved significantly since its early applications in the late twentieth century. Today, onshore wind is a cornerstone of the global energy transition, offering a cost-effective, scalable, and low-carbon alternative to fossil-fuel-based generation (International Energy Agency [IEA], 2024). In many regions, particularly in Europe, North America, and parts of Asia, onshore wind is now among the cheapest sources of new electricity, with its levelized cost of electricity (LCOE) falling to between USD 30–50 per megawatt-hour (MWh), depending on site quality and financing conditions (IRENA, 2023).

Despite this global progress, the pace and pattern of onshore wind deployment differ sharply between developed and developing economies. In developed countries such as Germany, Denmark, and the United States, the sector benefits from decades of technological refinement, strong policy support, and robust grid infrastructure that facilitates large-scale integration. These nations have also invested in research and development (R&D), enabling the production of larger, more efficient turbines and the optimization of maintenance practices (World Bank, 2023). In contrast, developing economies particularly in Africa, Southeast Asia, and Latin America face structural and financial barriers that slow deployment. High capital costs, inadequate grid networks, and weaker institutional frameworks often hinder project implementation, despite vast untapped wind resources. Moreover, limited local manufacturing capacity and dependency on imported components constrain the sector's growth potential (IEA, 2022). Nonetheless, as technology costs decline and international partnerships expand, onshore wind represents a promising pathway for achieving energy access and sustainable growth in developing regions.

### Onshore Wind in Developed Economies

In developed regions particularly Europe, North America, and Oceania onshore wind power has reached full technological and commercial maturity. Countries such as Germany, Spain, the United Kingdom, and Denmark have decades of experience integrating large volumes of wind power into national grids. The European Union (EU) collectively hosts over 200 gigawatts (GW) of onshore wind capacity, contributing nearly 15% of total EU electricity generation

(WindEurope, 2024). Germany alone has installed over 60 GW, supported by long-term feed-in tariff policies and favourable land-use planning frameworks (IEA, 2023). Similarly, in North America, the United States is a global leader with more than 145 GW of onshore wind capacity as of 2024, spread across states such as Texas, Iowa, and Oklahoma. The combination of large land availability, well-developed grid systems, and competitive procurement through power purchase agreements (PPAs) has made wind one of the lowest-cost energy sources in the U.S. market (U.S. Department of Energy [DOE], 2024).

The cost competitiveness of onshore wind in developed economies has improved dramatically over the past two decades. According to the IEA (2024), the levelized cost of electricity (LCOE) for onshore wind now ranges between $25 and $50 per megawatt-hour (MWh) in high-resource regions placing it among the cheapest sources of new generation alongside utility-scale solar photovoltaic (PV). Key drivers of these cost reductions include technological advancements (e.g., larger rotors and taller towers), economies of scale in manufacturing, optimized logistics, and advanced digital monitoring systems that reduce operation and maintenance costs.

Furthermore, regulatory and institutional frameworks in developed countries have evolved to support consistent deployment. Long-term policy mechanisms such as contracts for difference (CfDs) in the UK, renewable portfolio standards (RPS) in the U.S., and market-based auction systems in the EU have provided price stability and investment confidence. Mature grid interconnection standards and robust transmission infrastructure further enable the integration of variable wind generation while maintaining system reliability. In addition, access to low-cost finance through established capital markets and green bonds has made large-scale projects feasible with favourable risk profiles (IEA, 2024).

The technological landscape in developed economies is also advancing toward repowering the replacement of older, smaller turbines with modern high-capacity machines. Repowering not only increases total generation capacity but also optimizes land use and grid connection points. For instance, Denmark and Germany have initiated large-scale repowering programs that significantly enhance the productivity of existing wind sites without requiring new land acquisitions (WindEurope, 2023).

### Onshore Wind in Developing Economies

In developing economies, deployment of onshore wind is expanding but remains geographically concentrated and less uniform. Countries such as Brazil, Mexico, Vietnam, South Africa, and Kenya have emerged as regional leaders, leveraging both international investment and domestic policy reforms to promote renewable energy. For instance, Brazil has installed over 25 GW of onshore wind, benefiting from competitive auction schemes and strong wind resources in its northeastern region (International Renewable Energy Agency [IRENA], 2023). Mexico, prior to recent policy shifts, deployed significant capacity under its clean energy auction framework, while Vietnam rapidly expanded its wind capacity from less than 300 MW in 2018 to over 4 GW by 2023 through feed-in tariffs (World Bank, 2023).

In Africa, the pace of deployment has been slower but promising. South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has facilitated the addition of over 3.5 GW of onshore wind capacity, contributing significantly to diversification away from coal (IRENA, 2022). Kenya hosts one of Africa's largest projects the Lake Turkana Wind Power Project, a 310 MW installation that supplies nearly 17% of Kenya's electricity (World Bank, 2023). Despite such progress, the continent's total wind capacity remains below 10 GW, representing a small fraction of its estimated potential of over 50,000 TWh per year (IRENA, 2023).

Key constraints in developing economies include grid limitations, permitting challenges, and financing barriers. Transmission infrastructure is often underdeveloped, leading to curtailment risks and reduced investor confidence. Inadequate wind resource mapping and meteorological data also hinder project planning, especially in countries lacking long-term anemometric data. Furthermore, high cost of capital often exceeding 10–15% compared to 3–5% in developed markets significantly inflate project costs (World Bank, 2023). Regulatory uncertainty, lengthy land acquisition processes, and limited access to local technical expertise further slow deployment.

Technologically, developing economies tend to adopt mid-size turbines (1.5–3 MW) rather than the very large (>5 MW) machines common in Europe and North America. This reflects logistical constraints such as road width, bridge load capacity, and the absence of high-capacity cranes. However, ongoing improvements in transport infrastructure and modular turbine designs are gradually enabling the deployment of larger machines even in regions with weaker logistics. For example, in Vietnam and Brazil, recent projects have begun using 4–5 MW class turbines, bringing them closer to global standards (IRENA, 2023).

### Companies

### Vestas

Vestas is a global leader in sustainable energy solutions, driven by its mission to accelerate the world's transition to renewable energy and create a sustainable future. Founded on the belief that wind energy will form the backbone of future energy systems, Vestas designs, manufactures, installs, and services wind turbines and hybrid energy systems across the globe. With a legacy of industry firsts and unmatched experience in both the installation and maintenance of wind projects, the company has played a crucial role in reducing global $CO_2$ emissions and shaping the renewable energy landscape.

Headquartered in Denmark, Vestas combines advanced engineering and data-driven innovation to deliver high-efficiency wind turbines such as the V150 series, developed at Østerild, which sets new benchmarks for energy output and operational reliability. The company's integrated service model, spanning development to operation, ensures that wind farms achieve optimal performance throughout their lifecycle, further enhancing the economic and environmental value of clean energy deployment.

Vestas's sustainability philosophy extends beyond technology it embodies a holistic approach grounded in simplicity, collaboration, accountability, and passion. In response to the Intergovernmental Panel on Climate Change (IPCC) findings that global warming must be limited to 1.5°C, Vestas is addressing three critical challenges: accelerating renewable deployment, driving large-scale electrification, and enabling Power-to-X solutions like green hydrogen for non-electrifiable sectors.

Through continuous innovation, strategic partnerships, and its unwavering commitment to sustainability governance, Vestas not only delivers renewable energy at scale but also inspires a global shift toward a carbon-neutral future ensuring that today's energy transformation sustains generations to come.

### Siemens Gamesa (now Siemens Energy & SGRE)

For over four decades, Siemens Gamesa, now part of Siemens Energy, has been at the forefront of the global wind energy revolution transforming the limitless potential of wind into a powerful force for sustainable progress. From its first wind turbines to the world's most advanced offshore projects, the company has consistently driven technological innovation, efficiency, and reliability in renewable energy generation.

Founded on a vision to harness wind power for industrial and domestic use, Siemens Gamesa pioneered many of the technologies that define today's modern wind sector. Its innovations have contributed to powering factories, illuminating homes, and reducing global dependence on fossil fuels. The 2017 merger between Siemens Wind Power and Gamesa strengthened this legacy, creating one of the world's largest and most capable wind energy companies.

Today, Siemens Gamesa continues to lead in both onshore and offshore wind projects, delivering turbines and integrated energy solutions that set global benchmarks for performance and sustainability. Its advanced offshore platforms among the largest and most powerful ever built are central to global decarbonization efforts. Through continuous research, engineering excellence, and a commitment to renewable transformation, Siemens Gamesa remains a driving force in ensuring that the world's lights stay on through clean, reliable, and renewable wind energy.

### Cost & Savings

The economic case for onshore wind energy is one of the strongest arguments for accelerating the renewable transition in Africa and globally. According to data from the National Renewable Energy Laboratory (NREL, 2024), the levelized cost of electricity (LCOE) for onshore wind averages about US$42 per megawatt-hour (MWh), equivalent to US$0.042 per kilowatt-hour (kWh). This represents a significant reduction compared to traditional fossil-based generation sources such as gas, which typically costs around US$75 per MWh under standard operating and fuel price assumptions. The difference of US$33 per MWh translates directly into substantial savings for utilities, industries, and national grids transitioning toward wind power.

To illustrate, a mid-sized utility purchasing or generating around 100,000 MWh of electricity per year could realize up to US$3.3 million in annual savings simply by replacing gas-fired generation with wind-based power (NREL, 2024). Beyond the direct financial benefits, wind energy provides price stability because its operating costs are largely fixed once infrastructure is installed. Unlike gas and diesel power generation, which are heavily exposed to volatile global fuel markets, wind energy harnesses a free natural resource wind eliminating exposure to price shocks and import dependencies.

In addition to cost savings, wind energy offers environmental and strategic advantages. By displacing fossil-based generation, each megawatt-hour of wind power typically avoids 0.4–0.6 tons of $CO_2$ emissions, supporting decarbonization and national sustainability goals. Over a 20-year project life, these avoided emissions can translate into millions of dollars in potential carbon credit revenues under voluntary or compliance markets.

However, the viability of onshore wind projects is site-specific, depending on factors such as wind resource availability, grid connectivity, land acquisition, and permitting processes. When developed in optimal conditions, onshore wind provides reliable, low-cost, and sustainable energy, reinforcing its role as a cornerstone of modern, resilient energy systems (NREL, 2024).

### Offshore Wind (Fixed-Bottom & Floating)

Offshore wind has emerged as a central pillar of decarbonisation strategies in many countries because of its large, consistent wind resources and proximity to coastal load centres. Two broad technological families dominate the field: fixed-bottom foundations (monopiles, jackets, gravity bases) for relatively shallow waters, and floating foundations (spar, semi-submersible, tension-leg platforms, and newer barge concepts) that extend deployment into deep-water continental shelves. This essay describes technical variants, assesses maturity and deployment status, discusses key performance metrics, outlines environmental and social impacts, examines supply-chain and critical-minerals risks, surveys innovation frontiers, compares value propositions, and evaluates deployment and scaling issues all while oscillating between developed and developing economy contexts.

Fixed-bottom offshore wind turbines are conceptually similar to onshore machines (rotor, nacelle, tower, generator), but their foundations are engineered for marine loading, scour, and installation constraints. The most common foundation for depths up to ~40–50 m is the monopile (a driven tubular steel pile). For intermediate depths and higher loading, jacket structures (lattice frames) or gravity-based foundations (concrete/steel bases that sit on the seabed) are used (NREL, 2024). Installation requires heavy marine vessels (pile drivers, jack-ups), port infrastructure capable of handling large components, and cable-laying capabilities.

Floating offshore wind decouples foundation design from seabed bearing capacity and depth. Three leading designs are spar-buoy, semi-submersible, and tension-leg platforms (TLPs); hybrids and multi-turbine floating platforms are also under development. Floating systems are anchored to the seabed with mooring lines and anchors and can operate in waters of several hundred meters depth, unlocking vast resource areas previously inaccessible to fixed foundations (IRENA, 2024). Floating systems use different materials and engineering for stability, dynamic motion control, and grid interface (mooring design, dynamic cables).

Component and system choices differ by region. Developed economies with shallow continental shelves (e.g., parts of Europe) have rapidly expanded fixed-bottom fleets; countries with deep coastal waters (e.g., Japan, parts of West Coast U.S., much of East Asia and some African coasts) increasingly invest in floating prototypes and associated port upgrades (GWEC, 2025; Reuters, 2025).

Globally, offshore wind is transitioning from niche to mainstream but remains concentrated: by end-2024 installed offshore capacity reached ~83 GW, with fixed-bottom representing the majority and floating wind still at pilot/early commercial scale (~0.3 GW) though growing (GWEC, 2025; NREL, 2024). Europe and China lead fixed-bottom deployment; the UK, Germany, the

Netherlands, and China host large commercial farms. Floating wind has reached commercial demonstration in Norway, the U.K., France, Portugal, Japan, and China, and governments (UK, France, Japan, Korea) have announced ambitious floating targets supported by port investments (IRENA, 2024; Reuters, 2025).

Cost trajectories differ: fixed-bottom LCOE has fallen significantly (though higher than onshore), while floating LCOE remains materially higher today but shows strong learning-rate potential with scale (NREL, 2024; Santhakumar et al., 2023). Several industry and academic studies suggest that floating wind LCOE could fall to near fixed-bottom levels at high cumulative capacity (tens to hundreds of GW) due to scale, serial fabrication, and supply-chain maturation (Santhakumar et al., 2023).

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### Cost & Saving for Offshore Wind

The cost and savings potential of offshore wind energy are becoming increasingly compelling as technology advances and deployment scales up globally. According to the National Renewable Energy Laboratory (NREL, 2024), the levelized cost of electricity (LCOE) for fixed-bottom offshore wind currently averages around US$117 per megawatt-hour (MWh), with variations depending on site conditions, water depth, and grid connection costs. Although this figure is higher than onshore wind or solar generation, offshore wind offers a unique advantage in replacing expensive, high-emission power sources such as fuel-oil peaker plants or imported liquefied natural gas (LNG).

When compared to power generation from imported LNG or fuel oil, which can cost approximately US$150 per MWh, offshore wind provides an immediate cost advantage of about US$33 per MWh (NREL, 2024). For instance, a coastal utility generating or purchasing 100,000 MWh annually could achieve annual savings of US$3.3 million by transitioning from fuel-oil-based generation to offshore wind. Beyond direct cost reductions, offshore wind projects also offer long-term price stability, as their fuel source the wind over ocean waters is free, inexhaustible, and not subject to global commodity price fluctuations.

The economic benefits are amplified in large coastal states and countries, where offshore wind farms can be developed at scale and integrated efficiently into national grids. These projects also stimulate local economies by creating thousands of high-value jobs in marine construction, operations, and maintenance, while reducing dependence on imported fossil fuels. Moreover, offshore wind energy plays a crucial role in decarbonization strategies, offering a clean, stable power supply that complements variable solar and onshore wind resources. While initial capital expenditure remains high, ongoing technological improvements, including larger turbines and floating platforms, continue to drive costs down, making offshore wind increasingly competitive and essential for achieving global energy transition goals (NREL, 2024).

### Hydropower (Reservoir, Run-of-River, Pumped Storage)

Hydropower remains the world's largest single source of renewable electricity and a uniquely flexible component in low-carbon power systems. It spans a spectrum of technologies from large reservoir (storage) dams that provide long-duration generation and system inertia, to run-of-river plants that offer lower-impact riverine generation, to pumped-storage hydropower (PSH) that acts as the grid's dominant long-duration "battery." Despite its maturity, hydropower's role and future trajectory are shaped by contrasts between developed and developing economies: mature fleets in advanced economies are being modernized or decommissioned in places, whereas many developing countries still prioritize new large projects for development and energy access.

**Reservoir (storage) hydropower** uses a dam and impounded reservoir to store water at elevation and release it through turbines to produce electricity on demand. Reservoirs provide multi-hour to multi-seasonal storage, grid flexibility, spinning inertia, and flood control co-benefits. Typical civil works include the dam, spillways, intake structures, penstocks, powerhouse, and transmission interfaces. Turbines vary by head and flow: Kaplan and bulb turbines for low-head high-flow sites, Francis turbines for medium head, and Pelton wheels for high head (IHA, 2024; IEA, 2023).

**Run-of-river** schemes divert part of a river through a penstock to a powerhouse and return flow downstream, with little or no impoundment. They generally have smaller reservoirs or forebays, lower storage capacity, and thus produce power that closely follows river discharge and seasonal hydrology. Many run-of-river plants are modular and have lower capital intensity and footprint compared with large dams (IHA, 2024).

**Pumped-storage hydropower (PSH)** uses two reservoirs at different elevations: during low-demand periods it uses surplus electricity to pump water uphill; during peak demand it releases the water to generate electricity. PSH is the dominant form of large-scale grid storage today, providing long-duration capacity, synchronous inertia (in conventional PSH), black-start capability, and multiday energy shifting (IHA; U.S. DOE, 2024). Variants include conventional closed-loop PSH (upper and lower reservoirs), off-river or pumped storage using artificial reservoirs, and subterranean or seawater-based configurations (IRENA, 2023).

Globally, hydropower is a mature, widely deployed technology. The International Hydropower Association (IHA) reported a global hydropower fleet of approximately 1,412 GW in 2023, with pumped storage around ~179 GW and annual additions continuing but trending below the acceleration needed for ambitious net-zero pathways (IHA, 2024). Developed economies Europe, North America, Japan host large fleets built in the 20th century that are now undergoing refurbishment, modernization, or selective removal where ecological or safety concerns prevail. In these markets the emphasis is on repowering, turbine retrofits, digital condition monitoring, and non-structural measures to reduce environmental impacts (IEA, 2023).

### Portable Hydro Generators

Portable hydro generators are compact renewable energy systems that convert the kinetic energy of flowing water from streams or rivers into usable electricity. Unlike conventional fuel-powered generators, these systems rely entirely on natural water flow, making them quiet, emissions-free, and highly sustainable. Power output ranges from small personal chargers rated at 10W–50W to larger micro-hydro systems capable of producing 1kW or more, sufficient for basic household or off-grid energy needs.

The operating principle is straightforward. Water is directed through a pipe, known as a penstock, which channels the flow toward a turbine. As the water moves through the turbine, it spins the blades, converting mechanical energy into rotational motion. This rotation drives a generator, producing electricity that can be used immediately or stored in batteries. Performance depends largely on two factors: the flow rate of the water and the available head, defined as the vertical drop between the water source and the turbine.

Applications vary by scale. Small-scale units rated between 10W and 50W are suitable for camping or charging mobile devices directly from a stream. Larger micro-hydro systems, producing 1kW or more, can power lighting, televisions, and small appliances in off-grid homes or cabins. For example, a 500W unit can generate up to 4,000 kWh per year with consistent water flow. Designs range from handheld portable units to semi-permanent installations, offering flexible clean energy solutions where water resources are available.

### Pump as turbine

A pump as turbine (PAT), sometimes referred to as a “pump in reverse,” is an unconventional but increasingly important hydropower technology used to convert the kinetic and pressure energy of flowing water into mechanical and electrical energy. Functionally, a PAT operates in a manner similar to a Francis turbine, serving the same core purpose of transforming fluid energy into rotational motion of a runner, which is then converted into electricity through a coupled generator (Agarwal, 2012). Unlike conventional turbines that are custom-designed for specific site conditions, pumps are mass-produced, widely available, and manufactured in standardized sizes across global markets. When operated as a turbine, the pump’s rotor runs in the opposite direction to its normal pumping mode, allowing the connected motor typically an asynchronous induction motor to function as a generator. This reversibility significantly lowers capital costs and shortens deployment timelines, making PATs particularly attractive for small-scale and decentralized hydropower applications.

PATs also play a critical role in micro pumped-storage hydropower (PSH) systems, where the same unit can alternate between pumping and generating by reversing rotational direction and adjusting speed (Morabito & Hendrick, 2019). Because the best efficiency point differs between pumping and turbine modes, variable-frequency drives are often required to optimize performance under fluctuating loads. Centrifugal or radial pumps are the most commonly used PATs, though axial, mixed-flow, and submersible designs are also applied depending on head and flow conditions (Ramos, 2000).

### Rubber Dams

Rubber dams are a modern form of adjustable weir system designed to regulate water levels efficiently and flexibly using an elongated rubber membrane that is securely anchored to a concrete foundation. Unlike conventional fixed weirs, rubber dams can be inflated or deflated using either water or air, allowing operators to actively control the height of the dam and, by extension, the upstream water level and overflow conditions. This adaptability makes rubber dams particularly valuable in river regulation, flood management, irrigation control, and small hydropower schemes.

In **water-filled rubber dams**, the rubber body is filled with river water through a regulating shaft system. Hydrostatic pressure within the shaft determines the dam height, which is monitored and controlled via a headwater probe connected to a weatherproof control cabinet located near the weir. The regulating shafts are divided into chambers equipped with hydraulic devices such as flaps and gates that allow precise control of filling and drainage. A key advantage of water-filled systems is their ability to deliver unrestricted, continuous regulation of dam height. As river inflow increases, the dam automatically lowers to pass excess water, and as inflow decreases, the dam is gradually raised again using a filling pump. In cold climates, circulation of slightly warmer river water (above 1°C) prevents ice formation within the dam during winter operation. Hydroconstruct's standard design enhances durability through hot-dip galvanized steel components, PVC pipes embedded in concrete, and stainless-steel anchor bolts.

**Air-filled rubber dams** operate on a similar principle but use compressed air rather than water to inflate the rubber membrane. Air is supplied through a piping system connected to a shaft and operating room that houses fans, regulating devices, and control equipment. Condensed moisture is drained through a shaft base positioned below the weir sill level. Control is likewise automated through a headwater probe. The principal advantage of air-filled systems is their rapid response time, particularly after flood events, as air inflation and deflation can be achieved much faster than water-based systems. Under normal conditions, the dam remains inflated and can be continuously lowered by up to 15% of its height. During extreme flows, it may be fully deflated, forming a characteristic V-shaped buckling of the membrane.

**Overall, rubber dams offer several advantages over conventional weirs, including shorter construction times, long service life, minimal energy requirements, ease of maintenance, and high resistance to seismic activity. Their flexibility and resilience make them an increasingly preferred solution for modern water management and low-impact hydraulic infrastructure.**

In developing economies, hydropower remains a central tool for electrification and industrialization. Significant new projects often large reservoir dams have been financed and constructed across Africa, Latin America, and Asia (e.g., Uganda's Karuma Dam; Reuters, 2024). Many of these projects are financed with international partners and export-credit arrangements. PSH deployment is expanding as grids integrate variable renewables, but much of the global PSH capacity remains concentrated in a few countries (e.g., China, Europe, Japan) while many emerging markets are only beginning to plan or finance such projects (IHA, 2024; IRENA, 2023).

Companies

**GE VERNOVA**

GE Vernova stands as a global leader in renewable energy innovation, with its hydropower turbines and generators representing over 25% of the total installed capacity worldwide. The company's hydropower solutions are central to advancing the global energy transition by offering a reliable, storable, and flexible source of renewable power that stabilizes electric grids and enhances energy security. Hydropower currently supplies more than 15% of the world's electricity, making it a cornerstone of low-carbon energy generation.

GE Vernova's hydropower technology is distinguished by its low lifecycle carbon footprint, outperforming other renewable and conventional energy sources in sustainability metrics. As one of the oldest and most cost-effective means of producing decarbonized electricity, hydropower supports national energy independence while mitigating the impacts of climate-related disruptions.

The company offers a comprehensive portfolio that spans from individual equipment to full turnkey hydropower solutions, covering every stage from "water to wire." This includes design, manufacturing, installation, and maintenance services tailored for both new plants and existing hydropower assets. By combining deep technical expertise with global experience, GE Vernova continues to drive innovation in renewable energy systems, ensuring that hydropower remains a cornerstone of the world's sustainable energy future.

**Waterlily Turbine**

The WaterLily Turbine is a compact, portable hydroelectric generator designed to convert the kinetic energy of flowing water and, in some cases, wind into usable electricity for small electronic devices. It is primarily intended for low-power applications such as charging phones, tablets, GPS devices, and power banks, making it well suited for camping, off-grid living, and emergency situations where conventional electricity or sufficient sunlight for solar charging is unavailable. The turbine operates on a simple but proven principle. As water flows past its propeller blades, the blades rotate, driving an internal generator in which magnets pass over coils to produce an electric current. This process mirrors the basic physics of large-scale hydropower systems, albeit on a much smaller and highly portable scale. Under optimal conditions, the WaterLily can generate up to 15 watts of power at water speeds of approximately 7.2 miles per hour, while still delivering a modest trickle charge of around 3.6 watts in slow-moving streams with currents as low as 1 mile per hour.

**A key advantage of the WaterLily is its portability and versatility**. Weighing approximately 2.85 pounds, it is easy to transport and deploy in rivers, streams, or even when towed behind a boat. It can also function as a small wind turbine in suitable conditions. The device is built for durability, featuring robust materials such as stainless-steel components and protective accessories, including anchoring systems and dry bags for electronics. As a result, it provides a reliable, renewable power option for outdoor, off-grid, and emergency energy needs.

**Andritz Hydro**

ANDRITZ Hydro develops and supplies Pumps as Turbines (PATs), an innovative and cost-effective approach to small hydropower generation, energy recovery, and pumped-storage applications. PATs are based on standard centrifugal pumps operated in reverse, enabling the conversion of hydraulic pressure and flow energy into mechanical energy, which is then transformed into electricity. By repurposing widely available pump technology, ANDRITZ delivers robust, high-efficiency solutions that reduce capital expenditure while maintaining industrial-grade reliability. A major application of ANDRITZ PAT technology is pumped-storage hydropower. In these systems, reversible pump-turbines move water to an upper reservoir during periods of low electricity demand and generate power during peak demand, providing essential grid balancing and flexibility. PATs are also widely used for energy recovery in industrial and municipal systems such as water networks, paper mills, and process industries where excess pressure would otherwise be dissipated. Instead, this wasted energy is recovered and converted into useful electricity. In small hydropower projects, PATs offer an economical alternative to conventional turbines, making them particularly suitable for remote or decentralized generation.

When operating as turbines, water enters the impeller from the discharge side, reversing the normal pump flow. The hydraulic pressure and velocity rotate the impeller, which drives a generator to produce electricity. ANDRITZ PAT solutions achieve efficiencies of up to 87 percent, supported by wear-resistant materials and customized hydraulic designs. ANDRITZ's portfolio includes large reversible pump-turbines, small pump-turbine units such as the ACT/FPT series, and screw turbines for low-head applications, providing flexible, single-source solutions across a wide range of hydropower needs.

### Cost and Savings of Hydropower

Hydropower remains one of the most cost-effective and sustainable sources of electricity within the global renewable energy portfolio. According to the International Renewable Energy Agency (IRENA, 2024), the levelized cost of energy (LCOE) for new hydropower projects varies significantly depending on geographical, hydrological, and infrastructural conditions. However, typical estimates indicate that new hydropower plants produce electricity at around US$0.057/kWh (US$57/MWh), placing it among the most competitive renewable energy technologies in operation today.

When compared with fossil fuel-based power generation particularly peaking plants using fuel oil or natural gas at costs between US$0.15–0.20/kWh (US$150–200/MWh) the potential savings are substantial. For instance, a grid operator replacing 100,000 MWh of fossil peaker electricity with new hydropower could realize annual savings between US$9.3 million and US$14.3 million, depending on the fuel type and prevailing energy market prices. These savings arise not only from lower operational costs but also from hydropower's minimal fuel dependency and long asset lifespan, which often exceeds 50 years with appropriate maintenance (IRENA, 2024).

Additionally, hydropower contributes to long-term grid stability and flexibility, providing both baseload power and energy storage capacity through pumped-storage systems. This dual functionality enables grid operators to integrate higher shares of variable renewables such as solar and wind without compromising reliability. Furthermore, hydropower's low lifecycle carbon footprint enhances its economic value in regions implementing carbon pricing or emissions trading schemes, thereby amplifying its cost-saving potential.

**Overall, hydropower's combination of competitive generation costs, long-term savings, and ancillary grid benefits positions it as a cornerstone technology for countries seeking both economic efficiency and energy decarbonization. Its cost-effectiveness, proven technology base, and adaptability to diverse regional contexts make it an essential component of the global clean energy transition (IRENA, 2024).**

### Geothermal Energy

Geothermal energy harnesses heat stored in the Earth to provide heat and electricity with high-capacity factors and low operational emissions. Technologies range from conventional hydrothermal plants that exploit natural reservoirs to engineered systems that create permeability in hot rock. Geothermal's characteristics firm, low-emissions baseload power and potential for direct heat use make it strategically valuable for decarbonisation. Yet its deployment, costs, risks and social-environmental trade-offs vary substantially between developed and developing economies. This essay describes the major geothermal variants, assesses maturity and deployment, presents core performance metrics, examines environmental and social impacts, considers supply-chain and critical-material issues, reviews innovation frontiers, and evaluates comparative deployment challenges.

Geothermal electricity technologies are commonly categorized as dry-steam, flash (single- and multi-flash), and binary (organic Rankine cycle, ORC) plants. Dry-steam plants use naturally occurring steam to drive turbines; flash plants extract high-pressure hot water and flash it to steam to drive turbines; binary plants transfer heat from moderate-temperature geothermal fluids to a secondary working fluid with a lower boiling point, enabling electricity generation from lower temperatures (U.S. DOE, n.d.; NREL, 2024). For direct heat (district heating, industrial process heat, greenhouse heating), geothermal heat exchangers and district networks are used.

Beyond conventional hydrothermal systems, Enhanced Geothermal Systems (EGS) sometimes called engineered or hot-dry-rock systems create or stimulate permeability in hot, low-permeability rock by hydraulic stimulation and circulatory wells. EGS can, in principle, greatly expand the accessible resource base beyond tectonically active regions (RFF, 2020; IEA, 2024). Closed-loop concepts (e.g., U-loop, coaxial) circulate a working fluid in wells without interacting with native fluids, reducing some environmental concerns but adding engineering complexity (IEA, 2024).

Shallow geothermal (ground-source heat pumps) and low-enthalpy resources serve heating/cooling needs and are widespread in both developed and developing markets, often with simpler permitting and faster payback than power plants.

Conventional hydrothermal geothermal is a mature, commercially proven technology. Global installed geothermal electric capacity exceeded ~16–17 GW by end-2024, concentrated in a handful of countries (United States, Indonesia, Philippines, Turkey, New Zealand, Kenya, Iceland) with abundant hydrothermal resources (IRENA, 2025; IRENA Renewable Capacity Statistics). Capacity additions in 2023–24 were modest compared with solar and wind but record growth in interest and investment is evident, particularly in supporting heat and industrial decarbonisation (IRENA, 2025).

EGS and deep geothermal for heat and power are at demonstration to early-commercial stages. The International Energy Agency notes geothermal has scale-up potential if drilling, stimulation and learning-by-doing reduce costs; it could supply a material share of electricity and firm capacity by mid-century with sustained investment (IEA, 2024; FT coverage). Technology firms and major data centre operators have been investing in next-generation geothermal (fracturing/drilling, closed-loop systems) to get 24/7 firm low-carbon power (FT, 2024).

Deployment patterns differ by income group: developed economies (U.S., Iceland, New Zealand, parts of Europe) have older fleets and focus on optimization and expansion into heat; developing economies with high geothermal potential (Indonesia, Philippines, Kenya, East Africa Rift countries, parts of Latin America) pursue new major projects for power and local development, but often face financing, regulatory and technical barriers (IRENA, 2025; World Bank resources).

### Nuclear Power in the Electricity Transition

Nuclear power occupies a distinctive and increasingly critical place within the broader decarbonisation of electricity generation. While renewables such as wind and solar have made tremendous progress in both deployment and cost reduction, their very nature intermittent, weatherdependent and often distant from load centres means that a fully decarbonised grid reliant only on variable renewables faces substantial challenges. Nuclear power, by contrast, offers high-capacity factors, firm (dispatchable) zerocarbon generation, and high-power density, making it a potent complement to variable renewables and a cornerstone for deep decarbonisation strategies (World Nuclear Association, 2025; IAEA, 2024).

### Role and Features

One of the most significant technical advantages of nuclear power is its ability to operate at high-capacity factors typically in the range of 80 % to 95 %, far higher than most renewables (World Nuclear Association, 2024). By providing large volumes of continuous generation irrespective of weather or daylight, nuclear reactors deliver what is commonly referred to as "firm lowcarbon power," which does not require backup generation or extensive storage to maintain grid stability. The International Atomic Energy Agency (IAEA) reports that the global average operating capacity factor for nuclear reactors reached approximately 83 % in 2024, further underscoring nuclear's reliability and performance (World Nuclear Association, 2025).

In addition to these operational strengths, nuclear power brings high power density: a relatively small footprint compared with large wind or solar farms can deliver very large amounts of energy. Large reactors also contribute essential grid services such as inertia, voltage support, frequency regulation which are vital as the grid incorporates more and more variable renewables. In recent years, advanced reactor designs and small modular reactors (SMRs) are being developed with improved flexibility, reduced construction risks, and enhanced safety features, further strengthening nuclear's role in future electricity systems (IAEA, 2024).

Because of these inherent characteristics, nuclear is often characterised as a key complement to renewables: it provides the firm foundation upon which variable generation can scale, thereby helping maintain stability, reliability and costefficiency in heavily decarbonised electricity systems. Without firm lowcarbon generation, the need for large amounts of storage, backup generation, or renewable overbuild can significantly increase system cost and complexity.

### Benefits & Challenges

**Benefits:**

- High reliability and dispatchability make nuclear an ideal choice for replacing retiring fossil plants or serving grids with limited storage capacity.
- High-capacity factor means large volumes of energy from each reactor, reducing perunit generation cost over the lifetime.
- Firm generation ensures grid stability, provides inertia, and supports high penetration of variable renewables.
- Potential for coproduction of hydrogen or high-temperature heat (e.g., for industry) further enhances value chains beyond electricity (OECD/NEA, 2022).

**Challenges:**

- Very high upfront capital cost and lengthy lead times (often 8–10 years or more) remain major barriers.
- Financing risk and the cost of capital heavily influence overall economics; delays and cost overruns in past builds often deter investment (NEA, 2020).
- Site selection, licensing, regulatory frameworks, safety concerns, waste management and decommissioning create complex implementation challenges.
- Public acceptance and geopolitical risks, especially in emerging markets, can slow deployment or increase financing premiums.

### Relevance for Africa

For African countries, nuclear power offers a strategic, longterm decarbonisation option especially in regions with large baseload demand centres, industrial clusters, or where high renewable penetration is challenging due to grid integration or resource constraints. Although initial construction costs are substantial, once operational nuclear plants provide decades of stable, lowcarbon generation with minimal fuel costs. With appropriate financing models (e.g., concessional loans, international partnerships, SMRs) nuclear can underpin energy security and enable industry development in a lowcarbon context. In addition, pairing nuclear with hydrogen production systems or industrial heat could enable integrated energyindustry hubs, giving Africa a leapfrog opportunity into nextgen lowcarbon infrastructure.

### Cost and System Savings

Economically, nuclear's contribution goes beyond simply lowcarbon generation it helps deliver substantial systemlevel cost savings when integrated into decarbonised electricity systems. In a modelling study by the OECD's Nuclear Energy Agency (NEA), it was found that under stringent carbonconstraint scenarios the inclusion of new nuclear capacity reduces overall system costs by 711 % compared to scenarios where nuclear expansion is assumed constrained. In deeper decarbonisation scenarios, the savings can rise to around 4050 % (OECD/NEA, 2022).

For example, the OECD/NEA report states that if new nuclear build is not allowed, achieving the same emission reduction would require about sixfold more variable renewable capacity, which would lead to doubling of electricity system costs in some cases (OECD/NEA, 2022). In other words, nuclear helps reduce the required scale and therefore cost of renewables, storage and grid reinforcement that would otherwise be needed.

More specifically, studies such as *Nuclear Energy and Renewables: System Effects in Lowcarbon Electricity Systems* (OECD/NEA, 2012) highlight that excluding nuclear from lowcarbon systems increases not only the direct generation cost but also hidden system costs (e.g., due to intermittency and required flexibility) by as much as onethird depending on the country and penetration of renewables.

In terms of levelised cost of electricity (LCOE), while nuclear has high upfront capital cost, the steady output over many decades means that breakthrough nuclear targets (for example ~US$1,000 per kW installed in favourable settings) could lead to estimated LCOEs of around US$4250/MWh, making nuclear competitive with other firm lowcarbon technologies (OECD, 2020).

Thus nuclear power delivers twofold economic benefit:

- Direct lowcarbon generation at a relatively stable marginal cost;
- Indirect system cost savings by reducing the overall need for additional renewables, storage, and balancing infrastructure.

## Hydrogen in Electricity Generation and Flexibility

Hydrogen is emerging as a cornerstone technology for decarbonising electricity systems and providing flexibility in energy networks dominated by variable renewable energy. Unlike conventional fossil fuels, hydrogen can serve multiple functions across the energy system, offering a unique combination of long-duration storage, dispatchable generation, and industrial feedstock potential. These capabilities make hydrogen particularly relevant in scenarios with high shares of intermittent renewable generation, such as solar and wind, and complement firm low-carbon sources like nuclear power (IRENA, 2023; IEA, 2023a).

### Role and Concepts

Hydrogen's versatility in electricity systems stems from its ability to store, transport, and release energy over long periods. One key role is as a long-duration energy storage medium. Surplus electricity from renewables or nuclear can be converted into hydrogen through electrolysis splitting water molecules into hydrogen and oxygen. This hydrogen can later be used in multiple ways: it can be combusted in hydrogen turbines or engines, fed into fuel cells for electricity generation, used to supply industrial heat, or act as fuel for transport systems (IEA, 2023a; IRENA, 2023).

In electricity generation, hydrogen functions as a dispatchable source, similar to natural gas but with near-zero direct carbon emissions when produced from renewable or nuclear electricity. This capability allows system operators to balance supply and demand, particularly during periods of low renewable output or high electricity demand. By decoupling generation from immediate demand, hydrogen effectively extends the temporal flexibility of the grid, enabling seasonal storage and mitigating the need for costly overbuilds of solar, wind, or battery storage (IRENA, 2023).

Hydrogen also plays a crucial role as an industrial feedstock and fuel, providing low-carbon pathways for hard-to-abate sectors such as steel, cement, and chemical manufacturing. When electricity systems are integrated with hydrogen production, power supply becomes more flexible and value creation is enhanced: electricity generated during periods of low market prices or excess production can be converted into hydrogen, creating a new revenue stream and improving the economics of the electricity system (IEA, 2023a).

### Cost Dynamics

The economics of hydrogen in electricity systems are influenced by several factors: electricity prices, electrolyser capital costs, capacity factors, storage, compression, and transport costs. Today, green hydrogen, produced using renewable electricity, is typically 2–3 times more expensive than fossil-based “grey” hydrogen derived from natural gas without carbon capture (IRENA, 2023). Current costs are estimated at approximately US$4–6 per kilogram, compared to grey hydrogen at roughly US$1.5–2 per kilogram (IEA, 2023b).

However, cost trajectories are optimistic. With falling renewable electricity costs, improvements in electrolyser efficiency, and scaling effects, green hydrogen could reach under US$2/kg by 2030 in regions with abundant solar or wind resources (IRENA, 2023). In addition, nuclear-powered hydrogen production offers a promising route to cost-effective hydrogen, particularly using high-temperature or advanced reactors. Estimates indicate that hydrogen production costs using nuclear energy could range from US$0.90–2/kg, depending on reactor type, electricity cost, and capacity factor (NEA/IEA, 2022).

From a system perspective, integrating hydrogen into electricity networks can lead to substantial cost savings. By producing hydrogen during periods of surplus generation, systems reduce curtailment of renewable energy and delay the need for additional storage capacity. Modelling studies show that in high renewable penetration scenarios, coupling hydrogen production with nuclear or wind/solar can reduce overall system costs by 10–30% compared to scenarios without hydrogen, primarily through deferred investment in batteries, gas turbines, and grid reinforcement (IRENA, 2023; IEA, 2023a).

### Benefits

Hydrogen offers several key benefits for electricity systems:

1. **Seasonal and long-duration storage:** Unlike lithium-ion batteries, which are ideal for short-term storage (hours to days), hydrogen can store energy for weeks to months, helping balance seasonal fluctuations in renewable generation (IRENA, 2023).
2. **Grid flexibility and reliability:** Hydrogen provides dispatchable electricity, contributing to frequency regulation, inertia, and load-following capability, critical for grids with high shares of variable renewables (IEA, 2023a).

3. **Revenue and operational optimization:** Electrolysers can operate flexibly, producing hydrogen when electricity prices are low or generation exceeds demand, turning otherwise stranded electricity into valuable hydrogen (IRENA, 2023).
4. **Decarbonisation of hard-to-abate sectors:** Hydrogen can directly replace fossil fuels in industrial heating, chemicals, and transport, linking power generation decarbonisation with broader emission reduction strategies (IEA, 2023b).
5. **Integration with nuclear power:** Nuclear plants can supply both electricity and hydrogen simultaneously. This integration converts fixed-cost nuclear output into multiple revenue streams electricity sales during peak demand and hydrogen production during off-peak periods improving plant economics and system flexibility (NEA/IEA, 2022).

### Challenges

Despite the clear advantages, hydrogen deployment in electricity generation faces significant challenges:

1. **High current production costs:** Green hydrogen remains expensive, requiring substantial electricity inputs and large capital investments for electrolysers.
2. **Infrastructure needs:** Storing, transporting, compressing, and distributing hydrogen at scale remains technologically and economically challenging due to its low volumetric energy density.
3. **Efficiency losses:** Electrolysis, storage, and reconversion to electricity entail round-trip efficiency losses (typically 30–40%), lower than battery storage for short-duration applications (IRENA, 2023).
4. **Technology maturity:** Hydrogen-fired turbines and fuel cells for grid-scale dispatch are less mature than conventional gas-fired plants, contributing to high capital costs and operational uncertainty.
5. **Integration complexity:** Effective integration requires coordination between electricity markets, hydrogen production, storage, and demand, which can increase operational and regulatory complexity.

### Applications in Electricity Systems

Hydrogen's most impactful application in electricity systems lies in temporal decoupling of supply and demand. Electrolysers can operate during periods of low electricity prices, producing hydrogen for later conversion to electricity during peak demand or when renewable output is insufficient. This approach reduces curtailment, allows higher renewable penetration, and lowers system-wide investment needs for batteries and peaking plants (IEA, 2023a).

When paired with nuclear power, hydrogen becomes even more strategic. Nuclear plants, with their high-capacity factors, can run continuously and allocate surplus output to hydrogen production. This arrangement transforms nuclear generation from a single revenue stream (electricity) into a dual-stream operation (electricity + hydrogen), improving economics and reducing system costs. It also enables nuclear to provide seasonal and operational flexibility, addressing one of the traditional criticisms of nuclear as “inflexible” generation (NEA/IEA, 2022).

For regions such as Africa, hydrogen offers unique opportunities. Surplus renewable energy from solar-rich regions (e.g., Sahara, Sahel, or Southern Africa) can produce hydrogen for domestic consumption or export, while nuclear-hydrogen systems in industrial clusters can supply both electricity and industrial feedstocks in low-carbon form. Early deployment of hydrogen infrastructure can catalyse industrial decarbonisation, energy security, and local job creation.

**Example of Companies**

**1. Linde plc**

Linde plc is a global leader in industrial gases and engineering solutions, recognized for its pivotal role in advancing the hydrogen economy. The company operates across multiple sectors, including healthcare, manufacturing, chemicals, and energy, with a strong focus on industrial gases such as oxygen, nitrogen, and, critically, hydrogen. In recent years, Linde has strategically positioned itself at the forefront of clean energy solutions, particularly in clean hydrogen production, encompassing both blue hydrogen produced from natural gas with carbon capture and green hydrogen generated via electrolysis using renewable electricity. This dual capability allows Linde to support decarbonisation across industrial, transport, and power generation sectors, offering scalable technology solutions and the necessary infrastructure for a low-carbon energy transition (Linde plc, 2024).

In the context of electricity generation, Linde’s hydrogen technologies are essential for enabling dispatchable low-carbon power and long-duration energy storage solutions. By producing and supplying high-purity hydrogen, Linde provides utilities, industrial operators, and governments with the feedstock needed to fuel hydrogen turbines, fuel cells, and hybrid energy systems. This positions Linde not only as a technology provider but also as an enabler of the broader clean energy ecosystem, facilitating the integration of hydrogen into power systems while reducing dependence on fossil fuels.

Financially, Linde remains robust. In 2024, the company reported revenues of US$33 billion, reflecting strong global demand across its industrial gases and engineering services portfolio. Importantly, Linde has committed substantial capital to hydrogen infrastructure, with a project backlog exceeding US$10 billion. These investments underscore its strategic focus on the hydrogen sector and its role in scaling low-carbon energy technologies. Key projects include a US$2 billion clean hydrogen facility in Alberta, Canada, designed to produce both blue and green hydrogen for industrial and power applications; a US$1.8 billion hydrogen and nitrogen complex in Beaumont, Texas, supporting both domestic and export markets; and a US$400 million industrial gas plant in Louisiana, expanding Linde's hydrogen production and distribution capabilities (Linde plc, 2024).

Beyond project execution, Linde also invests in engineering, technology development, and partnerships, ensuring its hydrogen solutions are commercially viable and scalable. By combining production capacity, engineering expertise, and financial backing, Linde facilitates the deployment of hydrogen in sectors that are traditionally hard to decarbonize, including heavy industry and power generation. In doing so, Linde contributes significantly to both operational cost savings and emissions reduction, demonstrating the economic and environmental potential of hydrogen at a global scale.

### NEOM Green Hydrogen Company

NEOM Green Hydrogen Company is a landmark initiative in the global clean energy landscape, representing a strategic joint venture primarily between Air Products & Chemicals (APD) and ACWA Power. This venture is pioneering the development of the world's largest carbon-free green hydrogen facility, designed to produce green ammonia for export markets. The project will harness 4 gigawatts (GW) of renewable energy, combining solar and wind generation to power electrolysis at scale, ensuring a zero-carbon hydrogen supply chain (IRENA, 2023; NEOM Green Hydrogen, 2024).

The total investment for this transformative project is estimated at US$8.4 billion, reflecting the scale and ambition of deploying integrated renewable generation, electrolyser systems, and green ammonia production infrastructure. To support this capital-intensive project, the NEOM Green Hydrogen Company successfully secured US$6.1 billion in non-recourse financing, sourced from a consortium of 23 local, regional, and international banks. This financial structure mitigates investment risk for project sponsors while demonstrating strong confidence in the commercial viability of large-scale green hydrogen ventures (NEOM Green Hydrogen, 2024).

From a revenue and financial perspective, the partners bring substantial industrial and financial capacity to the project. Air Products & Chemicals reported annual revenues of approximately US$12.1 billion for its fiscal year ending September 30, 2024, underlining its global footprint in industrial gases, engineering, and hydrogen solutions. ACWA Power, which manages a portfolio of 94 projects including the NEOM initiative, reported total investment costs of approximately US$97 billion and a net profit of SAR 927 million (~US$247 million) in the first half of 2024, showcasing its expertise in utility-scale renewable energy deployment and project financing (ACWA Power, 2024).

The NEOM Green Hydrogen project exemplifies how large-scale, integrated renewable energy and hydrogen systems can create significant economic and environmental value. Beyond producing low-carbon fuel for global export, the project generates employment, strengthens technological capacity, and sets a precedent for replicable green hydrogen ecosystems worldwide. By leveraging large-scale financing and strategic industrial partnerships, NEOM Green Hydrogen is not only advancing global decarbonisation goals but also creating a financially robust model for hydrogen adoption at industrial scale.

### Renewable Energy Savings Potential for Africa and Nigeria

The transition to renewable energy in Africa, particularly in Nigeria, represents not only a pathway toward decarbonization but also a significant financial opportunity for both industrial and utility-scale adopters. Across the continent, heavy reliance on diesel-based generation for backup and off-grid power continues to drive up energy costs, eroding profit margins and economic productivity. According to the International Renewable Energy Agency (IRENA, 2024), replacing 1,000 MWh/year of diesel-generated electricity equivalent to the annual consumption of a medium-sized industrial facility with solar photovoltaic (PV) power can save approximately US$650,000 per year, based on a conservative diesel generation cost of US$0.70 per kWh.

Scaling this transition across 10,000 MWh/year a realistic figure for a large commercial or retail chain operating multiple sites would result in aggregate annual savings of roughly US$6.57 million (IRENA, 2024). These numbers illustrate the immediate economic gains achievable by substituting diesel with clean energy, even before accounting for environmental and social benefits. For many African industries, such savings directly translate into enhanced competitiveness, improved operational stability, and increased investment capacity for expansion or innovation.

At the utility scale, similar dynamics apply. The U.S. National Renewable Energy Laboratory (NREL, 2023) documents that replacing natural gas peaker plants producing electricity at US$75 per MWh with onshore wind generation costing around US$42 per MWh can yield US$33 per MWh in avoided fuel and operational costs. For a medium-sized African utility purchasing 100,000 MWh/year, this equates to US$3.3 million in annual savings. In Nigeria, where natural gas-fired generation dominates the grid yet suffers from supply and infrastructure constraints, this transition could ease fiscal pressures while enhancing grid reliability.

Beyond direct energy cost reductions, solar and wind systems coupled with battery storage create additional financial value through demand management, outage avoidance, and business continuity. The inclusion of storage systems allows enterprises and utilities to flatten demand peaks, thereby avoiding costly demand charges and protecting operations from frequent power disruptions a pervasive challenge across sub-Saharan Africa (NREL, 2023). The resilience premium the value associated with uninterrupted power can often be monetized, making renewable systems more attractive even in cases where the direct energy cost parity has not yet been fully achieved.

Moreover, innovative financing structures, such as zero-capex or Power Purchase Agreement (PPA) models, have begun to transform renewable adoption across African markets. These models enable companies to deploy solar or hybrid renewable systems without upfront capital expenditure, instead paying a fixed or indexed tariff over time that remains lower than the cost of diesel or unreliable grid power (Enée, 2024). This approach allows firms to convert potential savings into immediate improvements in cash flow, significantly lowering the financial barriers to entry for renewable adoption.

Local factors including diesel price volatility, grid tariff adjustments, and cost of capital affect the specific magnitude of savings. In high-risk or remote areas where diesel logistics add a premium to generation costs, the payback period for renewable systems can be under three years, offering rapid returns on investment. Meanwhile, in urban centres like Lagos, where industrial consumers face rising grid tariffs and frequent outages, solar-plus-storage systems deliver both cost savings and reliability benefits.

In essence, the African renewable energy transition represents an economic imperative as much as an environmental one. The cumulative effect of replacing expensive, volatile fossil-based power with stable, low-cost renewables could save African businesses and utilities billions of dollars annually, while also reducing emissions and dependency on imported fuels. For Nigeria, with its high solar potential and growing wind resources, these transformations align with both the Energy Transition Plan (ETP) and broader sustainable development goals, unlocking a future where energy affordability and sustainability go hand in hand.

**Energy storage, flexibility & grid modernization (balancing supply & demand)**

The accelerating global shift toward renewable energy sources particularly solar and wind has fundamentally transformed how electricity systems must be managed. Unlike conventional thermal plants, renewable energy generation is variable and weather-dependent, leading to temporal mismatches between supply and demand. This variability underscores the need for energy storage, flexibility mechanisms, and grid modernization to ensure system reliability, stability, and affordability (International Energy Agency [IEA], 2022). Balancing these dynamic flows is essential to support deep decarbonization and enable the integration of high shares of renewables into modern power systems.

**Energy storage** technologies play a critical role by absorbing excess energy when generation exceeds demand and releasing it when supply falls short. Short-duration storage systems such as lithium-ion batteries have become integral to grid operations because of their high round-trip efficiency and rapid response times. Meanwhile, long-duration and seasonal storage options, including pumped hydro, compressed air, and emerging hydrogen-based systems, address prolonged deficits in renewable output (IRENA, 2023). These storage systems not only stabilize frequency and voltage but also facilitate energy arbitrage, grid balancing, and peak-load shifting.

**Grid flexibility** extends beyond storage and refers to the ability of an energy system to respond to rapid changes in electricity supply and demand. This involves both supply-side and demand-side measures. On the demand side, technologies such as demand response programs, vehicle-to-grid (V2G) integration, and smart appliances enable consumers to adjust consumption patterns in response to real-time price or grid signals. On the supply side, smart grids, microgrids, and digitalized grid management systems enhance observability, control, and coordination across distributed energy resources (World Bank, 2023). These innovations collectively increase the grid's resilience, reduce curtailment of renewables, and enhance overall efficiency.

**Grid modernization** is the enabling infrastructure that ties storage and flexibility together. It includes the digitalization of grid operations, expansion of transmission networks, deployment of advanced metering infrastructure (AMI), and investment in real-time monitoring systems. In developed economies, modernization efforts focus on upgrading aging infrastructure and integrating smart technologies. In developing economies, the challenge often involves expanding grid access while incorporating flexibility from the outset (Gonzalez-Salazar et al., 2021).

In essence, energy storage, flexibility, and grid modernization represent the triad upon which a resilient, decarbonized electricity system depends. Together, they enable the smooth operation of renewable-rich grids by balancing intermittency, ensuring reliability, and optimizing energy use across spatial and temporal scales.

### The nature of variability and the balancing challenge

Variable renewable energy (VRE) sources such as solar photovoltaic (PV) and wind output fluctuate on multiple time scales seconds, minutes, hours, diurnal cycles, and seasons. Because electricity supply and demand must balance instantaneously (neglecting small tolerance zones), the grid needs mechanisms to absorb or release energy and adjust to fluctuations (grid balancing). Without flexibility, high penetrations of VRE can lead to curtailment, reliability risks, frequency excursions, and inefficiencies (the so-called "cannibalization" effect, where excess generation depresses value).

To manage variable supply, three main pillars of flexibility are essential:

1. **Storage**: to absorb surplus generation when supply exceeds demand, and release it when demand overshoots supply.
2. **Demand flexibility**: to shift or modulate demand in response to supply patterns (demand response, load shifting).
3. **Transmission (and interconnection)**: to move electricity across geographic regions so that variability in one area can be smoothed by complementary production elsewhere.

These three act together: storage handles local temporal mismatches, demand flexibility reduces peaks and aligns consumption, and transmission enables spatial smoothing of variability. As renewable share rises, the value of short-term storage grows, but beyond moderate penetration, long-duration storage or interregional transfers become increasingly necessary. From a systems perspective, variability means there will be times when generation exceeds local demand (requiring absorption or export) and times when demand exceeds local generation (requiring dispatch or import). Without flexibility, some renewable generation must be curtailed, reducing utilization and raising system costs.

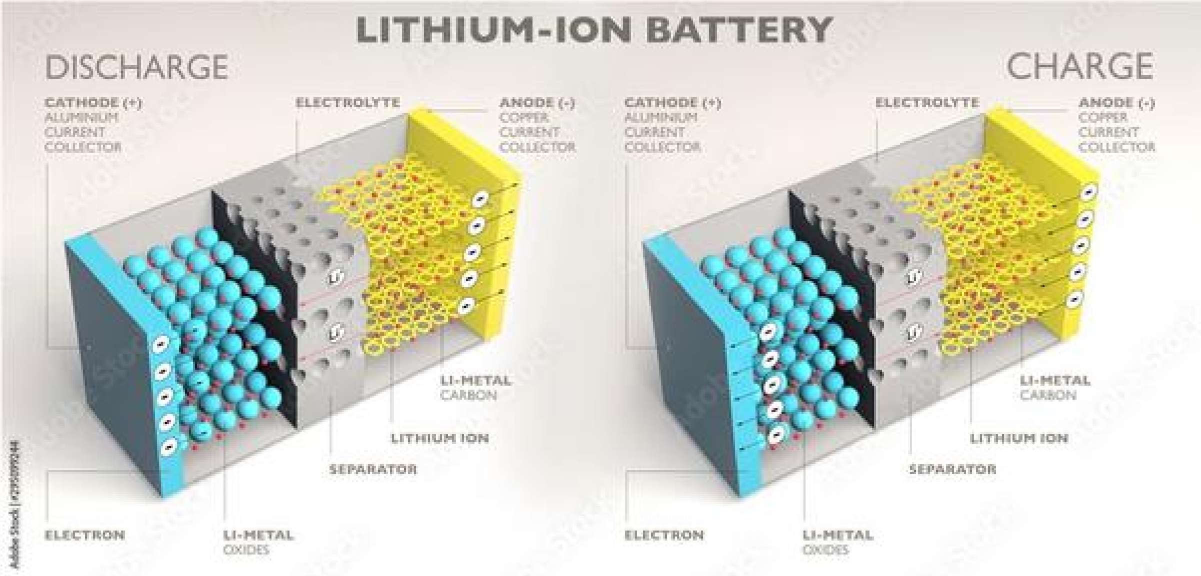
In developed economies, grids are older but increasingly have the institutional resources, capital, and regulatory frameworks to adopt storage, demand flexibility, and wide interconnections. In developing economies, weaker infrastructure, limited capital, and regulatory uncertainty make scaling these flexibility tools more challenging but also more necessary where isolated grids or renewable penetration is rising.

### Short-Duration Storage Technologies

Short-duration storage (typically < 6–10 hours) is the first line of flexibility. Key technologies include lithium-ion batteries, sodium-ion batteries, flow batteries, ultracapacitors (supercapacitors), and flywheels.

#### Lithium-ion batteries

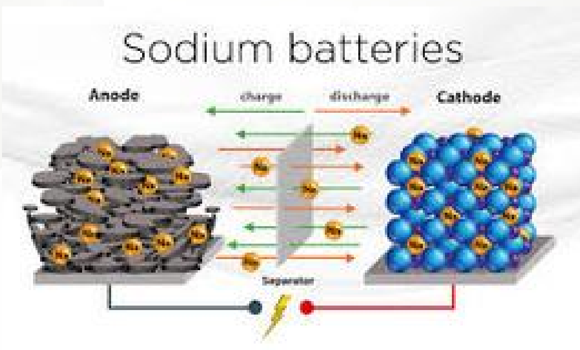
Lithium-ion (Li-ion) is the dominant battery technology today. Its advantages are high round-trip efficiency (typically 85–95 %), good power density, fast response, modular scalability, and a proven track record. Cycle life depends on chemistry, depth-of-discharge, temperature, and usage patterns commercial systems often guarantee thousands of cycles (e.g. 5,000–10,000).




Costs (per kWh storage) have fallen sharply over the last decade. A recent review of grid-scale storage indicates lithium-ion is near cost-parity for shorter durations (e.g. up to 4–6 hours) in many markets. Limitations include limited duration (for 24+ h storage it becomes economically challenging), degradation over time, and resource constraints (lithium, cobalt, nickel).

### Sodium-ion batteries

Sodium-ion (Na-ion) is an emerging alternative that uses more abundant sodium instead of lithium, potentially lowering material costs and supply risk. The round-trip efficiency is somewhat lower (~80–90 %), and cycle life is still improving. It may be more viable for mid-duration applications or behind-the-meter storage where cost is critical. Research is ongoing.




### Flow batteries

Flow batteries (e.g. vanadium redox flow, iron-chromium, organic flows) separate energy storage (in liquid electrolyte tanks) from power conversion (cell stacks). They excel in scalability of energy capacity by enlarging tanks. Round-trip efficiency is moderate (typically 65–85 %), depending on chemistry.


Cycle life is very high (electrolytes degrade slowly) and the energy capacity can be decoupled from power capacity. Costs are higher per kW of stack and per kWh of storage currently. Flow batteries are attractive for mid-duration storage (e.g., 8–12 hours) in systems where lifetime and durability are critical.

### Ultracapacitors / supercapacitors

Ultracapacitors have extremely fast charge/discharge capabilities, very high cycle life (hundreds of thousands to millions of cycles), and excellent power density, but very low energy storage density (i.e. short discharge durations). These are typically used for ancillary services (frequency regulation, smoothing fast fluctuations) rather than bulk energy shifting.

### Flywheels

Flywheels store kinetic energy in a rotating mass. Round-trip efficiency is high (70–90+ %) depending on bearing losses; cycle life is excellent (millions of cycles). But energy capacity is low, so they are suited for seconds-to-minutes bridging applications (frequency, inertia).

In developed economies, Li-ion has been broadly deployed for grid-scale, behind-the-meter, and utility applications. Flow batteries and alternatives are entering pilot stage. In developing economies, short-duration storage is often the first choice where grid reliability is low battery microgrids, backup systems, and solar-plus-storage deployments are increasingly common. However, cost, local supply, and maintenance capacity remain constraints.

The global battery energy storage industry has seen exponential growth driven by technological advancements and increasing demand for renewable energy integration. The top companies, BYD, Tesla, MANLY Battery, Fluence, Samsung SDI, CATL, Panasonic, LG Chem, Enphase Energy, and Johnson Controls are leading this transformation through diverse product portfolios, regional expansions, and record-breaking revenues. Grouping these companies by the type of storage solutions they provide and their regional presence reveals how each contributes uniquely to advancing global renewable energy goals.

### 1. Asian Market Leaders: Large-Scale and Lithium-Based Storage Systems

Asia dominates the battery energy storage sector, with companies such as BYD, CATL, Samsung SDI, LG Chem, Panasonic, and MANLY Battery leading innovation in lithium-ion and large-scale systems. These companies collectively account for a major share of the world's energy storage deployment and production capacity.

BYD, headquartered in China, is one of the largest global producers of energy storage systems. In 2023, BYD shipped 28.4 GWh of battery storage systems and reported a $600 billion revenue, marking a 42.04% increase from the previous year. Its flagship innovations the Blade Battery and MC-1 commercial system have positioned it as a leader in scalable storage for both grid and commercial applications.

BYD  Blade Battery

Similarly, CATL, also based in China, commands a 40% global market share in energy storage batteries, achieving a $60 billion revenue (400.9 billion RMB) in 2023. The company's high-density "Tianheng" system, featuring zero capacity degradation over two years, sets industry benchmarks for efficiency and durability.


CATL Tianheng" system

Samsung SDI of South Korea generated substantial income from its energy storage division, shipping 185 GWh of lithium-ion batteries in 2023 and securing a landmark $800 million deal with NextEra Energy for 6.3 GWh of storage systems in 2024. LG Chem, another South Korean giant, reported $4.6 billion (6.16 trillion KRW) in revenue for Q2 2024, driven by the expansion of its U.S. energy storage production capacity and innovations such as dry electrode and LFP technologies. Meanwhile, Panasonic, headquartered in Japan, continues to play a crucial role in providing high-quality, integrated residential and industrial storage solutions, partnering with Tesla and others to enhance renewable energy resilience.

On a smaller but significant scale, MANLY Battery, based in Shenzhen, China, focuses on modular, customizable lithium storage batteries for solar, UPS, and industrial applications. With production facilities spanning 65,000 square meters and a daily capacity of 6 MWh, MANLY has built a strong export market with certifications such as UL and CE, strengthening Asia's dominance in battery manufacturing.

**2. North American Innovators: Grid-Scale and Residential Storage Systems**

The United States leads in integrated renewable energy storage through companies like Tesla, Enphase Energy, and Johnson Controls, each contributing to different segments of the energy ecosystem.

Tesla remains at the forefront of large-scale battery energy storage systems through its Powerwall and Megapack. In 2023, Tesla installed 14.7 GWh of storage globally, representing a 125% year-on-year increase, and recorded $7.9 billion in net profit a 115% growth.


Tesla Megapack


Tesla Powerwall

The company's "Master Plan Part 3" envisions deploying 240 TWh of storage by 2050, aligning with a fully renewable energy economy. Its global projects in the U.S., South America, Japan, and Australia demonstrate its leadership in the commercial and utility-scale storage domain.

Enphase Energy, another American firm, specializes in residential and commercial microinverter-integrated storage systems. By 2023, it had deployed over 4 million systems in 150 countries and expanded production to the U.S., Mexico, and India. Enphase's 2023 launch of the IQ EV Charger and its plan to enter the European market in 2024 underscore its integrated approach to energy storage and management.

Johnson Controls, also U.S.-based, combines building energy management systems with battery storage to optimize energy use in real-time. For the fiscal quarter ending December 2023, it recorded $6.09 billion in net sales and $374 million in profit, demonstrating strong growth. Its integration of battery storage with smart building automation has made it a trusted partner in public infrastructure projects.

### 3. European and Global Integrators: Utility-Scale and Grid Storage Solutions

In Europe, Fluence a joint venture between Siemens (Germany) and AES (U.S.) has emerged as a top-tier grid and utility-scale energy storage provider. With operations in 47 regions and over 225 projects completed, Fluence reported a $4.8 million net income in Q4 2023 its first profitable quarter.


Gridstack Pro System

Its Gridstack Pro system and FluenceOS7 operating software optimize grid management, making it Europe's largest and the world's second-largest energy storage integrator. The company's 2024 partnership with Excelsior Energy Capital to deploy 2.2 GWh of U.S.-based storage further strengthens transatlantic energy collaboration.

Across regions, these ten companies demonstrate that battery energy storage is central to renewable energy's future. Asia leads in manufacturing and innovation, with companies like BYD and CATL setting global production records. North American firms such as Tesla and Enphase Energy are advancing integrated and distributed storage solutions, bridging renewable generation and consumer usage. Meanwhile, Europe's Fluence drives grid-scale innovation, ensuring stability and scalability for renewables. Collectively, these companies generated hundreds of billions in revenue in 2023–2024, signaling robust global demand for clean energy storage. As governments and industries accelerate decarbonization efforts, their technologies from BYD's Blade Battery to Tesla's Megapack and Fluence's Gridstack Pro will remain pivotal to ensuring reliability, scalability, and sustainability in the global renewable energy transition.

### Cost & Savings

The economics of short-duration energy storage particularly lithium-ion battery systems are increasingly attractive as costs decline and grid tariffs rise. Utility-scale lithium-ion battery systems with 2–4-hour durations currently average around US$300/kWh installed, with costs expected to fall further as manufacturing scales and battery chemistries improve (NenPower, 2024). For adopters such as utilities, factories, and commercial facilities, the financial case for deploying storage stems from avoiding high-cost peak generation, reducing demand charges, and increasing the self-consumption rate of renewable energy. In regions where grid instability forces frequent reliance on diesel backup, these savings become even more pronounced.

To illustrate, suppose an industrial facility installs 1 MWh of lithium-ion storage to offset peak energy costs of approximately US$0.25/kWh (US$250/MWh). If the amortized cost of stored energy using the battery system is US$0.12–US$0.15/kWh, the company avoids roughly US$0.10–US$0.13 per kWh in peak demand charges or diesel generation costs. Over 1 MWh of peak energy avoided daily, this translates to annual savings of roughly US$40,000–US$47,000. While the initial capital investment may appear high, the reduced operational costs and increased reliability make the payback period achievable within 3–5 years, depending on financing and usage profiles (International Renewable Energy Agency [IRENA], 2024).

In a more extensive scenario, consider a commercial campus consuming 2,000 MWh/year of peak electricity at US$0.25/kWh, amounting to an annual expenditure of US$500,000. Replacing that with stored electricity from a lithium-ion system delivering energy at US$0.12/kWh (accounting for amortization, efficiency losses, and operation), the effective annual savings would be approximately US$260,000. These savings represent over 50% reduction in annual electricity costs during peak hours, with additional benefits in energy resilience, reduced downtime, and predictable energy budgeting.

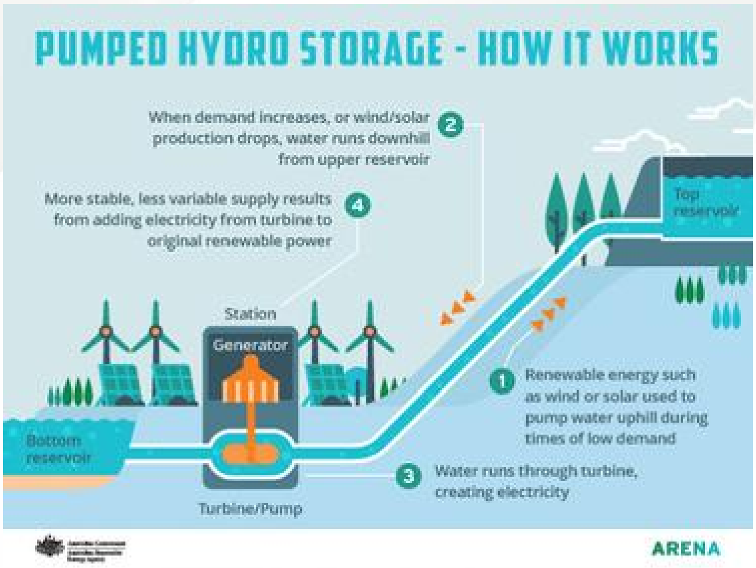
Beyond lithium-ion, supercapacitors and flywheels offer ultra-fast response times, making them valuable for frequency regulation and voltage stabilization. Although their cost per kWh is relatively high, their unique role in preventing blackouts, equipment damage, or production losses adds considerable indirect financial value. For instance, avoiding a single day of production downtime potentially costing tens or hundreds of thousands of dollars can justify the investment in such high-speed systems (U.S. Department of Energy [DOE], 2023). In sum, short-duration storage technologies deliver not only measurable cost savings but also significant value through operational stability and grid reliability. As battery prices continue to decline and energy markets evolve, the total economic benefit of deploying such storage systems will continue to strengthen, particularly in emerging markets like Africa where energy insecurity remains a major cost driver.

### Long-Duration Storage & Seasonal Solutions

As renewable penetration deepens, short-duration storage is insufficient to handle multi-day variability, seasonal imbalances, or extended droughts in hydro systems. Long-Duration Storage (LDS) and seasonal storage technologies fill this gap.

### Pumped Hydro Energy Storage (PHES)

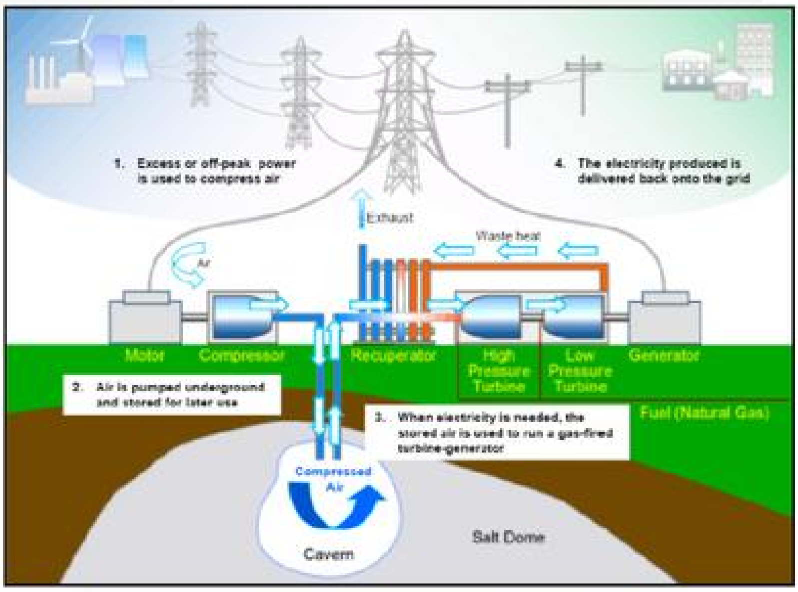
Pumped storage is the most mature and deployed large-scale storage. It uses surplus electricity to pump water uphill to a reservoir, then releases it through turbines when needed. Round-trip efficiency is typically 70–80 %. PHES can provide hours to tens of hours of discharge, with very long lifetimes and low variable costs (main cost is infrastructure). It constitutes the majority of installed energy storage globally.



The limitations are geographical: need suitable elevation difference and hydrology, environmental constraints, permitting and capital complexity. In developed economies, PHES is often used for grid balancing and peak shaving; in developing ones, less often used due to topography, finance and regulation constraints, though potential exists in regions with suitable terrain.

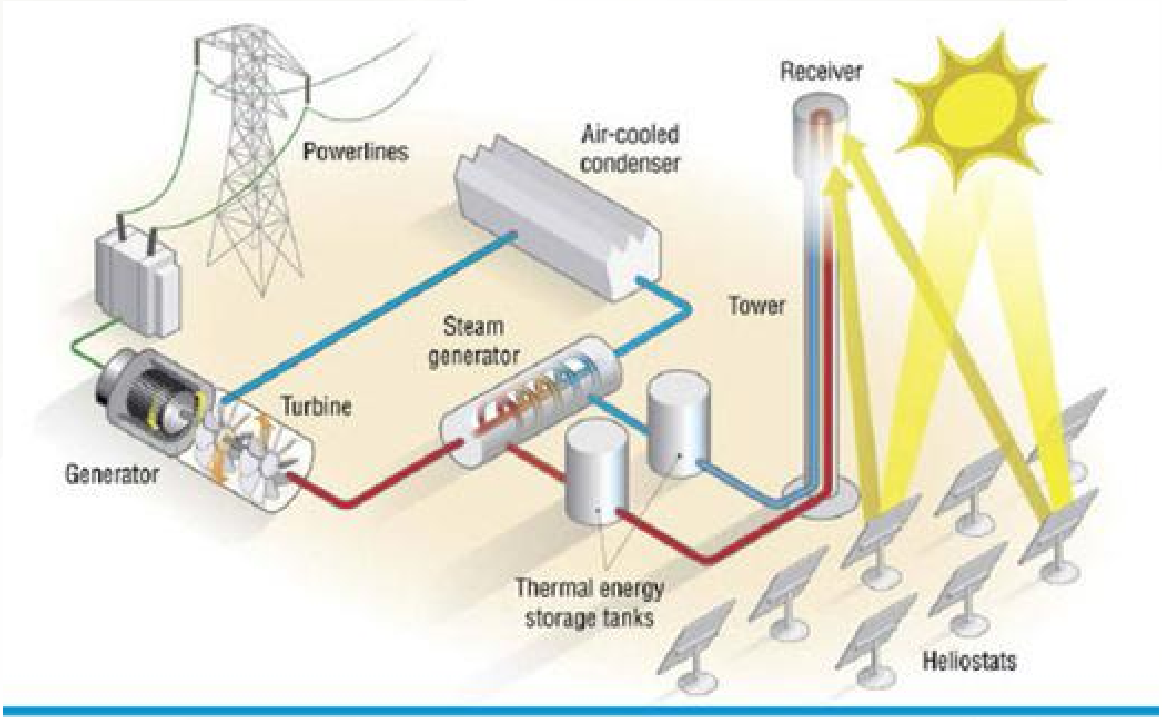
### Compressed Air Energy Storage (CAES)

CAES compresses ambient air (often in underground caverns) using excess electricity, and later expands it through turbines to generate power. There are variations (adiabatic, diabatic, isothermal). Round-trip efficiency ranges from 40–70 % depending on design (efficiency losses in compression, heat management). CAES can support long-duration discharge. There are commercial installations (e.g. in Germany, USA). CAES is limited by geological site availability, capital cost, and thermal integration complexity.




### Thermal storage

Thermal energy storage (TES) stores heat (or cold) rather than electricity. In power systems, TES is often used with concentrated solar power (CSP) plants (molten salt, phase-change materials). TES can buffer diurnal variations or multi-hour shifts. It is less general-purpose for arbitrary grids but very mature in CSP contexts. For seasonal or decadal storage, solar-thermal + heat networks or underground thermal storage can act as seasonal buffers, though with losses.




Thermal Storage

**Power-to-Hydrogen / Chemical Storage (Seasonal)**

For very long-duration and seasonal storage, the conversion of excess electricity into hydrogen (via electrolysis), ammonia, or synthetic fuels is promising. Energy is stored chemically, and reconverted later via fuel cells or turbines. Efficiency is lower (~40–70 % round-trip overall including electrolysis, storage losses, reconversion), but energy density and seasonal continuity are strengths. Power-to-hydrogen is likely essential for decarbonising sectors with long-duration energy needs (heating, industry, transport) and accommodating seasonal imbalances.

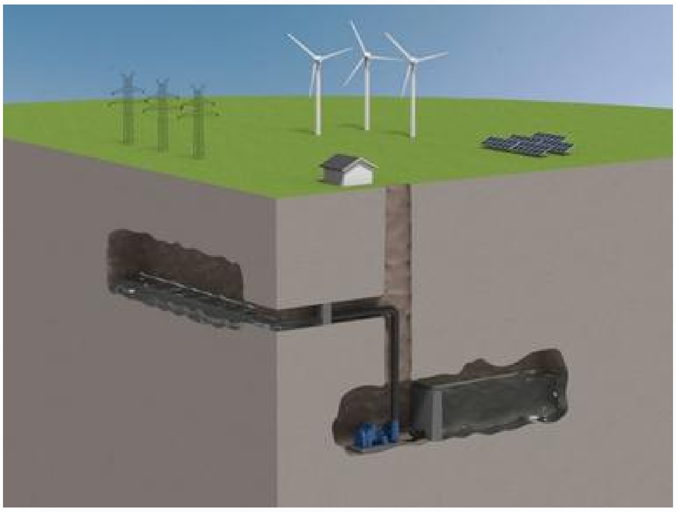
Hybrid chains combining PHES + hydrogen or other storage pathways can balance costs and flexibility. For example, modeling shows combining pumped hydro with hydrogen enables high renewable penetration with lower emissions and cost (Asim et al., 2025). Many R&D efforts focus on hydrogen-to-power systems and fuel cell/turbine reconversion.

In developed economies, seasonal hydrogen storage projects and integrated renewable+hydrogen systems are being piloted. In developing economies, uptake is nascent; cost, infrastructure, and regulatory support are focal challenges.

**Examples of companies pushing these technologies**

**SENS (Sustainable Energy Solutions Sweden/Sweden Holding AB)**

SENS is developing *underground pumped hydro storage* (UPHS) and hybrid pumped hydro + battery systems. One of their core projects is in Pyhäsalmi, Finland, where they are planning an underground pumped storage facility (UPHS) in an old mine, together with a battery energy storage system (BESS) (Sens, 2025). The specifics: initially a 75 MW underground pumped hydro unit, and a BESS component that was planned to be 85 MW, but has been doubled to 170 MW. The pumped hydro component has storage capacity: ~530 MWh, with a max output of about 75 MW.



SENS is a smaller company; the published financials show modest revenues and losses. For instance, as of the half-year report for Jan-June 2025, net sales were 39,000 SEK (Swedish krona) and the company had negative operating profit. In 2024 their annual revenue was around 20.15 million SEK with about 68% growth from 2023. Since pumped hydro (especially underground or in old mines) has very high upfront capital cost, permitting, geological, environmental challenges, and long project timelines, SENS is still in development phases. But the combination with battery storage (hybrid) helps generate earlier revenue (from frequency regulation, arbitrage, etc.). The increased battery size (170 MW) improves near-term revenue streams.

**Hydrostor (Canada, Global A-CAES developer)**

Hydrostor is developing several Advanced Compressed Air Energy Storage projects globally. Key ones include:

a. **Silver City Energy Storage Centre**, Broken Hill, New South Wales, Australia: 200 MW / 1,600 MWh (8-hour duration) A-CAES project.
b. **Willow Rock Energy Storage Centre**, Southern California, USA: 500 MW / 4,000 MWh A-CAES project.
c. **Goderich, Ontario, Canada**: Hydrostor has already completed a commercial A-CAES facility here.

Hydrostor has raised financing of about US$200 million recently (from entities like Canada Growth Fund, Goldman Sachs, CPP Investments) to scale its A-CAES projects in Canada and globally.

**Hydrostor Silver City project**

The Silver City project has also secured a grant from the Australian government agency ARENA of AUS$45 million to help with its infrastructure and development costs.  In terms of economic benefits, the Silver City project is associated with commitments like USD ~670 million in local economic benefits (jobs, etc), plus grid-reliability value.

Hydrostor's A-CAES is seen as long-duration storage (8+ hours, sometimes multi-day), lower environmental impact (relative to pumped hydro in some contexts), and more flexible siting (underground or caverns) than PHES. The challenge is getting financing, permitting, demonstration that systems perform over time, and securing offtake contracts / power purchase agreements (PPAs).

**Storelectric (UK / international CAES & hybrid CAES / hydrogen)**

Storelectric is developing CAES projects in the UK, including the TeesCAES project. This is part of the UK's Long-Duration Electricity Storage (LDES) Cap & Floor regime; it has passed the eligibility assessment and is in project assessment (Storeletric, 2025). They also have other proposals/pipeline projects: small (40 MW) up to large (500 MW) plants in UK, Netherlands, possibly France, etc.

Storelectric publishes forecasts for revenue for its CAES plants: in UK, a 40 MW size plant is expected to produce revenue of around £14 million per year; a 500 MW plant potentially up to £129 million per year in similar conditions.

Their business model depends strongly on regulatory support (e.g. cap & floor regime in the UK), government incentives, offtake/contracted income for storage & ancillary services. Storelectric benefits from patented technology (thermal energy storage of heat of compression, etc.) and is working to scale its plants. But huge capex, permitting, securing of suitable caverns (salt caverns or other underground geologies), site acquisition etc remain big challenges.

The current landscape of large-scale energy storage through Pumped Hydro Energy Storage (PHES) and Compressed Air Energy Storage (CAES) technologies reflects a sector in transition from development to deployment. While most PHES and CAES developers are still in the planning or pre-construction phases, some, like Hydrostor's Goderich, Ontario project, have reached commercial operation. PHES projects, including SENS's Pyhäsalmi facility in Finland, are moving toward "ready-to-build" status but remain capital-intensive with long development timelines.

In terms of revenue generation, the industry remains early-stage. Hydrostor has attracted major funding and projects with significant local economic benefits, though its operational revenue remains modest. Corre Energy currently operates at a loss but has secured long-term offtake deals, including a €1 billion contract over 15 years for its Ahaus, Germany project. Storelectric projects potential future earnings in the tens to hundreds of millions of pounds annually once plants are operational, while SENS currently earns primarily from project development and consultancy rather than operational energy sales. Geographically, project siting aligns with favourable geology and regulatory support notably in Canada, Finland, the UK, Germany, the Netherlands, Australia, and California. Despite high capital costs and developmental risks, these projects promise long-term multi-billion-euro lifecycles, positioning CAES and PHES as key components in the global renewable energy transition.

### Cost and Saving

Long-duration and seasonal storage technologies play a crucial role in advancing global decarbonization by bridging the intermittency gap of renewable energy sources such as solar and wind. These technologies including pumped hydro energy storage (PHES), compressed air energy storage (CAES), thermal storage, and power-to-hydrogen or chemical storage systems are designed to store energy over extended periods, from several hours to days or even weeks. By enabling energy shifting and grid flexibility, they make it possible to achieve higher renewable penetration while maintaining grid reliability and cost efficiency (International Renewable Energy Agency [IRENA], 2023).

Among these technologies, pumped hydro energy storage (PHES) remains the most mature and widely deployed solution. According to IRENA (2023), new pumped hydro projects have an estimated capital cost of approximately US$148/kWh, making them one of the lowest-cost long-duration storage options globally. The high efficiency and long lifespan of PHES often exceeding 40 years further enhance its economic viability. For example, a utility relying on peaker plants costing around US$150/MWh (US$0.15/kWh) for 100,000 MWh of annual electricity generation spends approximately US$15 million per year. Replacing this setup with PHES that utilizes off-peak renewable power at an effective cost of US$57/MWh (US$0.057/kWh) would yield savings of about US$93 per MWh, or nearly US$9.3 million annually. This translates into a fuel and operational cost reduction of roughly 60%, while simultaneously cutting emissions and improving system reliability (UNFCCC, 2023).

Similarly, compressed air energy storage (CAES) offers cost-effective and scalable storage potential, particularly where geological conditions allow for underground caverns or depleted gas fields. While installation costs for CAES systems are site-specific, studies have reported ranges around US$119/kWh, and in favourable conditions, costs can drop as low as US$50/kWh (SpringerLink, 2022). When used for peak shaving or renewable integration, CAES can generate savings comparable to pumped hydro by displacing expensive fossil-fuel-based generation. For instance, replacing 100,000 MWh of peak gas generation at US$0.15/kWh with CAES-driven renewable power at US$0.06/kWh yields potential annual savings of US$9 million, demonstrating a clear financial incentive for utilities and industrial users to adopt the technology.

Beyond direct cost reductions, thermal energy storage and power-to-hydrogen (PtH) systems contribute significantly to long-term economic and energy security goals. Thermal storage systems often using molten salts or phase-change materials can store heat for later electricity generation or industrial use, offsetting expensive natural gas or diesel costs. Meanwhile, power-to-hydrogen systems convert surplus renewable electricity into hydrogen, which can later be used for electricity generation, heating, or industrial feedstock, effectively acting as seasonal energy storage. Though initial capital investments are high, the decoupling of renewable generation from real-time consumption leads to grid-wide savings and reduced curtailment costs, while unlocking new industrial revenue streams.

In practical grid terms, integrating large-scale renewables with long-duration storage can reduce fuel and operational expenditures by 50–60%, minimize renewable energy wastage, and enhance overall resilience. These savings are not limited to direct cost avoidance but extend to improved grid reliability, lower maintenance expenses, and increased national energy independence. For developing economies like those in Africa, such technologies present a pathway not only to decarbonize but to stabilize energy prices and accelerate economic competitiveness through sustainable, cost-efficient energy systems.

When energy adopters integrate both short-duration and long-duration storage technologies within a modernized grid, the potential for cost savings and new revenue streams becomes transformative. These savings arise from several interlinked mechanisms that fundamentally reshape how power is produced, distributed, and consumed. Avoided fuel and import costs form one of the most direct benefits. In many African countries, reliance on costly diesel and heavy-fuel oil for backup or peak generation remains common, with costs often exceeding US$200 per MWh (IEA, 2022). By deploying energy storage systems such as lithium-ion or pumped hydro, utilities and industrial consumers can shift demand toward cheaper off-peak or renewable power sources. For example, a utility replacing a peaker plant costing US$150/MWh with pumped hydro storage operating at an effective cost of US$57/MWh could save around US$9.3 million annually for 100,000 MWh of shifted energy (IRENA, 2023).

Avoided outage and curtailment costs also generate substantial economic advantages. Across sub-Saharan Africa, power interruptions lead to losses estimated at 1–5% of GDP annually due to production downtime and equipment damage (World Bank, 2023). Industrial facilities that install short-duration batteries or hybrid systems can reduce these losses by maintaining power continuity and stabilizing voltage during grid disturbances. Increased self-consumption and renewable utilization offer another stream of value. Energy storage allows excess renewable generation especially solar to be stored and used during peak hours, rather than curtailed or sold at low export tariffs. Studies show that self-consumption rates can improve by up to 40% when paired with efficient storage (IEA, 2023).

Grid services and revenue diversification further enhance returns. Storage assets can participate in ancillary markets, providing services such as frequency regulation, reactive power support, and demand charge reduction. These applications can yield additional revenues of US$10–30/MWh depending on the regulatory framework (BloombergNEF, 2024). Finally, longer asset lifetime and reduced replacement costs play a crucial role. Long-duration technologies like PHES or CAES typically operate for 40–60 years with minimal degradation, unlike conventional fossil plants requiring frequent maintenance (UNFCCC, 2023). Over time, these factors combine to reduce total cost of ownership and increase system resilience.

In sum, the transition to renewable electricity generation technologies has profound implications for carbon emissions, investment flows, and global energy systems. As of 2024, renewables accounted for around 46.4% of global installed power capacity, with record additions of approximately 585 gigawatts (GW) of new capacity in that year alone. Cost-competitiveness has improved radically: new solar photovoltaic (PV) projects achieved levelised costs of about US$0.043 per kWh, making them roughly 41% cheaper than the lowest-cost fossil-fuel alternatives. Globally, investment in renewable power generation topped US$728 billion in 2024, with many hundreds of billions more flowing into grid infrastructure, storage and modernisation. Likewise, alternative technologies for storage, flexibility and grid modernisation are key enablers of decarbonisation. Short-duration storage (lithium-ion, flow batteries, supercapacitors) tackles hourly smoothing, peak shaving and reliability; long-duration storage (PHES, CAES, thermal, power-to-hydrogen) unlocks multi-hour, multi-day and seasonal shifting of energy, enabling very high shares of renewables. The economics are compelling: savings of millions of dollars per year are entirely plausible for utilities and large industrial users when shifting from diesel or fuel-peaked generation to storage-enabled systems. As storage costs decline, and as grid-modernisation advances, these technologies will be among the most important platforms in the global and African energy transition.

From a carbon-savings perspective, the substitution of fossil-fuel generation with renewables reduces $CO_2$ emissions by the gigatonne scale, although precise global figures are challenging to isolate. The reduction in fuel burn, combined with declining carbon intensity, means each new megawatt of renewable capacity displaces fossil generation and associated emissions over its lifetime. While some embodied emissions exist in manufacturing and installation, the lifecycle $CO_2$ footprint of solar and wind is a fraction of coal or gas. Regionally, Asia-Pacific dominates both capacity and investment, reflecting abundant resources, large markets and aggressive policy frameworks. Europe and the Americas follow, with Middle East, Africa and

Oceania yet contributing a smaller share, pointing to an urgency of scaling investments in emerging regions.

Turning to Nigeria, renewable electricity generation particularly solar has begun to gain traction. While still modest in absolute terms compared to global leaders, Nigeria's corporate and industrial sectors are increasingly turning to solar and hybrid power as cost-reduction strategies, displacing diesel generator use and significantly lowering operational emissions. The deployment of renewable systems in factories, commercial properties and institutions is translating into real savings and carbon reduction, albeit without comprehensive national figures publicly available.

Bringing all these strands together, the global investment in renewables not only signals a technology shift but realises systemic savings financial and environmental. The combination of low operational costs, sharply reducing capital and levelised cost metrics, and avoided fuel and carbon expenses means adopters worldwide are already seeing tens of billions of dollars in annual savings. In Nigeria and similar markets, switching from diesel- or fuel-dependent systems to solar and renewables can yield annual savings in the hundreds of thousands to millions of dollars per facility, while contributing to global emissions reduction. In sum, the expansion of renewable electricity generation technologies is a central pillar of the decarbonisation agenda delivering lower cost power, reduced carbon emissions, and attractive investment economics across regions and sectors.

Renewable energy generation and advanced storage systems have become the backbone of the global decarbonisation effort, proving that clean power is not only achievable but economically superior. As nations deploy solar, wind, and battery technologies at unprecedented speed, the world is witnessing a historic shift one where reliability, resilience, and affordability increasingly emerge from low-carbon innovation rather than fossil dependence. The integration of energy storage and modern grids has erased long-standing doubts about renewable variability, demonstrating that smarter systems can balance demand, stabilise networks, and deliver substantial cost savings for households, industries, and entire communities. With the power sector rapidly transforming, the next frontier becomes clear: electrifying the way we move. The following section on Electrifying Transport & Low-Carbon Mobility explores how clean electricity is extending its influence beyond the grid into vehicles, cities, and national transport systems driving down emissions, reducing fuel costs, and reshaping mobility for a sustainable future.

# Section 3

# Electrifying Transport & Low-Carbon Mobility

## Electrifying transport & low-carbon mobility

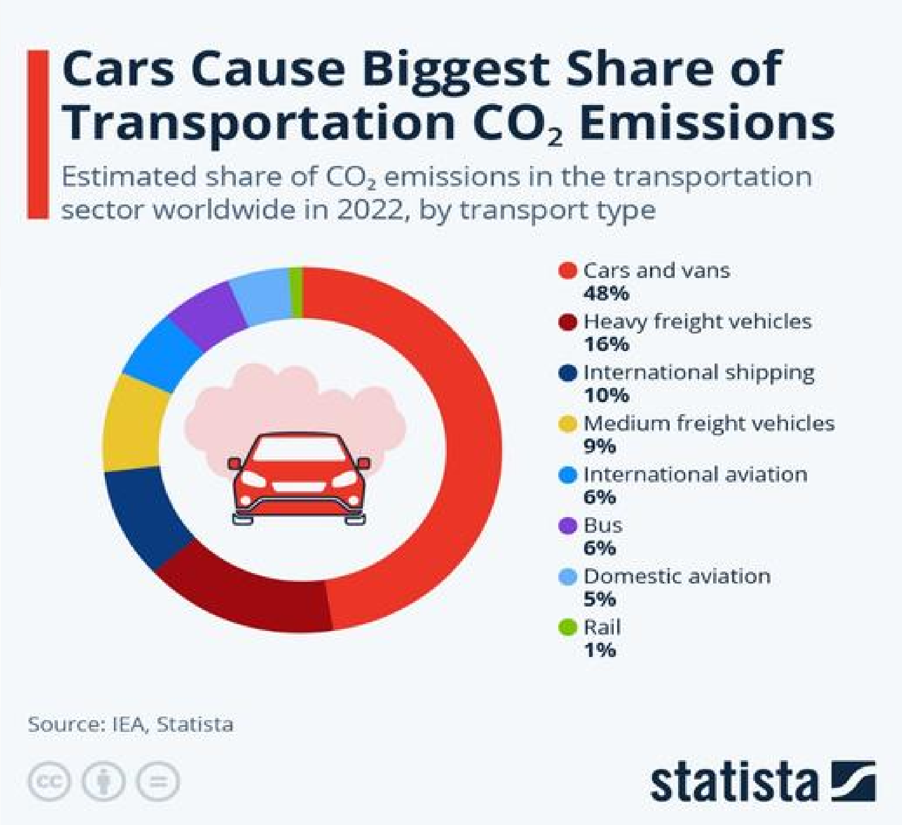
The transport sector is a significant contributor to global greenhouse gas (GHG) emissions, accounting for approximately 24% of direct $CO_2$ emissions from fuel combustion (International Energy Agency [IEA], 2023). Decarbonizing transport is therefore essential for achieving net-zero targets. Electrification of transport, including battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell vehicles (FCEVs), is emerging as a cornerstone of low-carbon mobility. These technologies offer substantial reductions in tailpipe emissions and, when powered by renewable electricity, can dramatically cut lifecycle emissions relative to conventional internal combustion engine vehicles (Hawkins et al., 2013; IEA, 2023).

Electric mobility adoption is supported by advances in battery technology, charging infrastructure, and supportive policies such as subsidies, tax incentives, and emission standards. Battery energy density improvements, cost reductions, and fast-charging developments have made BEVs increasingly viable for passenger and freight transport in developed and developing economies alike (IEA, 2023). Hydrogen fuel cells, although less mature, offer potential for heavy-duty, long-range, and maritime transport, particularly were battery energy density limits practicality.

Beyond vehicle electrification, system-level strategies such as modal shifts to public transit, active transport (walking, cycling), and shared mobility complement technological solutions. Integration with smart grids and renewable electricity enhances environmental benefits, enabling vehicle-to-grid (V2G) services and flexible charging that supports grid stability (Sims et al., 2022). Challenges remain, particularly in developing economies, including high upfront vehicle costs, limited charging infrastructure, grid capacity constraints, and supply-chain dependence on critical minerals such as lithium, cobalt, and nickel (Gaines et al., 2021). Policy, investment, and technological innovation must therefore be aligned to accelerate the global transition toward low-carbon mobility while ensuring equitable access and minimizing social and environmental risks. Electrifying transport is thus a multidimensional challenge requiring coordination across technology, infrastructure, policy, and behavioural change, forming a critical component of sustainable energy transitions worldwide.

### Transport Share of Emissions and Decarbonisation Levers

The transport sector is one of the largest and fastest-growing contributors to global greenhouse gas (GHG) emissions. According to the International Energy Agency (IEA, 2023), transport accounts for roughly 24% of direct $CO_2$ emissions from fuel combustion worldwide, placing it among the most difficult sectors to decarbonize due to its reliance on fossil fuels, high energy intensity, and complex infrastructure. The challenge is compounded by the diversity of transport modes, including road, rail, maritime, and aviation, each with distinct fuel demands, technological pathways, and operational characteristics. The sector's emissions profile is strongly linked to socio-economic factors such as income levels, urbanization rates, and motorization trends, as well as geographic and infrastructural factors that determine the modal composition and efficiency of transportation systems.




Regionally, the contribution of transport to overall emissions varies significantly. In high-income OECD countries, transport can represent more than 30% of energy-related $CO_2$ emissions, driven largely by passenger vehicles, freight transport, and aviation (Sims et al., 2022). Passenger vehicles dominate urban and suburban mobility, contributing heavily to total road transport emissions due to high vehicle kilometres travelled (VKT), the prevalence of internal combustion engines (ICEs), and continued reliance on petroleum-based fuels (Hawkins et al., 2013). Freight transportation, particularly road freight, further increases the sector's carbon footprint, given its dependence on diesel engines and long-haul logistics, often over extensive national and continental networks. In addition, aviation and shipping, while contributing less in absolute terms relative to road transport, are particularly difficult to decarbonize due to limited alternatives to high-density liquid fuels, long operational lifetimes of vehicles and vessels, and the need for high energy density fuels for long-distance travel (IEA, 2023).

In developing economies, the situation presents both challenges and opportunities. Road transport and urban mobility are growing rapidly as vehicle ownership rises with economic development and urbanization. Emerging economies in Asia, Africa, and Latin America are experiencing accelerated motorization, leading to higher energy demand and emissions. For example, cities in Southeast Asia have seen substantial increases in private vehicle ownership over the past decade, placing pressure on urban infrastructure and contributing to congestion, air pollution, and GHG emissions (Creutzig et al., 2015). Similarly, in Sub-Saharan Africa, although vehicle ownership is still comparatively low, population growth, urbanization, and improvements in road networks are increasing the demand for mobility, signalling a potential rapid rise in transport-related emissions unless low-carbon pathways are adopted early (IEA, 2023).

Passenger vehicles are the primary source of transport-related $CO_2$ emissions globally. The high contribution of passenger cars is a consequence of several factors. First, passenger mobility is extensive, with individuals relying heavily on private vehicles in regions where public transport is limited, inefficient, or socially less desirable. Vehicle kilometres travelled (VKT) are high in both urban and intercity travel contexts, compounding fuel consumption. Second, the technology mix remains heavily dominated by conventional ICEs powered by gasoline or diesel, which have relatively high carbon intensity per kilometre compared to electric or hybrid alternatives (Hawkins et al., 2013). Third, vehicle size and performance expectations in high-income economies, such as larger SUVs and higher-powered vehicles, amplify energy consumption and emissions. In contrast, in developing economies, smaller vehicles or motorcycles dominate, but rapid increases in ownership rates could lead to significant emissions growth unless cleaner vehicle technologies are deployed (Sims et al., 2022).

Freight transport also plays a crucial role in the emissions profile of the transport sector. Globally, road freight contributes substantially to transport $CO_2$ due to heavy reliance on diesel fuel and long-distance hauling. In developed economies, freight logistics benefit from relatively efficient vehicles, optimized routing, and regulatory frameworks such as emissions standards. Yet, despite these efficiencies, road freight remains a key contributor due to the sheer scale of goods movement (Creutzig et al., 2015). In developing economies, freight emissions are exacerbated by less efficient vehicles, older fleets, poor road conditions, and a lack of optimized logistics, often leading to higher fuel consumption per ton-kilometre (IEA, 2023). Interventions targeting freight decarbonization, such as shifting to rail or electrified logistics for urban deliveries, can substantially reduce emissions but require significant infrastructure investment and policy support.

Aviation and maritime transport add complexity to the sector's decarbonization challenge. Aviation is energy-intensive, relying on jet fuels that are currently difficult to replace at scale. Long-haul flights have high per-passenger emissions, and projected growth in global air travel could substantially increase sectoral emissions if mitigation strategies are not implemented (IEA, 2023). Similarly, international shipping depends on heavy fuel oil and has limited low-carbon alternatives currently available, such as ammonia, hydrogen, or biofuels, which require technological maturation and global regulatory frameworks. While aviation and shipping contribute less than road transport to total $CO_2$ emissions, their high carbon intensity and long asset lifetimes make them critical targets for decarbonization strategies.

The transport sector's high emissions are closely tied to urban design and mobility patterns. Cities designed around private vehicle use often have low-density urban sprawl, limited public transit, and car-centric infrastructure, leading to high energy intensity per passenger-kilometre. In contrast, compact urban forms with integrated public transport networks, cycling infrastructure, and pedestrian-friendly design can substantially reduce emissions by enabling modal shifts away from private ICE vehicles (Creutzig et al., 2015). Developing economies have an opportunity to embed low-carbon urban mobility solutions as they expand, whereas developed economies must overcome entrenched urban forms and vehicle ownership habits to achieve substantial reductions in emissions.

Addressing transport emissions requires multifaceted decarbonization strategies. Electrification of passenger vehicles through battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and conventional hybrids provides a pathway to reduce tailpipe emissions, particularly when coupled with low-carbon electricity generation (Hawkins et al., 2013). In developed economies, supportive policies such as incentives, emission standards, low-emission zones, and widespread charging infrastructure accelerate the adoption of electric mobility. In developing economies, the deployment of electric mobility faces barriers including higher upfront costs, limited electricity grid capacity, and nascent policy frameworks, yet early electrification can prevent carbon lock-in and enable rapid reductions as vehicle ownership grows (IEA, 2023).

Finally, the transport sector's decarbonization is inseparable from improvements in fuel efficiency, alternative fuels, and behavioural interventions. Increasing the energy efficiency of vehicles through better engine design, aerodynamics, and lightweight materials reduces fuel consumption per kilometre travelled. The integration of sustainable biofuels, synthetic e-fuels, and hydrogen can provide carbon-neutral options for hard-to-electrify sectors like aviation and heavy-duty transport (Creutzig et al., 2015). Additionally, modal shifts, urban planning, and shared mobility options can further reduce emissions, highlighting the importance of integrated strategies combining technology, policy, and behavioural change.

In all, the transport sector's significant contribution to global GHG emissions particularly through passenger vehicles, freight, and aviation underscores its central role in climate mitigation efforts. Developed economies face challenges in optimizing existing systems and reducing emissions from high vehicle usage, whereas developing economies must manage rapidly growing mobility demands while avoiding carbon-intensive pathways. Road transport dominates emissions in both contexts, highlighting the need for electrification, modal shifts, improved vehicle efficiency, and sustainable fuels. Urban planning, supportive policy frameworks, and infrastructure development are critical enablers for achieving meaningful reductions in transport-related $CO_2$ emissions globally.

### Complementary Levers

Decarbonisation of transport relies on multiple complementary levers, which can be broadly categorized into modal shifts, vehicle technology improvements, and low-carbon fuels.

### Modal Shift

Modal shift represents a critical lever for reducing transport-related emissions by altering how people and goods move, thereby lowering the energy intensity per kilometre travelled. For passenger mobility, shifting from private vehicle use to public transportation, cycling, walking, or shared mobility services can significantly reduce $CO_2$ emissions. Public transit systems including buses, trams, and metros carry many passengers simultaneously, which spreads energy use over more individuals and reduces per-capita fuel consumption compared to single-occupancy vehicles (Creutzig et al., 2015). Active mobility modes such as cycling and walking produce negligible emissions and also deliver co-benefits for public health and urban liveability. Emerging shared mobility solutions, including ride-hailing services with pooled trips and mobility-as-a-service (MaaS) platforms, provide further opportunities to reduce reliance on private vehicles and optimize vehicle occupancy, particularly in urban areas where congestion and parking constraints are significant (IEA, 2023).

For freight transport, modal shift is equally important. Road haulage, particularly long-distance trucking, is highly carbon-intensive per ton-kilometre, primarily due to diesel fuel consumption and lower efficiency at partial loads. Shifting freight movement to rail or inland waterways can dramatically reduce emissions intensity. Rail freight benefits from higher energy efficiency and, when electrified, can leverage low-carbon electricity, offering significant reductions in lifecycle emissions compared to conventional trucks (Creutzig et al., 2015). Inland water transport, where feasible, provides another low-emission alternative for bulk goods, though navigable waterways and infrastructure quality can limit applicability. Implementing modal shift for freight often requires coordinated logistics planning, investment in multimodal terminals, and regulatory support, including incentives for rail use or penalties for high-emission road freight (IEA, 2023).

The feasibility and impact of modal shift differ between developed and developing economies. In developed countries, dense urban forms, established public transit networks, and well-maintained rail infrastructure enable meaningful reductions in private vehicle use. Cities such as Copenhagen, Amsterdam, and Tokyo exemplify successful integration of cycling, public transit, and walking as core urban mobility modes, achieving substantial reductions in per-capita transport emissions (Creutzig et al., 2015). Conversely, developing economies often face challenges such as underdeveloped transit networks, limited rail and waterway infrastructure, dispersed urban settlements, and rapid urbanization, which constrain modal shift opportunities. In these contexts, urban planning that prioritizes compact, mixed-use development, along with investments in mass transit and non-motorized transport infrastructure, is essential to facilitate modal shift and prevent high-carbon mobility lock-in as vehicle ownership grows (IEA, 2023). Ultimately, modal shift is not only a technical strategy but also a systemic one, requiring integration of urban design, infrastructure investment, policy incentives, and behavioural change. Effective implementation can deliver both climate mitigation benefits and improved accessibility, equity, and quality of urban life across regions.

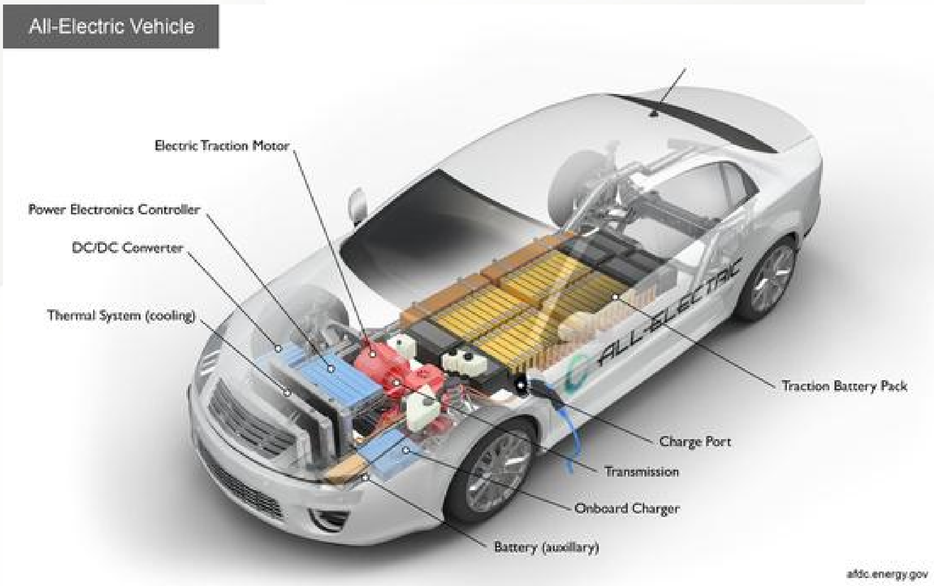
### Vehicle Technology

Vehicle technology is a central lever in the decarbonisation of the transport sector, with electrification emerging as the most transformative pathway for passenger vehicles. Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and conventional hybrids represent the spectrum of technologies offering varying degrees of emission reduction, operational efficiency, and market readiness.

### Battery Electric Vehicles (BEVs)

A Battery Electric Vehicle (BEV) replaces the internal-combustion engine (ICE) with an electric powertrain that consists principally of an electric traction motor (or motors), an inverter and power electronics to control the motor, a high-voltage rechargeable battery pack with a Battery Management System (BMS), and on-board charging hardware and thermal management systems. Unlike plug-in hybrids, BEVs have no ICE and rely entirely on stored electrical energy for motive power (Macharia et al., 2023). BEVs operate entirely on electricity, eliminating tailpipe emissions and offering the potential for near-complete lifecycle decarbonisation when coupled with low-carbon electricity grids. According to Hawkins et al. (2013), BEVs can reduce lifecycle greenhouse gas emissions by 40–80% compared to conventional internal combustion engine (ICE) vehicles, depending on the carbon intensity of electricity generation.

Most modern BEVs use lithium-ion (Li-ion) cells configured into modules and packs. Advances in cell chemistry (NMC, NCA, LFP) and cell formats (pouch, prismatic, cylindrical) have improved energy density, cycle life, safety and cost. LFP (lithium-iron-phosphate) cells have grown in popularity for lower-cost, high-cycle applications; high-nickel NMC/NCA chemistries remain common where range density is prioritized. The BMS monitors cell voltages, temperatures and state-of-charge to protect and balance the pack. Recent research focuses on higher energy-density materials, solid-state designs and improved fast-charging tolerance.




BEV adoption has accelerated in developed economies due to supportive policies, infrastructure investment, and consumer incentives. Norway, for instance, has achieved remarkable penetration of BEVs, with more than 80% of new passenger car sales in 2023 being fully electric, driven by tax exemptions, free parking, and extensive public charging infrastructure (IEA, 2023). Similarly, California has leveraged zero-emission vehicle mandates, rebate programs, and a dense network of fast-charging stations to stimulate BEV uptake, demonstrating how policy frameworks and infrastructure deployment synergistically accelerate emissions reductions (Waseem et al., 2025).

BEV architectures vary (rear-, front-, or all-wheel drive; single or multiple motors), but the common theme is simplified mechanical complexity compared with ICEs: fewer moving parts, instantaneous torque from motors, and regenerative braking that recovers energy. Inverters convert DC battery power to AC for motors; onboard chargers convert AC grid power to DC for battery charging. Charging systems are evolving rapidly from slow AC (Level 1/2) to high-power DC fast chargers (50 kW–350+ kW) and emerging bidirectional charging (V2G/V2L) capabilities.

### Global adoption trends and policy drivers

Electric car sales surged in the early 2020s and continued rapid growth into 2023–2024. According to the International Energy Agency's *Global EV Outlook 2024*, global electric-car sales reached record levels in 2023 (nearly 14 million) and EVs accounted for a substantially growing share of new-car markets; China, Europe and the United States together represent the bulk of sales and policy support. Projections in 2024–2025 anticipated continued expansion, with EV market shares rising in China (the largest market), Europe, and the U.S. driven by tighter emissions rules, purchase incentives, and falling battery costs (IEA, 2024).

Key adoption drivers:

- **Policy and regulation:** purchase incentives, tax credits, fuel economy/emissions standards, and phase-out timelines for ICE sales in some jurisdictions.
- **Total cost of ownership (TCO):** rapidly falling battery pack costs and lower operating/maintenance costs are making BEVs economically competitive for many buyers.
- **Model availability:** OEMs now offer multiple BEV platforms and price segments (from affordable compact BEVs to premium SUVs).
- **Charging infrastructure rollout:** public and private investment in urban fast charging and depot charging for fleets (IEA, 2024).

Despite these gains, global adoption is uneven: outside the three major markets (China, Europe, U.S.), EV share of new car sales remained modest around single digits in many regions indicating the work still needed to reach mass adoption

### Who is pushing BEVs?

A range of established automakers and new market entrants are driving the global transition toward battery electric vehicles (BEVs), each contributing distinctive technological and strategic strengths to the industry. Tesla remains one of the most influential players in this regard as the company has produced over 1.77 million cars as of the end of 2024, having popularized the concept of long-range BEVs through a vertically integrated business model that combines battery technology, software systems, and proprietary charging infrastructure.

### Tesla

Tesla's innovations in gigafactory-scale production, over-the-air software updates, and the global expansion of its Supercharger network have set performance and convenience benchmarks for the industry, allowing the company to maintain its leadership in BEV deliveries and consumer recognition (Autovista24, 2024). Tesla, Inc. stands at the forefront of the global transition toward sustainable energy and advanced electrification technologies. Founded in 2003 and headquartered in Austin, Texas, the company's mission is to accelerate the world's shift to sustainable energy through innovation in electric mobility, energy storage, and renewable generation. Over the years, Tesla has evolved from an electric vehicle (EV) startup into a diversified energy and technology enterprise, combining automotive manufacturing, battery technology, artificial intelligence, and robotics into a vertically integrated ecosystem.

In 2024, Tesla reported an annual revenue of $97.69 billion, marking a modest 0.95% increase from $96.77 billion in 2023. Despite a slight decline in vehicle sales from 1,808,581 units in 2023 to 1,789,226 units in 2024, the company maintained its leadership in the EV market through efficiency improvements and diversification of its revenue streams. Tesla's investor base remains broad, comprising more than 4,000 institutional investors who collectively own about 48.1% of its shares, alongside millions of retail shareholders underscoring its widespread global appeal and investor confidence.

Tesla's product portfolio spans three major domains: electric vehicles, energy systems, and artificial intelligence/robotics. Its electric vehicle lineup includes the Model S and Model X luxury series, the mass-market Model 3 and Model Y, and the recently introduced Cybertruck and Semi-truck designed to revolutionize both consumer and commercial transport. The company's energy products further extend its sustainability mission, featuring the Powerwall (home battery system), Megapack (grid-scale energy storage), Solar Roof, and traditional solar panels enabling decentralized, renewable electricity generation and storage for homes, businesses, and utilities.


Beyond electrification, Tesla has invested heavily in artificial intelligence (AI) and robotics, reflecting its vision of integrating automation into everyday life. Its Optimus humanoid robot is under development to perform complex human-like tasks, while its Full Self-Driving (FSD) software and forthcoming Robotaxi service aim to redefine autonomous transportation. These ventures position Tesla not only as a carmaker but also as a technological pioneer in AI-driven mobility and industrial automation.

Tesla's activities encompass the design and manufacturing of vehicles and energy systems, the operation of a global Supercharger network for EV charging, and direct sales, servicing, and financing of its products. The company's vertically integrated model allows tight control over innovation, cost, and customer experience. Simultaneously, its research and development divisions focus on improving battery efficiency, AI algorithms, and sustainable production methods cementing Tesla's reputation as a transformative force in global decarbonisation and the future of electrified industry.

**BYD**

In parallel, BYD of China has emerged as a formidable force, leveraging its mastery of both battery and vehicle production to deliver affordable and efficient BEVs. BYD had produced its 8 millionth new energy vehicle (NEV) by July 4, 2024, and its cumulative pure electric vehicle sales reached 1.6059 million units by Q3 2025, with total new energy vehicle sales exceeding 3.02 million in 2023 (BYD, 2025). The company's control over its local supply chain, vast domestic market, and diversification into global exports have enabled BYD to challenge Western incumbents and even surpass Tesla in total unit sales in some markets (EV Magazine, 2024).

BYD Company Ltd., known by its acronym Build Your Dreams, is a global high-technology enterprise and a leading force in the clean energy and electric mobility revolution. Founded in 1995 and headquartered in Shenzhen, China, BYD operates across a diverse range of sectors including automobiles, rail transit, renewable energy, and electronics all unified under its mission to provide zero-emission, sustainable energy solutions for a cleaner future.


In 2024, BYD achieved record-breaking performance, cementing its position as the world's largest manufacturer of new energy vehicles (NEVs). The company reported annual revenue of RMB 777.1 billion (approximately USD 107.1 billion), marking a 29% year-over-year increase from RMB 602.32 billion (USD 85 billion) in 2023. Its total vehicle sales reached 4,272,145 NEVs, representing a remarkable 41.26% growth compared to the previous year's 3,024,417 units. These sales comprised 1,764,992 battery electric vehicles (BEVs) and 2,485,378 plug-in hybrid electric vehicles (PHEVs), showcasing BYD's balanced strength across both pure and hybrid electrification technologies.

BYD's automotive division anchors its global reputation. The company produces a wide spectrum of vehicles under several distinct brands and series, including the Dynasty Series, Ocean Series, Denza, Fangchengbao, and Yangwang. Popular models such as the Han, Tang, Seal, Dolphin, Atto 3 (Yuan Plus), Seagull, Qin, and Song cater to multiple market segments from compact sedans to premium SUVs. This diverse lineup reflects BYD's commitment to making electric mobility accessible to a broad consumer base, both domestically and internationally.

Beyond vehicles, BYD is also a pioneer in battery technology. It is one of the world's largest manufacturers of rechargeable batteries, including its groundbreaking Blade Battery, which uses Lithium Iron Phosphate (LFP) chemistry for superior safety, longevity, and energy density. The Blade Battery has become a benchmark innovation in EV safety, influencing global standards for thermal management and crash resistance.

Complementing its automotive and battery operations, BYD provides integrated energy solutions, including solar panels, grid-scale energy storage systems, and off-grid renewable installations further advancing global decarbonization efforts. The company also manufactures mobile handset components and electronics, maintaining strategic partnerships with leading technology firms, and develops commercial electric vehicles such as buses, trucks, vans, and forklifts key contributors to emission reduction in logistics and public transport.

In addition, BYD has expanded into rail transit systems, notably with its SkyRail monorail and SkyShuttle tram projects, which integrate battery-electric propulsion for urban mass transport efficiency.

Publicly listed on both the Hong Kong (1211.HK) and Shenzhen (002594.SZ) stock exchanges, BYD boasts a market capitalization of approximately ¥800 billion (USD 119 billion). Its investor base comprises a wide mix of institutional and retail shareholders. A notable HK$43.5 billion share placement in March 2024 strengthened its equity structure and investor confidence, highlighting sustained market trust in BYD's innovation-driven growth.

**Other Players**

Meanwhile, traditional automotive giants are rapidly transforming their portfolios to remain competitive in a low-carbon mobility era. Firms such as Volkswagen Group, Hyundai–Kia, BMW, Stellantis, and General Motors are investing billions of dollars in dedicated BEV platforms, battery partnerships, and digital ecosystems. Volkswagen's modular electric drive matrix (MEB) platform, GM's Ultium battery architecture, and Hyundai's E-GMP platform illustrate how legacy manufacturers are positioning for scalable BEV production while targeting ambitious emission-reduction goals by the 2030s (Autovista24, 2024).

Beyond vehicle manufacturing, battery cell producers and component suppliers are the backbone of BEV cost efficiency and technological advancement. Contemporary Amperex Technology Co. Limited (CATL) currently dominates the global battery market, holding the largest market share and supplying multiple automakers worldwide. CATL's production scale, innovation in lithium iron phosphate (LFP) and high-nickel chemistries, and strategic partnerships have significantly driven down battery costs and improved performance. BYD, LG Energy Solution, and Panasonic follow closely, each contributing to supply-chain resilience and technological diversity in the sector (CnEVPost, 2025). The close collaboration between automakers and battery manufacturers determines not only vehicle range and affordability but also influences the pace of global BEV adoption, as long-term supply agreements and joint ventures increasingly define competitive advantage in the electric mobility landscape (EV Magazine, 2024).

### BEV penetration in Africa

Africa's adoption of battery electric vehicles (BEVs) remains comparatively low when measured against global benchmarks, yet the continent is witnessing a gradual but meaningful emergence of electric mobility across certain markets and transport segments. Although overall sales of BEVs outside major global hubs such as China, Europe, and the United States remained modest through 2023–2024, with electric vehicles accounting for only a small single-digit share of new vehicle sales in most African countries, localized progress is becoming evident (International Energy Agency [IEA], 2024). South Africa currently leads the continent's electric mobility landscape, owing to its well-established automotive manufacturing base, relatively advanced infrastructure, and policy experimentation. The South African government and industry stakeholders have begun to explore targeted incentives and policy frameworks to stimulate demand and investment in BEVs. The *GreenCape Electric Vehicles Market Intelligence Report (2024)* highlights steady growth in new-energy vehicle sales, including hybrids, alongside emerging opportunities in micro-mobility and last-mile electrification. However, despite these advances, South Africa's passenger BEV fleet remains small compared to its internal combustion engine (ICE) vehicle population (GreenCape, 2024).

In East Africa, particularly in Kenya, Rwanda, and Uganda, BEV adoption has taken a more grassroots trajectory, focusing on electric two- and three-wheelers that cater to urban mobility, delivery services, and public transport. These smaller electric vehicles are proving competitive on operating cost and maintenance compared with their petrol counterparts, especially in densely populated urban corridors. Several pilot projects, including solar-powered charging stations and public–private partnerships, have been launched to foster adoption and improve infrastructure reliability (Student Energy, 2024). Meanwhile, North Africa, led by Morocco, is integrating EV manufacturing into broader industrialization strategies. Morocco's well-developed automotive sector and export linkages to European markets have made it a strategic hub for electric vehicle assembly and component production, aligning national policy with global decarbonization objectives (Student Energy, 2024).

Overall, research on EV adoption in Africa indicates that current progress is concentrated in micro-mobility, fleet electrification (such as taxis and delivery vehicles), and pilot demonstration projects, rather than widespread private-passenger transitions. This underscores the need for continued infrastructure investment, policy coherence, and public awareness to expand BEV adoption across the continent (IEA, 2024; Student Energy, 2024).

### Barriers Specific to Africa and Nigeria

Despite the growing interest in electric mobility, several structural and systemic barriers continue to impede the widespread adoption of battery electric vehicles (BEVs) across Africa, including Nigeria. One of the most prominent challenges is the high upfront cost and limited model availability of BEVs in African markets. Although global battery prices have declined significantly over the past decade, enabling greater affordability elsewhere, the retail cost of new BEVs remains prohibitive for most African consumers due to currency volatility, import duties, and the absence of large-scale local manufacturing. Affordable BEV models suitable for mass-market consumers are still scarce, and while the importation of used BEVs offers a potential entry point, such vehicles often arrive with diminished battery health and uncertain performance, posing long-term sustainability and safety concerns (Nipes Journal, 2024).

A second major obstacle relates to charging infrastructure scarcity and unreliable electricity supply. Across many African cities, public direct current (DC) fast chargers are extremely limited, and existing urban grids often lack the capacity to support widespread BEV charging. Frequent power outages, weak rural electrification, and insufficient distribution infrastructure further exacerbate the challenge. Although pilot projects involving solar-powered or hybrid charging stations have been launched in countries like Kenya, South Africa, and Nigeria, their deployment remains localized and far from the scale required to support national-level BEV adoption (Nipes Journal, 2024).

Equally significant are the policy and fiscal barriers that shape investment behavior and consumer uptake. Many African governments still impose high import tariffs on electric vehicles and related components, while offering limited fiscal incentives or rebates for EV purchases. The absence of clear policy frameworks, fragmented regulatory structures, and inconsistent implementation discourage large-scale private sector participation. In Nigeria, however, modest progress has been made through recent policy announcements that include import duty waivers on EVs and incentives to encourage local assembly. Yet, these measures remain in the early stages of implementation, and their effectiveness will depend on sustained enforcement and institutional coherence (EV24, 2024).

Lastly, after-sales support, skilled workforce development, and standardization present additional bottlenecks. The ecosystem for battery recycling, refurbishment, and second-life use is largely underdeveloped across Africa, and the lack of certified technicians and repair facilities limits consumer confidence in maintaining BEVs. Moreover, regulatory standards for charging systems, electrical safety, and interoperability are still evolving, creating uncertainty for both investors and consumers (International Energy Agency [IEA], 2024). Collectively, these constraints illustrate the complex interplay of economic, infrastructural, and institutional factors that Africa and Nigeria in particular must address to enable a sustainable transition to electric mobility.

Nigeria, has begun to demonstrate early policy signals that indicate a growing recognition of the role electric mobility can play in achieving energy diversification and carbon reduction goals. Government agencies such as the National Automotive Design and Development Council (NADDC) have initiated pilot BEV charging infrastructure projects across select states and tertiary institutions, including the establishment of solar-powered charging stations at Nigerian universities to promote renewable-powered mobility solutions (Nipes Journal, 2024). In addition, policy discussions have advanced toward introducing fiscal incentives such as tax waivers on imported electric vehicles and components, along with measures to encourage local assembly of BEVs by existing automotive firms. While these initiatives mark positive progress toward policy alignment, they still require stronger regulatory coordination, investor confidence, and long-term infrastructure planning to transition from isolated pilot schemes to scalable national programs (Nipes Journal, 2024).

From a market dynamics perspective, Nigeria's current economic realities present both opportunities and barriers for BEV adoption. The nation's volatile petrol and diesel prices, driven by fluctuating global oil markets and local subsidy reforms, make the operating cost advantages of BEVs increasingly attractive, particularly for high-mileage commercial operators such as taxi fleets, ride-hailing services, and last-mile logistics firms. However, the high upfront capital costs of BEVs, coupled with limited financing options and restricted model availability, continue to limit adoption among private buyers. Furthermore, used-vehicle import policies which have long shaped Nigeria's automotive market will significantly influence how affordable BEVs enter the consumer segment. The effectiveness of these policy reforms, alongside the establishment of credit facilities, charging infrastructure expansion, and local assembly partnerships, will ultimately determine the pace of Nigeria's transition toward sustainable mobility (EV24, 2024).

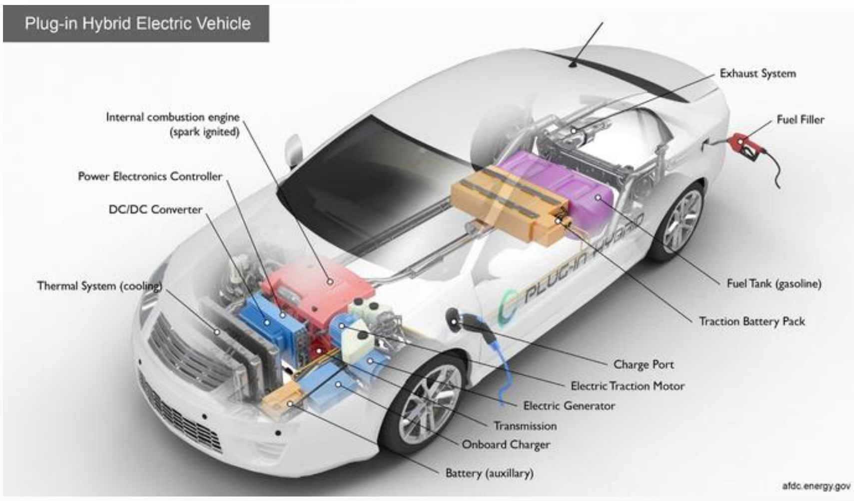
### Plug-in Hybrid Electric Vehicles (PHEVs)

A plug-in hybrid electric vehicle (PHEV) couples two propulsion systems: an internal combustion engine (or fuel-cell range extender in some designs) and one or more electric motors powered by an on-board rechargeable battery. This dual-mode functionality makes PHEVs particularly attractive in regions with limited or uneven charging infrastructure.

Unlike conventional (non-plug-in) hybrids, PHEVs can recharge their traction battery from the electricity grid via an external cord, allowing a significant all-electric driving range (typically 15–80+ km for mainstream models, though some larger PHEVs offer over 100 km depending on battery size and vehicle design). PHEVs operate in multiple modes: (a) charge-depleting (electric-first) mode, where the vehicle is driven primarily or wholly on battery energy until a lower threshold state-of-charge is reached; and (b) charge-sustaining (hybrid) mode, where the ICE and electric motor manage propulsion to keep battery state-of-charge within a target band. Manufacturers sometimes implement *blended* modes that combine both energy sources during a trip for performance or efficiency reasons. These operational strategies are governed by power electronics (inverters/converters), a battery management system (BMS) that supervises cell balancing and thermal management, and software that orchestrates when and how the ICE engages. PHEVs therefore deliver two advantages: the ability to drive shorter, daily trips emissions-free while retaining the long-range convenience of liquid fuels for long journeys or where recharging infrastructure is limited. (U.S. Department of Energy, 2025).

From a component perspective, PHEVs sit between HEVs and BEVs. Their battery packs are larger than standard hybrid systems (enabling useful electric range) but smaller than BEV packs (reducing cost and weight). Typical PHEV batteries use lithium-ion chemistries similar to BEV packs, and the drivetrain includes regenerative braking to recover kinetic energy. Charging hardware is usually AC on-board chargers with optional faster on-board or external DC charging in a few premium models. Thermal management, software calibration for blended mode, and durable ICE integration are engineering foci because PHEVs must achieve fuel-economy benefits without compromising reliability or emissions compliance. (IEA, 2024).

Germany provides a relevant case study: PHEV adoption has grown steadily as a transitional technology, supported by incentives such as purchase subsidies and reduced company car taxes, allowing users to experience electrified driving while avoiding “range anxiety” on long trips.




Lifecycle analyses show that PHEVs can reduce emissions by 30–50% compared to conventional ICE vehicles, assuming regular charging and high electric driving share (Hawkins et al., 2013). In contrast, developing economies often encounter constraints that affect the practical benefits of PHEVs. In India, the government's Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) program promotes PHEVs as a bridge technology; however, the limited availability of fast-charging stations and lower grid decarbonisation reduces overall emissions reduction potential. Users often rely on ICE operation, highlighting the importance of integrating charging infrastructure expansion with vehicle deployment to realise intended climate benefits (IEA, 2023).

### Global adoption trends and policy drivers

Global uptake of plug-in vehicles (both BEVs and PHEVs) accelerated through the 2010s and into the early 2020s. However, the composition of plug-in markets has shifted: BEVs have gained share steadily relative to PHEVs as battery energy density rose and charging infrastructure expanded. The International Energy Agency (IEA) *Global EV Outlook 2024* reports record electric car sales in 2023 (nearly 14 million) and continued growth into 2024, with BEVs constituting an increasing majority of plug-in sales in many major markets. Nonetheless, PHEVs still play a significant role where customers demand flexibility, where charging infrastructure is limited, or where policy incentives favour low-emission miles rather than zero-emission vehicles exclusively (IEA, 2024).

Regional patterns vary. China has become the dominant market for plug-ins overall and has driven substantial PHEV volumes through local manufacturers offering dual-mode product ranges (e.g., BYD's DM/DM-i models), while Europe and North America have trended toward BEV-heavy portfolios as policy and consumer incentives shifted. In some countries, PHEVs temporarily benefited from regulatory frameworks that granted emissions credits or tax advantages to vehicles that demonstrated a measured electric range; once rules tightened (or consumer preference shifted), PHEV shares changed. Overall, market monitors (ICCT, industry trackers) show that the ratio of BEVs to PHEVs has moved in favour of BEVs over the last decade, but PHEVs remain an important segment for certain buyers and fleets. ICCT+1

Key policy drivers that have shaped PHEV adoption include purchase incentives (tax credits, rebates tied to electric range), fleet procurement rules that count zero-emission miles, emissions-based taxation, and regulatory credit systems that allow automakers flexibility in meeting fleet $CO_2$ targets. Where incentives reward electrified miles regardless of full battery electrification, PHEVs can present a lower-risk, lower-cost pathway for buyers and OEMs especially during infrastructure transition phases.

**Who is pushing PHEVs**

**Vehicle OEMs**

PHEVs are promoted by both legacy OEMs and regional manufacturers that use the technology strategically. Historically important models include the Chevrolet Volt (one of the first mass-market "range-extended" PHEVs) and the Mitsubishi Outlander PHEV (a high-volume SUV PHEV in multiple markets). In recent years, major global groups have included PHEVs in their electrification roadmaps:

- **Toyota** — while globally famous for conventional hybrids (Prius), Toyota also offers plug-in variants (Prius Prime, RAV4 Prime) and treats PHEVs as part of a broader powertrain mix that includes hybrid and hydrogen options.

Toyota emphasizes lifecycle environmental performance and customer usability in markets with mixed infrastructure (Irwin, & Capparella, 2024).

- **Mitsubishi** — the Outlander PHEV was a high-volume PHEV pioneer and remains a reference point for SUV PHEVs in many markets.

- **European OEMs** — BMW, Volvo, Mercedes-Benz and Volkswagen groups have offered PHEV derivatives across model lines (sedans and SUVs), frequently pairing performance trims with PHEV powertrains to reduce fleet emissions while retaining customer familiarity (Autovista24, 2024).
- **Chinese manufacturers (BYD, Geely/Volvo/Polestar group, others)** — Chinese producers have been particularly active with plug-in strategies that include "dual mode" (DM)/PHEV families and plug-in hybrids as a transitional product to capture value across different buyer preferences; BYD's 'DM' line and other local brands have contributed large absolute PHEV volumes in China. This domestic push has substantially influenced global PHEV counts because of China's large market share (Parodi, 2024).

Manufacturers often position PHEVs as either (a) practical low-emission alternatives for regions with weak charging networks, or (b) performance-oriented variants that combine electric torque with ICE range and higher outputs.

### Battery and component suppliers

Although PHEV battery packs are smaller than BEV packs, the same global battery-cell suppliers (CATL, BYD, LG Energy Solution, Panasonic, Samsung SDI) supply cells and modules to PHEV programs. The economics of scale in battery manufacturing benefit PHEV dynamics falling cell costs make larger batteries more affordable, enabling extended electric range for successive PHEV generations. Battery management systems, power electronics, and integrated thermal systems are therefore central to PHEV performance and cost. (Fadhil, & Shen, 2025).

### PHEV advantages, criticisms and lifecycle considerations

PHEVs offer several immediate advantages: reduced tailpipe emissions during electric operation, lower fuel consumption for drivers who regularly charge, and reduced range-anxiety because the ICE provides long-distance flexibility. For fleets (taxis, corporate cars), PHEVs can substantially cut operational fuel costs if duty cycles are short and charging is regular.

However, PHEVs attract critique in three areas. First, real-world emissions depend heavily on charging behaviour; vehicles rarely achieve their lab-rated efficiency or electric-only miles if owners do not charge regularly, which undermines environmental benefits (the "penalty of not plugging in"). Second, PHEVs add mechanical and weight complexity the vehicle must carry both an ICE and an electric drivetrain which can reduce efficiency in charge-sustaining operation relative to purpose-built BEVs or efficient conventional hybrids. Third, policy gaming has been observed where regulatory credit systems can be exploited if PHEV electric range is weighted overly favourably. These critiques have influenced some markets and OEMs to prioritise BEVs for long-term decarbonization while retaining PHEVs as transitional options. (IEA, 2024).

### Penetration of PHEVs in Africa

PHEV penetration in Africa is currently low in absolute terms, mirroring the continent's broader slow uptake of electrified passenger vehicles compared with China, Europe and North America. However, PHEVs appear in markets where consumers or fleets seek a compromise between electrified operation and the reassurance of liquid fuels particularly in countries with limited or nascent charging infrastructure. Data and market reports indicate that most electric mobility traction across African countries has come from hybrids and smaller electric two- or three-wheelers, with plug-in four-wheelers (both BEVs and PHEVs) representing a smaller share concentrated in upper-end vehicle buyers, niche fleets and demonstration projects (EV24, 2025).

### Country snapshots

- **South Africa** is the continent's most mature automotive production hub and is witnessing increased offerings of hybrid and plug-in models often from Chinese entrants as well as established OEMs adapting to local demand. Recent launches (including PHEV SUVs from several brands) reflect a nascent market for new-energy vehicles where fiscal incentives and infrastructure evolution are still forming. South Africa's stronger dealer networks and service capacity make it a natural beachhead for PHEV introductions (Reuters, 2025).

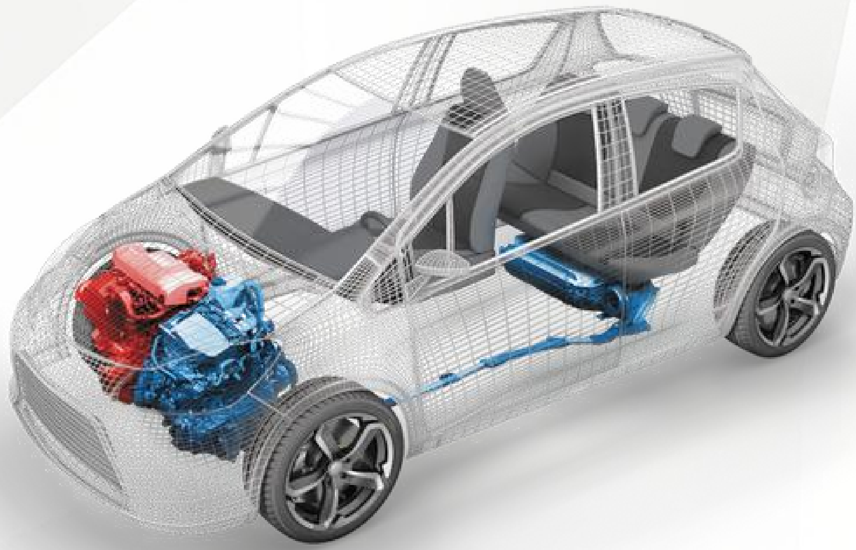
- **North Africa (Morocco)** leverages its manufacturing links to Europe and has industrial policy aiming to capture more value from new-energy vehicle production; PHEVs can be part of assembly strategies to serve export or regional markets.
- **East Africa (Kenya, Rwanda, Uganda)** currently shows greatest penetration in electric two- and three-wheelers and small urban vehicles. PHEVs are less common but could be attractive for commercial fleets seeking guaranteed range. Pilot charging projects and solar-paired solutions are emerging, which would support both BEVs and PHEVs.
- **Nigeria and other West African markets**: PHEVs are sporadically available via new imports (premium buyers) and used imports, but overall volumes are small. High import duties, limited charging infrastructure, and a used-vehicle market dominated by older ICE cars make broad PHEV uptake unlikely without deliberate policy change and infrastructure investment (EV24, 2024).

### Barriers and prospects for PHEVs in Africa

Barriers mirror those for BEVs but with nuances: the high upfront price of new PHEVs, scarcity of supportive financing, limited availability of models through domestic dealer networks, and weak public charging networks all constrain adoption. Yet PHEVs may be more politically and economically palatable in the short run because they do not force immediate dependence on charging infrastructure and can be marketed to buyers who require occasional long-distance travel. For fleets and corporate buyers that can centralise charging (e.g., municipal services, telecom fleets, delivery companies), PHEVs offer operational fuel savings and easier integration than pure BEVs while infrastructure builds out. Donor-backed pilot projects and public-private partnerships that combine solar charging, fleet procurement and technician training could accelerate targeted PHEV uptake where it makes sense (IEA, 2024).

### Conventional Hybrids

Conventional hybrids, which blend ICEs and electric drive, offer incremental improvements in fuel efficiency without requiring dedicated charging infrastructure. Hybrids are particularly effective in congested urban environments where regenerative braking and stop-start traffic conditions maximise energy recovery.



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## Conventional Hybrid

Japan has pioneered hybrid technology for decades, with Toyota's Prius achieving global recognition as a fuel-efficient alternative to conventional vehicles. In Tokyo, widespread hybrid adoption has contributed to measurable reductions in urban transport emissions, while retaining operational flexibility in areas where charging infrastructure is not yet fully developed. In developing economies, hybrids can also provide immediate emissions and fuel consumption reductions. For example, in South Africa, hybrids have been deployed in urban fleet vehicles to reduce fuel costs and emissions, while BEVs remain limited by grid constraints and the high upfront cost barrier (Creutzig et al., 2015).

The effectiveness of electrification in decarbonising passenger vehicles depends critically on supporting factors. Grid decarbonisation is essential; BEVs charged from coal-dominated grids offer smaller emissions benefits than those charged from renewable-dominated grids. Charging infrastructure density, vehicle range, total cost of ownership, and consumer acceptance further influence adoption rates. Developed economies often benefit from integrated policies, financial incentives, and advanced electricity grids that maximise the lifecycle emissions reduction of electrified vehicles. Conversely, developing economies face infrastructure gaps, higher relative vehicle costs, and weaker policy support, which may slow BEV uptake and necessitate transitional technologies such as PHEVs and hybrids (IEA, 2023).

In all, vehicle technology is a critical component of transport decarbonisation. BEVs represent the highest-emission reduction potential, PHEVs serve as transitional solutions bridging infrastructure gaps, and conventional hybrids provide incremental gains where full electrification is not yet feasible. The practical impact of these technologies varies across regions, with developed economies demonstrating rapid BEV adoption enabled by supportive policies and infrastructure, while developing economies rely more on hybrid and PHEV solutions to achieve near-term emission reductions. Policy support, grid decarbonisation, and charging infrastructure deployment are essential to maximise the benefits of electrified passenger vehicles globally.

### Cost & Saving

The electrification of light-duty vehicles particularly those used in urban delivery, ride-hailing, and taxi operations has emerged as a critical lever for decarbonising Africa's transport sector. Battery Electric Vehicles (BEVs) are increasingly cost-competitive with Internal Combustion Engine (ICE) vehicles due to steady declines in battery costs, improving energy efficiency, and the rising volatility of fossil fuel prices. In African cities like Lagos, Nairobi, and Accra where the majority of vehicles are imported, second-hand ICEs electrification presents both an economic opportunity and a public health necessity by reducing urban air pollution and operating costs (International Energy Agency [IEA], 2023).

Modern BEVs in the light-commercial and passenger fleet segments typically consume about 0.3 kWh per mile (~0.19 kWh per kilometre). When charged via grid or solar-powered charging networks, these vehicles deliver substantial operating savings compared to petrol or diesel engines. The charging ecosystem covers multiple layers: slow AC chargers for overnight depot or workplace charging, DC fast chargers for high turnover fleets, and megawatt-scale depot charging for multi-vehicle operations. Although site upgrades and infrastructure costs can be high initially, economies of scale and policy incentives continue to lower per-unit costs as deployment accelerates (Cadmus Group, 2023).

Below is a clearer and more rigorous breakdown of **transport energy cost calculations in Nigeria**, presented **distinctly for Petrol, Diesel, Grid-powered EV charging, and Solar-powered EV charging**, using transparent assumptions and step-by-step logic.

**Assumptions**

- Average petrol price: **₦960 per litre**
- Vehicle fuel efficiency: **12 miles per gallon**
- 1 US gallon = **3.785 litres**
- Exchange rate: **₦1,450/USD**

**Step 1: Cost per gallon**₦960 × 3.785 = **₦3,634 per gallon**

**Step 2: Cost per mile**₦3,634 ÷ 12 miles = **₦303 per mile**

**Dollar equivalent**₦303 ÷ 1,450 ≈ **US$0.21 per mile**

**Summary (Petrol)**

- **₦303 per mile**
- **US$0.21 per mile**

**2. Diesel (ICE Vehicle)**

**Assumptions**

- Diesel price: **₦1,100 per litre**
- Average diesel vehicle efficiency: **18 miles per gallon**

**Step 1: Cost per gallon**₦1,100 × 3.785 = **₦4,164 per gallon**

**Step 2: Cost per mile**₦4,164 ÷ 18 miles = **₦231 per mile**

**Dollar equivalent**₦231 ÷ 1,450 ≈ **US$0.16 per mile**

**Summary (Diesel)**

- **₦231 per mile**
- **US$0.16 per mile**

**3. Electric Vehicle – Grid Electricity**

**Assumptions**

- EV energy consumption: **0.30 kWh per mile**

- Grid electricity tariff (Band A): **₦209.50/kWh**

**Step 1: Cost per mile**0.30 kWh × ₦209.50 = **₦62.85 per mile**

**Dollar equivalent**₦62.85 ÷ 1,450 ≈ **US$0.043 per mile**

**Summary (Grid-Charged EV)**

- **₦63 per mile**
- **US$0.04 per mile**

**4. Electric Vehicle – Solar Power**

**Assumptions**

- Levelized cost of solar electricity: **₦64.07/kWh**
- EV energy consumption: **0.30 kWh per mile**

**Step 1: Cost per mile**0.30 kWh × ₦64.07 = **₦19.22 per mile**

**Dollar equivalent**₦19.22 ÷ 1,450 ≈ **US$0.013 per mile**

**Summary (Solar-Charged EV)**

- **₦19 per mile**
- **US$0.013 per mile**

To clearly illustrate the economic implications of different transport energy sources in Nigeria, a comparative cost-per-mile analysis is presented for petrol-powered vehicles, diesel-powered vehicles, and electric vehicles charged using grid electricity and solar power.

**Petrol-powered internal combustion engine (ICE) vehicles** remain the dominant mode of transport across Nigeria, particularly for taxis, logistics operators, and small commercial fleets. Using an average petrol price of **₦960 per litre**, and assuming a modest fuel efficiency of **12 miles per gallon**, the cost structure becomes quickly apparent. Converting litres to gallons (1 US gallon = **3.785 litres**), the cost of petrol equates to **₦3,634 per gallon**. When spread across 12 miles of travel, this results in an operating energy cost of approximately **₦303 per mile**, or **US$0.21 per mile** at an exchange rate of **₦1,450/USD**. This high per-mile cost underscores the financial strain petrol dependence places on mobility operators, especially in a context of volatile fuel pricing and limited subsidy support.

**Diesel-powered vehicles**, often perceived as more fuel-efficient, show only marginal improvement in operating economics. At a diesel price of **₦1,100 per litre** and an assumed efficiency of **18 miles per gallon**, the cost per gallon rises to **₦4,164**. Dividing this across the mileage yields an average cost of **₦231 per mile**, equivalent to **US$0.16 per mile**. While diesel offers about a **24% cost reduction** compared to petrol, it remains significantly more expensive than electrified alternatives and continues to expose operators to fuel price shocks and maintenance-intensive engines.

By contrast, **electric vehicles charged using grid electricity** demonstrate a fundamentally different cost profile. Assuming an EV energy consumption rate of **0.30 kWh per mile** and Nigeria's Band A grid tariff of **₦209.50 per kWh**, the cost of travel falls dramatically to **₦62.85 per mile**, or approximately **US$0.04 per mile**. Even at Nigeria's relatively high commercial electricity tariffs, grid-charged EVs deliver energy cost savings of over **75% compared to petrol** and **70% compared to diesel**, highlighting why electrification is gaining traction among fleet operators.

The most compelling economics emerge when **electric vehicles are charged using solar power**. Using a conservative levelized cost of solar electricity of **₦64.07 per kWh**, the cost per mile drops further to just **₦19.22**, equivalent to **US$0.013 per mile**. This represents a **94% reduction in energy cost compared to petrol** and a **92% reduction compared to diesel**. Solar-powered mobility not only eliminates exposure to fuel price volatility and grid unreliability but also delivers the lowest possible operating cost while achieving zero tailpipe emissions. Taken together, this comparison demonstrates that the transition from petrol and diesel to electric mobility particularly when paired with captive solar generation is not merely an environmental imperative but a powerful economic strategy for Nigeria's transport and logistics sectors.

For a vehicle covering 50,000 miles annually, the fuel savings alone total approximately US$2,150 per year (₦3.12 million). When maintenance savings estimated at 20–30% lower than ICEs due to fewer moving parts, regenerative braking, and no oil changes are added, the total annual savings per vehicle rise to about US$3,000–US$3,800 (₦4.35–₦5.5 million) (IEA, 2023). For fleet operators managing 50–100 vehicles, this equates to annual cost reductions between US$150,000 and US$380,000 (₦217 million–₦550 million), depending on vehicle usage and energy costs.

Establishing charging infrastructure is a key enabler of this transition. Small depot installations can cost around US$35,000 (₦50.7 million), while multi-megawatt fleet depots may range between US$800,000 and US$1 million (₦1.16–₦1.45 billion) (Cadmus Group, 2023). However, in Nigeria, hybrid systems combining solar photovoltaic (PV) and battery storage can offset unreliable grid supply, reducing reliance on diesel backup generators. For example, a solar-powered fleet depot in Lagos or Abuja could achieve operational emission cuts exceeding 90%, while providing predictable, low-cost charging (International Renewable Energy Agency [IRENA], 2022).

Africa's relative lack of entrenched fossil infrastructure offers a "leapfrogging" opportunity enabling cities to move directly toward renewable-powered mobility networks. Emerging financing mechanisms such as zero-capex lease models or Power Purchase Agreements (PPAs) make it possible for operators to electrify fleets without upfront investment. Under current economic conditions, BEV payback periods in Nigeria are typically 3–5 years, a figure that could shorten further with continued fuel price inflation and local assembly incentives.

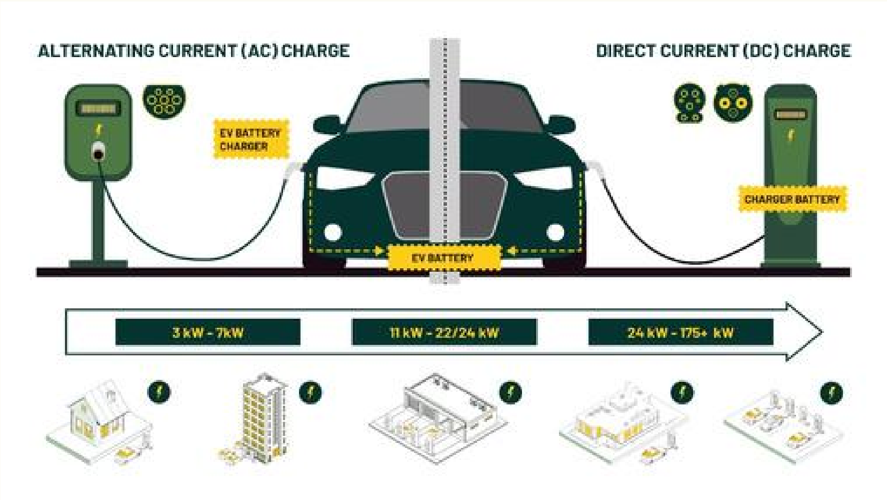
Given that transportation accounts for a significant share of urban emissions in Nigeria, widespread BEV adoption will yield not only environmental but also financial dividends. As fuel subsidy removals and exchange rate pressures push fossil fuel prices higher, the economic logic for electrification strengthens further. Each electric vehicle thus represents both a decarbonisation milestone and a financial hedge converting clean energy adoption into measurable business resilience and long-term profitability.

### Charging Networks, Grid Impacts, Standards, Smart Charging, and Non-Technology Enablers

The electrification of transport represents a cornerstone of global decarbonization strategies, yet its success hinges on the expansion and integration of efficient charging networks. Charging infrastructure comprising alternating current (AC) and direct current (DC) fast chargers forms the physical and operational backbone of the electric vehicle (EV) ecosystem. Its development is closely tied to grid capacity, smart charging technologies, and supportive policy frameworks that ensure equitable access and sustainable operation. However, the pace and nature of this evolution differ significantly between developed and developing economies due to disparities in grid stability, investment capabilities, and policy maturity (International Energy Agency [IEA], 2023).

### Charging Networks: AC and DC Fast Charging

EV charging infrastructure is commonly categorized into AC (slow to medium) and DC (fast to ultra-fast) systems. AC chargers, typically rated between 3.7–22 kW, are widely used for home and workplace charging, offering convenience for overnight or long-duration use (BloombergNEF, 2023). DC fast chargers (ranging from 50 kW to over 350 kW) deliver high power directly to the vehicle's battery, reducing charging time to 20–40 minutes crucial for commercial fleets, highways, and urban hubs (IEA, 2023).




In developed economies, public charging infrastructure has expanded rapidly through coordinated government and private sector initiatives. For instance, the European Union's Alternative Fuels Infrastructure Regulation (AFIR) mandates at least one fast charging station every 60 km along major highways by 2025 (European Commission, 2023). Similarly, the United States' National Electric Vehicle Infrastructure (NEVI) program allocates over $5 billion for nationwide DC fast charging corridors, targeting interoperability and uniform user experience (U.S. Department of Energy [DOE], 2023). These efforts are underpinned by robust grid capacity, established regulatory oversight, and public-private investment partnerships.

In contrast, developing economies face infrastructure gaps due to limited investment capacity, inconsistent power supply, and low EV penetration rates. For example, in India and Nigeria, unreliable grid conditions and high upfront costs hinder large-scale deployment of DC fast chargers (Akinlabi et al., 2022). As a result, many developing regions prioritize AC slow charging for two- and three-wheelers and light vehicles, leveraging existing distribution networks and lower-cost solutions. The FAME II program in India and South Africa's Green Transport Strategy illustrate emerging efforts to localize charging solutions using solar-powered or hybrid off-grid systems (IEA, 2023).

### Grid Impacts of Mass EV Charging

Mass EV adoption poses significant challenges to electricity grids. Charging demand can create localized peak loads, especially during evening hours when residential users plug in simultaneously. Without smart management, this can stress transformers, increase distribution losses, and necessitate costly grid reinforcement (Lopes et al., 2021).

In developed economies, utilities are investing in grid modernization, demand response, and dynamic pricing models to manage EV load profiles. The UK National Grid ESO's "Smart Systems and Flexibility Plan" estimates that unmanaged charging could increase peak demand by up to 30% by 2040, but smart charging and vehicle-to-grid (V2G) integration could halve that increase (UK Department for Energy Security and Net Zero, 2023). In California, real-time grid management platforms now coordinate EV charging schedules to align with renewable generation peaks, reducing both costs and emissions (DOE, 2023).

Developing economies face dual challenges: limited grid capacity and frequent outages. Expanding EV adoption in such contexts requires decentralized and resilient approaches. For instance, Kenya's Roam Electric and Ampersand Rwanda operate solar-powered microgrids for charging electric motorcycles, reducing dependency on unstable national grids (World Bank, 2023). Such localized systems demonstrate that renewable-based charging hubs can simultaneously enhance grid reliability and enable clean transport in resource-constrained environments.

### Standards and Interoperability

Technical standards and interoperability are critical for ensuring user convenience, safety, and compatibility across different charging systems and regions. Standards cover plug types (e.g., CCS, CHAdeMO, Type 2), communication protocols, safety mechanisms, and payment interfaces. In developed markets, standardization has been instrumental in scaling EV adoption. The European Union's CCS2 connector has become the de facto standard, while Tesla's North American Charging Standard (NACS) has recently been adopted by major automakers such as Ford and General Motors, reducing fragmentation in the U.S. (BloombergNEF, 2023).

Interoperability also extends to payment systems and roaming services. In Europe, platforms such as Hubject's eRoaming network allow drivers to charge across multiple providers with unified billing systems, mirroring the mobile telecom model (European Commission, 2023). Japan's CHAdeMO standard, meanwhile, pioneered bidirectional charging, enabling early V2G applications (IEA, 2023).

In developing economies, lack of standardization remains a key barrier. Multiple incompatible charging systems, absence of data-sharing frameworks, and non-uniform safety codes limit scalability. India's Bureau of Indian Standards has begun harmonizing plug and communication protocols through the IS 17017 framework, aligning with global norms (Akinlabi et al., 2022). However, many African countries lack formal regulatory frameworks, resulting in fragmented pilot projects that risk stranded assets and poor user adoption. Establishing international harmonization is thus essential for reducing technology costs and ensuring interoperability across regions.

### Smart Charging and Digital Integration

Smart charging refers to the use of digital control systems to manage when and how EVs draw power, aligning charging behaviour with grid conditions and renewable energy availability. This includes time-of-use pricing, load shifting, and vehicle-to-grid (V2G) systems where EVs discharge stored energy back into the grid during peak demand (Lopes et al., 2021).

Smart Charging Systems

In **developed economies**, smart charging is emerging as a key flexibility tool in grid decarbonization. For example, in the Netherlands, Enel X's smart charging network integrates over 20,000 chargers into the national grid, optimizing charging to absorb excess wind power during off-peak hours. Similarly, Japan's V2G pilot projects, such as TEPCO's Nissan Leaf integration, demonstrate how parked EVs can provide grid support and frequency stabilization (IEA, 2023).

In **developing economies**, digital integration remains nascent but promising. Mobile-based smart charging systems are being piloted in Kenya and Ghana, allowing users to locate, reserve, and pay for charging sessions through mobile apps linked to prepaid electricity systems (World Bank, 2023). These solutions, though small in scale, highlight how digital innovation can bypass legacy grid constraints and accelerate EV adoption in regions with limited infrastructure.

## Fuels

While vehicle electrification represents a critical pathway for reducing transport emissions, alternative fuels remain essential for decarbonising sectors where electrification is challenging, such as aviation, shipping, and long-haul heavy-duty transport. Biofuels, synthetic e-fuels, and hydrogen fuel cells each offer unique opportunities and challenges, and their deployment varies considerably between developed and developing economies.

Biofuels, derived from sustainable biomass sources, can partially replace conventional gasoline and diesel in existing internal combustion engine (ICE) vehicles, allowing near-term emissions reductions without requiring entirely new vehicle fleets. First-generation biofuels, such as ethanol from sugarcane or corn and biodiesel from vegetable oils, have been deployed extensively in several countries. Brazil provides a seminal case study: since the 1970s, Brazil's Proálcool program has promoted sugarcane ethanol as a substitute for gasoline. Today, over 80% of vehicles in Brazil are flex-fuel, capable of running on gasoline, ethanol, or any blend thereof, significantly reducing fossil-fuel dependence and lowering lifecycle greenhouse gas (GHG) emissions, particularly given the high energy yield and relatively low lifecycle emissions of sugarcane ethanol (de Oliveira et al., 2020). In Europe, advanced biodiesel and ethanol blends derived from second-generation feedstocks such as agricultural residues, waste oils, or cellulosic biomass are gaining traction to reduce the carbon footprint of road and aviation fuels.

However, sustainability criteria are critical: poorly managed biofuel production can lead to land-use change, food security concerns, and high lifecycle emissions (Creutzig et al., 2015).

In developing economies, biofuels offer dual benefits of emissions reduction and energy security. India has implemented initiatives to blend ethanol with gasoline, reaching an ethanol blending mandate of 10% by 2022, with plans to increase to 20% by 2025. This not only reduces fossil fuel consumption but also stimulates domestic agriculture and reduces foreign exchange dependency on oil imports (IEA, 2023). In sub-Saharan Africa, pilot programs in countries such as Kenya and Tanzania explore bioethanol from sugarcane or cassava as a localized solution for road transport, though infrastructure, supply chain development, and policy support remain limiting factors.

Synthetic e-fuels liquid or gaseous fuels produced from renewable electricity and captured $CO_2$ offer a promising pathway for carbon-neutral operation of existing ICE vehicles and hard-to-electrify sectors like aviation and shipping. For example, in Europe, several projects, such as the Sunfire and Electrochaea initiatives in Germany, have demonstrated the production of e-diesel and e-methanol from renewable electricity and $CO_2$, suitable for use in conventional engines. Although current production costs are high, scaling up electrolysis and carbon capture technologies could enable competitive, low-carbon fuels in the coming decades (IEA, 2023). In developing countries, synthetic fuels are still at a nascent stage due to high capital and electricity costs, but potential exists in regions with abundant renewable energy resources, such as Chile's Atacama Desert, which offers high solar irradiance suitable for green hydrogen and e-fuel production (IRENA, 2022).

Hydrogen fuel cells present a complementary strategy, particularly for long-range heavy-duty transport and buses. Hydrogen fuel cell electric vehicles (FCEVs) produce only water at the point of use when hydrogen is generated from renewable electricity ("green hydrogen"). Developed economies such as Japan, Germany, and South Korea are leading hydrogen adoption for transport. Japan's FCEV program, exemplified by the Toyota Mirai and hydrogen fuel cell buses in Tokyo, demonstrates zero-emission long-range operation with refuelling times comparable to conventional vehicles. Germany has similarly deployed hydrogen-powered trucks and established hydrogen corridors along major freight routes to decarbonise logistics (IEA, 2023). In developing economies, hydrogen adoption faces challenges including high production costs, lack of refuelling infrastructure, and limited policy support. However, countries with abundant renewable resources, such as Morocco and Chile, are exploring green hydrogen for industrial and transport applications, leveraging international partnerships to finance pilot projects and scale production (IRENA, 2022).

Beyond these technologies, hybrid strategies that integrate alternative fuels with partial electrification such as hydrogen-electric hybrid trucks or biofuel-electric buses offer near-term emissions reductions while enabling a gradual transition to fully renewable-powered transport systems. Importantly, the success of alternative fuels depends on policy frameworks, supply chain development, vehicle compatibility, and lifecycle sustainability. Developed economies demonstrate that policy incentives, infrastructure investment, and industrial coordination can accelerate adoption, while developing economies must overcome financial, technical, and logistical barriers to realise similar benefits.

In all, alternative fuels biofuels, synthetic e-fuels, and hydrogen play a critical role in decarbonising transport sectors that are difficult to electrify. Real-world examples from Brazil, Japan, Germany, and India illustrate how these technologies can reduce GHG emissions while supporting economic and energy security objectives. Scaling these solutions globally, particularly in developing economies, requires coordinated policies, investment in production and distribution infrastructure, and robust sustainability standards to ensure that emissions reductions are genuine and socially equitable (Creutzig et al., 2015; IEA, 2023; IRENA, 2022).

### Decarbonisation Pathways

Achieving deep decarbonisation in passenger transport necessitates integrated strategies that combine vehicle electrification, modal shifts, low-carbon fuels, and supportive infrastructure. The approaches differ significantly between developed and developing economies due to variations in vehicle ownership rates, urban density, electricity grid maturity, policy frameworks, and financial capacity. Understanding these regional differences is critical for designing effective policies and avoiding carbon lock-in in rapidly developing markets.

In developed economies, high vehicle ownership rates, mature electricity grids, and well-established regulatory frameworks provide a foundation for rapid deployment of low-carbon technologies. Electric vehicles (EVs), including Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), are at the forefront of decarbonisation strategies. For instance, Europe has witnessed a remarkable surge in EV adoption. Norway, in particular, exemplifies the successful integration of policy instruments and market mechanisms. As of 2023, over 85% of new passenger vehicle sales in Norway were electric, driven by purchase incentives, exemption from registration fees, reduced tolls, and extensive public charging infrastructure (IEA, 2023). Similarly, the Netherlands and Germany have implemented comprehensive subsidy programs, stringent fleet $CO_2$ emission standards, and tax benefits that have encouraged both individual and fleet adoption of EVs. These policies not only reduce tailpipe emissions but also leverage existing grid infrastructure to support high EV penetration while stimulating local green industries, including battery manufacturing and charging infrastructure development (Hawkins et al., 2013).

The United States provides another illustrative case, where federal and state-level incentives have facilitated EV deployment. California, as a global leader in EV adoption, has combined rebate programs, zero-emission vehicle mandates, and investments in fast-charging networks to accelerate the transition (Sims et al., 2022). Furthermore, vehicle-to-grid (V2G) pilot projects in California demonstrate the potential for EVs to provide grid flexibility and ancillary services, thereby integrating decarbonisation with broader energy system objectives. The relatively high purchasing power and policy stability in developed economies enable these interventions to scale rapidly, creating demonstrable reductions in per-capita transport emissions.

In contrast, developing economies face a complex set of barriers that slow electrification and low-carbon transitions. High upfront costs of BEVs and PHEVs, limited availability of charging infrastructure, and intermittent grid reliability are significant challenges. For example, in India, despite government incentives under the FAME II program (Faster Adoption and Manufacturing of Electric Vehicles), EV adoption remains below 2% of total vehicle sales in most states due to affordability constraints and uneven charging networks (IEA, 2023). Similarly, in Sub-Saharan Africa, countries such as Kenya and Nigeria are exploring pilot programs for electric buses and taxis, but widespread adoption is constrained by high import costs, insufficient financing mechanisms, and limited technical capacity for battery maintenance (IRENA, 2022).

However, developing economies also present unique opportunities for decarbonisation due to rapidly growing urban populations and expanding vehicle markets. Early adoption of EVs and other low-carbon solutions can prevent the establishment of carbon-intensive transport patterns. China exemplifies this approach, combining robust industrial policy with targeted subsidies to accelerate EV adoption. Over 10 million EVs were registered in China in 2023, supported by domestic battery manufacturing, extensive urban charging networks, and fleet electrification in public transport and taxis (Hawkins et al., 2013). These measures have simultaneously reduced oil imports, mitigated urban air pollution, and stimulated local technological innovation.

Modal shift strategies are complementary to vehicle electrification, particularly in dense urban contexts in both developed and developing economies. European cities such as Copenhagen and Amsterdam have successfully integrated cycling infrastructure, pedestrian zones, and efficient public transit to reduce reliance on private vehicles. In developing economies, cities like Bogotá and Medellín in Colombia have invested in Bus Rapid Transit (BRT) systems to provide high-capacity, low-emission alternatives to private cars. These investments not only reduce per-capita emissions but also enhance social equity by providing affordable mobility options (Creutzig et al., 2015).

Beyond electrification and modal shifts, fuel diversification remains an essential pathway. Biofuels and synthetic e-fuels can partially substitute fossil fuels in hybrid vehicles or conventional ICEs where EV deployment is slow or impractical. Brazil's long-standing ethanol program demonstrates the viability of integrating biofuels into national transport systems to reduce carbon intensity while supporting rural economies (de Oliveira et al., 2020). Similarly, pilot e-fuel production in Chile leverages abundant solar resources to create renewable fuels for long-distance freight and aviation, highlighting opportunities for developing economies to leapfrog into low-carbon transport solutions.

Integration of decarbonisation measures with broader urban planning and energy systems is critical. In developed economies, coordinated land-use planning, smart grids, and renewable electricity expansion ensure that EVs contribute maximally to emission reductions without overloading grids. In developing economies, urbanization patterns, limited grid capacity, and informal settlements require tailored strategies, including distributed charging infrastructure, renewable mini-grids, and blended financing models to make EV adoption viable and equitable (IEA, 2023; Sims et al., 2022).

In conclusion, decarbonisation of passenger transport demands multi-faceted strategies that are context-specific. Developed economies leverage high vehicle ownership, mature grids, and policy instruments to drive rapid electrification, modal shift, and fuel diversification. Developing economies face more structural barriers but possess the potential for early low-carbon adoption to prevent carbon lock-in. Real-world experiences from Norway, China, Brazil, and India illustrate how policy, technology, and infrastructure interact to shape emissions outcomes. To achieve global transport decarbonisation, tailored pathways that combine electrification, low-carbon fuels, modal shift, and integrated urban planning are essential, supported by international collaboration, financing mechanisms, and knowledge transfer.

**Heavy Transport and Long-Distance: Hydrogen Fuel Cells, E-Trucks, E-Highways, Sustainable Biofuels, and E-Fuels**

Decarbonising heavy transport and long-distance travel represents one of the most complex challenges in the global energy transition. Unlike passenger vehicles, which can more readily adopt battery-electric technologies, heavy-duty road freight, maritime shipping, and aviation are constrained by high energy density requirements, long operating hours, and limited refuelling infrastructure (International Energy Agency [IEA], 2023). These segments contribute disproportionately to greenhouse gas (GHG) emissions road freight alone accounts for nearly 30% of transport $CO_2$ emissions globally, while aviation and shipping combined contribute an additional 20% (Sorrell et al., 2020). Consequently, a mix of technological pathways, including hydrogen fuel cells, electric trucks (e-trucks), e-highways, sustainable biofuels, and synthetic e-fuels, are being pursued to enable deep decarbonisation of this sector.

**Hydrogen Fuel Cells for Heavy-Duty Transport**

Hydrogen fuel cell electric vehicles (FCEVs) are particularly well-suited for long-distance and heavy transport applications due to their high energy density and quick refuelling capability. Hydrogen can be produced through electrolysis powered by renewable electricity, leading to zero direct emissions when used in fuel cells. The only by-product is water vapor, making FCEVs an environmentally friendly alternative to diesel trucks and buses (IEA, 2022).

In developed economies, significant progress has been made in hydrogen mobility deployment. For instance, Japan's "Hydrogen Society" initiative supports hydrogen refuelling infrastructure and commercial FCEV fleets, including buses used during the Tokyo 2020 Olympics (Ministry of Economy, Trade and Industry [METI], 2022). Similarly, the European Union (EU) has launched the *Hydrogen Backbone Initiative*, targeting transnational hydrogen pipelines and refuelling corridors for freight transport (European Commission, 2023). In the United States, the

Department of Energy's Hydrogen Hubs program aims to establish regional hydrogen clusters integrating production, transport, and use in mobility and industry (U.S. DOE, 2023).

In developing economies, hydrogen remains in a nascent phase due to cost barriers and limited renewable electricity capacity. However, countries such as South Africa are exploring "green hydrogen corridors" to leverage their renewable potential and export markets (International Renewable Energy Agency [IRENA], 2022). Similarly, pilot hydrogen bus projects have been launched in India and China, supported by public-private partnerships and international funding (IEA, 2023). The major challenges remain the high cost of electrolyzers, limited refuelling networks, and the need for integrated policies to scale hydrogen logistics and safety standards.

### Examples of Companies developing Hydrogen Fuel Cells for Heavy-Duty Transport

Hydrogen fuel cell electric vehicles (FCEVs) for heavy-duty transport are emerging globally. While still nascent compared to battery trucks or conventional diesel, several vehicle OEMs, technology suppliers, and ecosystem players are pushing the frontier. Below, we group prominent examples by region and examine what is known about their revenue, deployment scale, and business challenges.

#### 1. Asia / Korea / Global OEMs

#### Hyundai (South Korea / global)

Hyundai is one of the few traditional automakers actively deploying heavy-duty fuel cell trucks. Its XCIENT Fuel Cell truck is already in commercial operation in Switzerland, the U.S., and elsewhere. In Switzerland, Hyundai's fleet surpassed 10 million cumulative kilometers of operation, showcasing operational reliability and real-world experience (Hyundai Group, 2025).


Hyundai XCIENT Fuel Cell Truck

Hyundai has delivered units not only in Switzerland but also is launching trucks in the U.S. under the NorCAL ZERO initiative, deploying 30 trucks in California and integrating the hydrogen ecosystem (refuelling, logistics) with its Metaplant logistics operations in Georgia, USA (PR Wire, 2024).

Hyundai's fuel cell business is nested under its HTWO hydrogen value-chain brand, which spans production, storage, and distribution as well as mobility. While Hyundai does not break out heavy-duty FCEV revenue publicly, the scale of deployment and investment in hydrogen infrastructure reflect strong strategic commitment.

**Other Asia OEMs**

Toyota, globally, is a recognized technology leader in fuel cells; although its strongest market presence has been in passenger and bus segments, Toyota offers fuel cell modules for potential integration into trucks and commercial vehicles via partners. Scania (Europe/Sweden) and Isuzu (Japan) are also developing fuel cell powertrain research, though they have not yet disclosed significant commercial revenue from heavy truck sales. These OEMs are positioning for future adoption, aligning with regional decarbonization policies in Europe, Asia, and Japan.

**2. North America**

**Nikola Corporation (USA)**

Nikola, founded as a zero-emission truck startup, has focused heavily on hydrogen FCEV for Class 8 long-haul trucking. In Q2 2024, Nikola achieved its strongest topline ever: USD 31.3 million in revenue, primarily through wholesaling 72 hydrogen fuel cell trucks to dealers (Nikola, 2025). Over the first three quarters of 2024, Nikola wholesaled 200 hydrogen trucks.


Nikola Hydrogen Truck

However, Nikola's broader financial health remains under pressure. The company has also emphasized revenue from regulatory credits and integrated fuelling via its HYLA brand. In early 2025, Nikola filed for bankruptcy protection, indicating how challenging the capital intensity and commercialization risk remain in heavy-duty hydrogen transport.

**Other U.S. / global aspirants**

General Motors has developed its HYDROTEC modular fuel cell systems intended for broader applications, including potentially trucks, locomotives, and industrial uses. While GM has not yet disclosed heavy-duty FCEV sales, its deep resources and existing industrial hydrogen experience position it as a potential player once the market scales.


HYDROTEC POWER CUBE

### 3. Europe

#### Scania (Sweden / Europe)

Scania, part of the Volkswagen Group's TRATON, is actively researching fuel cell powertrains for heavy-duty trucks in Europe. While no major commercial truck sales have been widely publicized yet, Scania's long history in European truck markets, combined with supportive EU emissions regulation, gives it a strategic advantage. Scania often collaborates in consortiums and pilot projects rather than publicizing standalone revenue from hydrogen trucks as of now.

#### Fuelling, Infrastructure, and Ecosystem Support

#### HTEC (Hydrogen Technology & Energy Corporation)

HTEC supports fleets by bundling fuel cell trucks with fuelling infrastructure in a no-CapEx leasing model. It provides vehicles, fuelling stations, maintenance, and hydrogen supply reducing the upfront barrier for fleet operators. HTEC (Hydrogen Technology & Energy Corporation) no-CapEx leasing model that is reshaping how hydrogen fuel cell technology is adopted within the heavy-duty transport industry. Traditionally, the high capital expenditure (CapEx) associated with purchasing fuel cell trucks and constructing refuelling infrastructure has been a significant barrier to entry for fleet operators. HTEC's approach removes this obstacle by bundling fuel cell vehicles, hydrogen fuelling stations, maintenance, and hydrogen supply into a comprehensive leasing package. Instead of purchasing the assets outright, fleet operators pay a predictable operational fee, allowing them to transition to zero-emission logistics without the financial strain of upfront investment.

This model effectively transfers the funding burden from operators to financiers and infrastructure developers, creating a shared-risk ecosystem that attracts institutional investors and accelerates deployment. By treating hydrogen mobility as a service, HTEC ensures steady cash flows and scalability while reducing adoption risk for end-users. The model also integrates public-private partnerships and leverages green investment funds, aligning with sustainability financing trends. As a result, this financing innovation is not only promoting hydrogen fuel cell technology but also positioning it as a commercially viable and financeable pathway toward decarbonizing the global freight and logistics sectors.

In sum, the heavy-duty hydrogen fuel cell ecosystem is scaling from pilot to early commercial phases, with Hyundai as the most successful incumbent OEM, Nikola the high-risk startup venture, and Scania, GM, Toyota/Isuzu playing strategic or developmental roles. Infrastructure integrators such as HTEC, along with global alliances like the Hydrogen Council, help knit the value chain together. As deployment grows, more robust revenue disclosures and economies of scale will clarify which models succeed in the race for zero-emission freight.

### Cost and Savings

Hydrogen fuel cell technology has emerged as one of the most promising pathways for decarbonising heavy-duty transport particularly trucks, buses, and long-haul logistics vehicles that require extended ranges, fast refuelling times, and high-power output. Unlike battery-electric systems that are limited by battery weight and charging downtime, hydrogen fuel cells generate electricity onboard through a chemical reaction between hydrogen and oxygen, emitting only water vapour as a by-product (International Energy Agency [IEA], 2024). This makes them particularly suitable for long-distance freight corridors, intercity buses, and commercial fleets that demand continuous operation.

Globally, major manufacturers such as Hyundai (XCIENT Fuel Cell Truck), Nikola Motors, Toyota, and Volvo Group are leading the commercial rollout of hydrogen-powered heavy vehicles. These trucks typically store compressed hydrogen in onboard tanks and can refuel in under 15 minutes similar to conventional diesel refuelling times providing ranges of up to 800 kilometres per tank (BloombergNEF, 2023). Although current hydrogen prices range between US$6 and US$8 per kilogram, technological improvements in electrolysers, renewable hydrogen production, and economies of scale are expected to reduce costs to around US$2/kg by 2030 (International Renewable Energy Agency [IRENA], 2023).

A heavy-duty truck that consumes approximately 10 kg of hydrogen per 100 kilometres currently incurs a fuel cost of US$0.70/km, compared to an equivalent diesel truck at around US$0.65/km based on global diesel price averages (IEA, 2024). However, as hydrogen prices fall to US$2/kg, the cost per kilometre would decline to US$0.25/km, representing savings of nearly US$0.45/km. For a truck covering 120,000 kilometres annually, this translates to US$45,000 in annual fuel cost savings. Beyond fuel, hydrogen trucks benefit from lower maintenance costs due to fewer moving parts, reduced mechanical wear, and the absence of oil and exhaust system replacements offering an additional 10–20% reduction in total operating costs (Hydrogen Council, 2023). In regions like Nigeria and South Africa, where diesel prices are rising and transport emissions remain high, hydrogen fuel cell technology offers a realistic path toward low-carbon logistics, energy diversification, and long-term cost competitiveness.

### E-Trucks and Battery-Electric Freight

Battery-electric trucks (e-trucks) represent another viable pathway for short- to medium-haul freight decarbonisation. Advances in lithium-ion battery energy density, coupled with improvements in fast-charging infrastructure, have made e-trucks increasingly competitive for ranges up to 400 km (BloombergNEF, 2023). Their operational cost advantage stems from higher drivetrain efficiency and lower maintenance costs compared to diesel trucks.

In Europe, companies such as Volvo, Daimler, and Scania have begun commercial deployment of heavy-duty e-trucks, with dedicated megawatt charging systems under development (European Automobile Manufacturers Association [ACEA], 2023). In the U.S., Tesla's Semi truck represents a landmark in long-range electric freight, capable of traveling 800 km per charge under optimal conditions (Tesla, 2023). Meanwhile, China leads the world in the deployment of electric logistics vehicles and e-buses, supported by strong industrial policy and local manufacturing capacity (IEA, 2023).

However, the challenges for e-trucks are significant in developing economies. Grid reliability, charging infrastructure, and high battery costs hinder widespread adoption. The high energy requirements for long-haul operations can strain electricity grids that already face supply constraints. Therefore, hybrid models that combine grid electricity and hydrogen fuel cells, or that utilize battery swapping for freight fleets, are being explored in markets such as India and Indonesia (IRENA, 2022).

### Examples of E-Truck OEMs

### North America / U.S.

### Tesla, Inc.

Tesla's flagship heavy-duty offering is the Tesla Semi, a Class 8 battery truck with ~500 mile range (Tesla, 2025). While full volume production is slated for 2026, Tesla is already running pilot deliveries. The company has publicly estimated 2024 electric truck revenue at USD 2.10 billion.

Tesla Truck

Tesla plans a factory capable of producing 50,000 Semis annually, leveraging its battery, software, and charging ecosystem strengths (Tesla, 2025).

### PACCAR Inc.

PACCAR parent of Kenworth and Peterbilt has entered the electric truck market by integrating battery packs and electrified drivetrains into its models, such as Kenworth T680E and Peterbilt

579EV. Its 2024 e-truck revenue is estimated at USD 550 million. Its strength lies in its deep dealer network across North America and relationships with fleet operators.

It is imperative to state that the development of these advancements in the electric truck segment of the market has already started attracting interest as numbers of the adopters are on the rise. Courier and parcel firms in the U.S. like UPS and Knight-Swift are gradually electrifying segments of their fleets. The adoption is more strategic: lowering fuel and maintenance costs, meeting ESG commitments, and hedging regulatory risks.

### Asia / China

#### BYD Auto Co., Ltd.

BYD is a dominant force in China's EV industry and is leveraging its vertically integrated battery business to produce commercial electric trucks (the T8 series). Its 2024 e-truck revenue is estimated at USD 1.75 billion.

T8 series truck by BYD

BYD's home market offers strong policy support, manufacturing scale, and integration across batteries, inverters, and EV platforms. Its international expansion is underway, particularly in Asia, Latin America, and Europe. In China, the local logistics and delivery sector is aggressively electrifying last-mile and medium-duty fleets, which provides a large local demand pull for BYD's commercial EVs.

### Europe

#### Volvo Group

Volvo has been among the most active in Europe in deploying electric trucks. Its models include FH Electric, FM Electric, and VNR Electric (for North America).

Volvo FH Electric

By April 2025, the company had sold over 5,000 electric trucks globally (Volvo Truck, 2025). Its 2024 e-truck revenue is estimated at **USD 1.20 billion**. In Europe, Volvo commands a leading position, with a 47% share of the heavy e-truck segment in several markets.

**Daimler Truck AG / Mercedes-Benz**

Daimler (which also markets under Freightliner in the U.S.) is rolling out battery electric models like eCascadia and eActros.

Its 2024 e-truck revenue is estimated at **USD 1.05 billion**. EV truck sales grew 17% year-over-year for Daimler in 2024 (Wissenbach, & Sychev, 2024). The company has set a goal for 50% of its European sales to be electric by 2030 and already has thousands of orders for its new fully electric heavy truck lines (Wissenbach, & Sychev, 2024).

In Europe, many logistics firms are adopting e-trucks for urban delivery and regional haul. Lower urban emissions zones, carbon pricing, and incentives make the total cost of ownership more favourable. While these e-trucks still represent a slice of total fleet revenue, they help cut fuel, maintenance, and regulatory compliance costs. Over time, as battery costs fall, the ROI improves strongly for these operators.

### Adoption by Courier & Logistics Operators

The adoption of electric trucks (e-trucks) by courier and logistics operators is transforming the global freight and delivery industry, largely due to the compelling economic, environmental, and strategic benefits that these vehicles provide. One of the most significant drivers is cost savings on fuel and maintenance, as electricity costs per mile are markedly cheaper than diesel, and electric drivetrains consist of fewer moving parts, resulting in lower maintenance requirements, minimal downtime, and longer vehicle lifespans. For instance, Tesla has emphasized that local and regional logistics operators can achieve a positive return on investment (ROI) within the typical diesel replacement cycle, especially as operational savings compound over time (Tesla, 2024). Given that fuel and maintenance costs constitute a major portion of logistics expenditure, this transition helps companies like UPS and DHL significantly reduce their operating costs while enhancing fleet efficiency (IEA, 2024).

In addition to cost efficiency, regulatory and environmental pressures are accelerating the adoption of e-trucks. Many urban centres across North America, Europe, and Asia now enforce low-emission zones, carbon pricing, and pollution penalties, which increase the cost of operating diesel fleets (European Commission, 2024). Courier companies adopting e-trucks can avoid such charges while aligning with corporate sustainability goals. The ability to brand delivery services as “green” also enhances customer loyalty, given the growing consumer preference for environmentally responsible logistics (BloombergNEF, 2024). Companies like DHL have leveraged this through their “GoGreen” initiative, integrating electric trucks into last-mile and regional deliveries to support their net-zero emissions targets by 2050 (DHL Group, 2024). This dual advantage regulatory compliance and brand value makes the ROI of e-truck adoption more favourable.

Government incentives, subsidies, and procurement programs further accelerate this transition. Many countries provide tax credits, grants, or direct rebates for electric commercial vehicles and related infrastructure, effectively lowering upfront capital expenditure (CapEx). In the United States, the Inflation Reduction Act (IRA) provides credits of up to $40,000 per medium- or heavy-duty EV, significantly reducing acquisition costs (U.S. Department of Energy, 2024). Similarly, the European Union's Green Deal and China's New Energy Vehicle (NEV) program offer direct funding and operational support for logistics operators transitioning to electric fleets (IEA, 2024). These policy measures reduce financial barriers, enhance payback periods, and enable companies like Knight-Swift Transportation to begin large-scale fleet renewals with electric models.

Scalability also plays a crucial role. As original equipment manufacturers (OEMs) like Tesla, Volvo, and Daimler scale production, per-unit manufacturing costs decline due to learning curves and supply chain efficiencies. Tesla's planned ramp-up to 50,000 Semi units annually and Volvo's milestone of over 5,000 global electric truck sales demonstrate growing production maturity and market validation (InsideEVs, 2025). These trends drive down acquisition costs, making e-trucks more accessible to logistics operators and improving the economics of total cost of ownership (TCO).

However, the transition carries risks and capital recovery challenges. High upfront costs for trucks and charging infrastructure remain obstacles, particularly for small to medium-sized operators (IEA, 2024). To mitigate this, some firms are adopting leasing and energy-as-a-service models, allowing them to pay predictable operational fees rather than invest heavily upfront. Despite these challenges, large courier companies with scale such as UPS, FedEx, and DHL are already realizing competitive advantages through lower lifetime costs, regulatory compliance, and improved cost predictability. Over time, companies that delay adoption risk being disadvantaged by rising fuel prices, stricter emissions policies, and stranded diesel assets. Ultimately, the economic logic, coupled with environmental imperatives and market incentives, is making e-truck adoption not just a sustainability goal but a strategic business decision that strengthens operational resilience and long-term profitability.

### Cost and Savings

The upfront cost of an E-truck remains higher, averaging around US$250,000 compared to about US$150,000 for a conventional diesel truck. However, the operating economics favour electrification. Electricity costs for commercial charging estimated at US$0.10 per kWh translate to about US$0.20 per kilometre in energy cost, while diesel fuel at US$1.20 per litre yields approximately US$0.65 per kilometre for similar payloads and routes (International Energy Agency [IEA], 2023). This represents a fuel cost reduction of roughly 70%, meaning operators save nearly US$0.45 per kilometre driven. Over a truck's typical 10-year lifespan, this equates to US$180,000–250,000 in total fuel savings, effectively offsetting the higher purchase price (McKinsey & Company, 2023; BloombergNEF, 2023).

For African fleet operators, particularly in Nigeria, where diesel prices exceed ₦960 per litre (≈US$0.67) due to subsidy removal and market volatility, the cost advantage is even more significant. Assuming a typical truck travels 80,000 kilometres annually, shifting from diesel to electricity can save approximately ₦3–4 million per year in energy costs alone, amounting to ₦30–40 million (≈US$20,000–27,000) over its service life. Furthermore, maintenance costs for E-trucks are 20–30% lower, owing to fewer mechanical parts, regenerative braking, and reduced oil and filter use (IEA, 2023).

When coupled with solar-based depot charging or power purchase agreements, electric freight fleets in Nigeria and across Africa could achieve payback periods of 5–7 years, while contributing to cleaner air and reduced dependence on imported diesel. Thus, E-trucks represent not just a climate solution but a strategic economic advantage for logistics and fleet operators on the continent.

### E-Highways and Electrified Road Systems

E-highways represent a novel approach to decarbonising long-distance road freight by directly supplying electricity to moving trucks through overhead catenary lines, conductive rails, or inductive wireless systems. This eliminates the need for large onboard batteries, thereby reducing vehicle weight and increasing efficiency (Siemens Mobility, 2022).

Germany, Sweden, and the United Kingdom have launched pilot e-highway corridors that demonstrate significant emission reductions and operational feasibility. For instance, Sweden's eRoadArlanda project successfully powered electric trucks through conductive tracks embedded in road surfaces (Swedish Transport Administration, 2022). Germany's Autobahn e-highway pilot on the A5 has shown that hybrid trucks can automatically switch between grid power and battery mode, reducing $CO_2$ emissions by up to 80% compared to diesel (Federal Ministry for Economic Affairs and Climate Action, 2023).

While e-highways hold promise, their capital cost and infrastructure requirements pose challenges in developing economies where road quality, grid coverage, and maintenance resources are limited. Nonetheless, long-term opportunities exist, particularly along high-volume freight corridors, where regional cooperation and concessional financing can enable incremental electrification.

### Cost and Savings

Infrastructure development for e-highways is capital-intensive, with construction costs averaging US$3–5 million per kilometre, depending on terrain, technology, and existing road conditions (IEA, 2024; Siemens Mobility, 2023). However, despite the high upfront investment, operational savings are substantial. Because electric traction is far more energy-efficient than diesel combustion, e-highway-enabled trucks can save up to US$200,000 per vehicle annually through reduced fuel and maintenance costs (IEA, 2024). The savings come primarily from replacing diesel often priced at US$1.20 per litre globally, or about ₦960 per litre (~US$0.67) in Nigeria with grid or renewable electricity costing US$0.10–0.15 per kWh, leading to energy cost reductions of 60–70%.

In the African context, deploying e-highways along strategic freight corridors such as Lagos–Kano in Nigeria or Nairobi–Mombasa in Kenya could yield transformative economic and environmental benefits. These routes handle massive freight volumes, and electrification could reduce fuel import dependency, cut logistics costs, and enhance trade competitiveness. Modeling suggests that using renewable-powered e-highways could reduce $CO_2$ emissions by up to 80% relative to conventional diesel freight (International Renewable Energy Agency [IRENA], 2023). Additionally, e-highway deployment offers multiplier effects: creating skilled jobs in infrastructure installation and maintenance, stimulating local manufacturing of components (such as conductors and substations), and supporting the integration of renewable energy into national grids. With appropriate public–private partnerships, concessional financing, and regional cooperation, Africa could leapfrog directly into electric freight transport, avoiding decades of high-emission diesel dependency while strengthening its long-term energy security.

### Sustainable Biofuels for Heavy and Long-Distance Transport

Biofuels derived from biomass such as agricultural residues, waste oils, and algae offer an immediate, drop-in solution for decarbonising existing internal combustion engines (ICEs). Advanced biofuels such as hydrotreated vegetable oil (HVO), cellulosic ethanol, and Fischer–Tropsch biodiesel can significantly reduce lifecycle emissions compared to fossil fuels when sourced sustainably (Creutzig et al., 2015).


In developed economies, biofuels are already integrated into national fuel mixes. The EU's Renewable Energy Directive (RED II) mandates a 14% renewable energy share in transport by 2030, largely through biofuel blending (European Commission, 2023). The United States has similarly implemented the Renewable Fuel Standard (RFS), supporting production of advanced biofuels from non-food feedstocks (U.S. Environmental Protection Agency [EPA], 2023).

Developing economies such as Brazil and Indonesia have long histories of biofuel use. Brazil's ethanol program based on sugarcane has achieved substantial GHG reductions and energy security benefits (Goldemberg et al., 2018). Indonesia's biodiesel mandate, using palm oil, has reduced fossil diesel imports but faces sustainability challenges related to land-use change and deforestation (World Resources Institute [WRI], 2022). The challenge remains ensuring feedstock sustainability and avoiding food-energy trade-offs, especially in regions with weak land governance.

### Cost and Savings

Sustainable biofuels such as biodiesel, bioethanol, and hydrotreated vegetable oils (HVO) offer a viable transitional pathway for decarbonising heavy-duty and long-distance transport, particularly in regions where full electrification or hydrogen infrastructure remains limited. These fuels can be used in existing diesel engines with minimal modification, making them an immediately deployable solution for emissions reduction. Currently, biofuel prices average around US$1.20 per litre, slightly lower than diesel at US$1.50 per litre (BP, 2024).

For a long-haul truck covering 100,000 kilometres annually, this price differential translates into annual fuel savings of between US$12,000 and US$18,000, depending on vehicle efficiency and local fuel costs. Beyond cost savings, sustainable biofuels also deliver significant environmental benefits—achieving up to 90% lower lifecycle greenhouse gas emissions compared to conventional diesel (International Renewable Energy Agency [IRENA], 2023). In African nations, where agriculture is a major economic sector, the production of biofuels from crops such as sugarcane, cassava, and oil palm offers added socio-economic advantages. Local biofuel industries can enhance energy security by reducing reliance on imported petroleum products while creating rural employment opportunities in feedstock cultivation, processing, and distribution. This synergy of economic and environmental benefits positions biofuels as a strategic bridge technology for the continent's low-carbon transport future.

### E-Fuels and Synthetic Alternatives

E-fuels, or synthetic fuels, are produced using renewable electricity to create hydrogen (via electrolysis) which is then combined with captured $CO_2$ to produce hydrocarbons such as methanol, ammonia, or synthetic diesel. These fuels can be used in existing ICEs, ships, and aircraft with minimal infrastructure modification (IEA, 2023).

In developed economies, Germany and Japan have taken leadership in e-fuel research, with demonstration plants producing synthetic kerosene for aviation (German Aerospace Centre [DLR], 2022). Chile's *Haru Oni* project, developed by Siemens Energy and Porsche, aims to produce e-methanol and e-gasoline using Patagonia's abundant wind power, providing a global model for low-carbon fuel export (Siemens Energy, 2023).

For developing economies, e-fuels offer potential as an export-oriented decarbonisation strategy where renewable resources are abundant but local demand is limited. However, high production costs currently over $3–5 per litre of gasoline equivalent remain a major barrier (IEA, 2023). Reducing electrolyzer and carbon capture costs through innovation and scale-up will be essential to competitiveness.

Decarbonising heavy transport and long-distance mobility requires a portfolio of solutions rather than a single technology. Hydrogen fuel cells, e-trucks, e-highways, sustainable biofuels, and e-fuels each play complementary roles depending on regional infrastructure, energy resources, and industrial capability. Developed economies are leading innovation and large-scale demonstration projects, while developing economies are beginning to adapt these models to local contexts, often leveraging renewable resource potential and international cooperation. Overcoming challenges related to cost, infrastructure, and policy alignment will be central to achieving a low-carbon freight and mobility system globally.

### Cost and Savings

E-fuels synthetic fuels produced by combining renewable hydrogen (via electrolysis) with captured carbon dioxide ($CO_2$) are rapidly emerging as a key pathway to decarbonising hard-to-electrify sectors such as aviation, shipping, and heavy industry. These fuels are chemically similar to conventional petroleum-based fuels, meaning they can be used in existing engines, pipelines, and refuelling infrastructure without major modification. Companies such as Porsche eFuels in Chile, HIF Global, and Airbus are at the forefront of developing large-scale e-fuel production facilities that integrate renewable energy sources like wind and solar for hydrogen generation (International Energy Agency [IEA], 2024).

Currently, e-fuels cost between US$4 and US$6 per litre, driven largely by the high cost of green hydrogen and the energy intensity of the synthesis process. However, technological advancements, economies of scale, and declining renewable electricity costs are expected to reduce prices to around US$1.50 per litre by 2035 (IEA, 2024). While this remains higher than the current marine fuel price of roughly US$0.90 per litre, e-fuels offer an economic advantage through carbon cost avoidance. As global carbon pricing becomes more widespread, shipping and aviation operators face penalties of US$200–300 per tonne of $CO_2$, equivalent to US$25,000–40,000 per ship annually in avoided carbon liabilities when using e-fuels instead of fossil fuels.

Beyond compliance, adopting e-fuels also improves brand reputation, ensures regulatory readiness, and supports sustainability commitments under international frameworks like the

International Maritime Organization's decarbonisation targets and ICAO's CORSIA framework. Thus, while e-fuels are still in their cost reduction phase, they represent a strategically valuable investment in the long-term competitiveness and resilience of global transport systems.

### Shipping & Aviation Strategies for Decarbonization

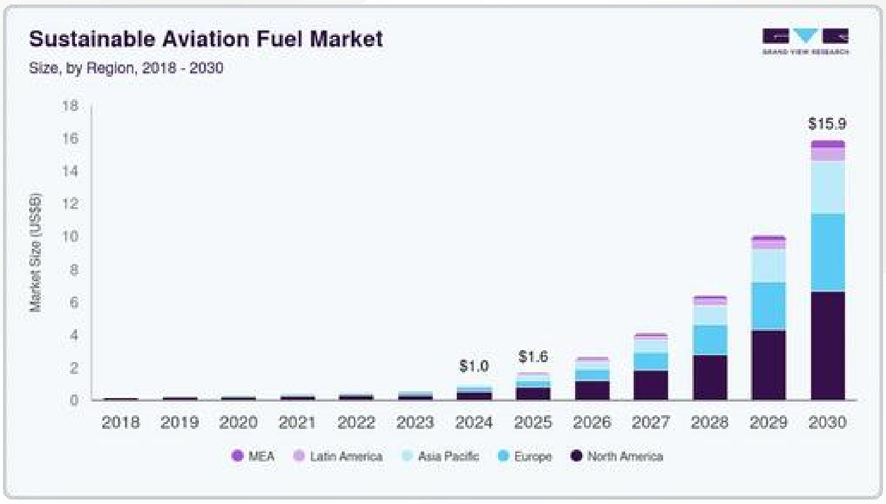
Shipping and aviation are among the hardest sectors to decarbonize because of their dependence on high energy-density fuels, long operating ranges, intermittent refuelling options, and existing infrastructure designed around conventional fossil fuels. Yet they also represent significant and growing portions of global greenhouse gas emissions. As such, decarbonization strategies in these sectors are multi-pronged, involving operational efficiencies, alternative fuels (biofuels, sustainable aviation fuels, e-fuels, ammonia, hydrogen), technological innovation, and policy regulation. Below is a detailed overview of major strategies, challenges, and illustrative cases.

### Key Strategies in Aviation

#### Sustainable Aviation Fuels (SAF) & Synthetic Fuels

Sustainable Aviation Fuels are drop-in or nearly drop-in replacements for conventional jet kerosene, produced using feedstocks such as waste oils and fats, agricultural residues, non-food crops, and synthetic processes that combine captured $CO_2$ and green hydrogen. SAF reduces lifecycle $CO_2$ emissions by up to ~80% compared with fossil jet fuel (IATA, n.d.; IATA, 2024). A recent report by DNV projects SAF to account for about 12% of global aviation energy demand by 2050 under current growth and policy trajectories, with synthetic e-fuels and hydrogen-based fuels gaining traction in the 2030s (DNV, 2024).

When we talk about SAF today, we're really at an inflection point the market is still small in absolute size, but the momentum behind it and the growth forecasts are eye-opening. Globally, the SAF market is widely estimated in the range of USD 1.3 to 1.7 billion in 2024. For example, Grand View Research (2025) USD 1.04 billion in 2024, projecting dramatic growth by 2030. Precedence Research puts it at USD 1.43 billion in 2024, expecting it to reach around USD 134.6 billion by 2034, growing at ~57.5% CAGR. Other forecasts are even more ambitious: some see USD 196–197 billion by 2034.




By 2025, analysts expect values in the ballpark of USD 2.0–2.3 billion. A Biofuels Digest report projects USD 2.06 billion in 2025 (Tomas, 2025). These numbers underscore both the nascent scale and the aspirations. The disparity in forecasts also highlights the uncertainty in key variables: feedstock availability, policy support, capital costs, and offtake deals.

### Regional Patterns & Drivers

It's helpful to slice the market geographically, because policy regimes, airline behaviour, and industrial structure vary.

### North America / U.S.

The U.S. is one of the most active regions in SAF development, thanks in part to incentives under the Inflation Reduction Act and SAF-specific credits. In the U.S., World Energy and Neste are among the early commercial suppliers. Airlines and fuel producers are signing long-term supply deals to hedge risk. However, actual production remains constrained. In 2024, global SAF production hit about 1 million metric tons (~1.3 billion litres), doubling from the prior year but still only covering about 0.3–0.5% of global jet fuel demand (IATA, 2024). In many U.S. discussions, the challenge is competing with low-cost fossil jet fuel while managing feedstock and capital costs.

**Europe**Europe is pushing SAF hard, especially under EU mandates like ReFuelEU Aviation, which starts forcing minimum blending percentages (2% SAF in 2025) (). Neste, headquartered in Finland but with refining operations in Rotterdam, is a major SAF player in Europe. In 2025, Neste expanded SAF production capability to 1.5 million tons (≈1.875 billion litres annually) (Neste, 2025). Eni (Italy) also began producing 100% biogenic SAF in its Gela facility in 2025 and aims to scale further. Many European airlines like Air France-KLM have inked long-term SAF purchase agreements.

### Asia & Other Regions

Asia is emerging as a fast-growing region, though relative scale is still smaller. Countries with strong biofuel feedstock potential e.g. Southeast Asia, Indonesia, Malaysia are seen as potential exporters of SAF or feedstocks (Financial Content, 2025). In India, for example, companies are beginning to certify and produce SAF from used cooking oil (e.g. Panipat refinery). Africa and Latin America have lower SAF capacity to date but significant feedstock opportunity (agricultural waste, residues). Some forecasts see APAC and Africa as high-growth markets over time.

### Key Producers & Their Scale

When it comes to the global Sustainable Aviation Fuel (SAF) landscape, a handful of pioneering producers are shaping the pace of growth and technological advancement. Neste, headquartered in Finland, stands as the undisputed leader in SAF production. In 2025, the company expanded its capacity through its Rotterdam refinery, adding approximately 500,000 tons per year and bringing its total global SAF output to around 1.5 million tons annually. Neste's total corporate revenue in 2024 reached EUR 20.6 billion, although this figure includes its broader renewable and petroleum product lines rather than SAF-specific earnings (Neste, 2024). Its success lies not only in scale but also in its consistent partnerships with major airlines such as Singapore Airlines, Lufthansa, and Air France-KLM, demonstrating confidence in its long-term supply capabilities.

Another key player, Gevo, based in the United States, has made significant strides through its alcohol-to-jet (ATJ) technology. The company secured a 14-year agreement with United Airlines to supply 260 million gallons of SAF, one of the largest deals of its kind (Business Wire, 2025).

While Gevo's operations extend into other renewable fuels, the agreement underscores its importance in establishing commercial viability for SAF. LanzaJet, meanwhile, achieved a milestone in 2024 with the commissioning of Freedom Pines Fuels, the world's first commercial-scale ethanol-to-SAF facility in Georgia, USA. This plant marks a crucial step toward scaling low-carbon aviation fuel derived from bioethanol.

World Energy is another early entrant, maintaining an active presence in SAF production and collaborating with major carriers such as Singapore Airlines. Similarly, SkyNRG, though smaller in production capacity, has carved out a niche as a strategic influencer in the SAF ecosystem, producing market outlooks and fostering collaborations across Europe and North America. Eni, the Italian energy major, has transitioned part of its operations toward fully biogenic SAF production, beginning at its Gela refinery in 2025 and planning further expansions. The global oil giants Chevron, ExxonMobil, Shell, BP, and TotalEnergies are also heavily investing in SAF technology, leveraging their existing infrastructure and capital strength to scale up production. Despite these advances, none of these firms yet report standalone SAF revenues; the segment remains a small but fast-growing component of their overall energy portfolios.

### Major Adopters & Demand Pull

On the demand side, major airlines and logistics companies are the driving force behind SAF's commercial uptake. United Airlines has positioned itself as a frontrunner, signing multiple long-term offtake agreements, including a 260-million-gallon supply contract with Twelve, a company producing e-fuels from captured carbon. Air France-KLM, one of the world's earliest large-scale SAF users, entered a landmark agreement with TotalEnergies to secure up to 1.5 million tons of SAF through 2035, solidifying Europe's lead in sustainable aviation.

Other prominent adopters such as Delta Air Lines, American Airlines, Emirates, Virgin Atlantic, and Singapore Airlines are actively pursuing SAF integration through joint ventures and demonstration flights. These initiatives are not merely symbolic they signal to markets and investors that large-scale demand for low-carbon fuels is real and growing. Logistics leaders like DHL have also stepped in, partnering with IAG Cargo to deploy 60 million litres of SAF across 2024–2025, reinforcing the corporate logistics sector's commitment to decarbonization.

Beyond these leaders, several carriers including British Airways, KLM, JetBlue, Alaska Airlines, and Air Canada are participating in SAF blending programs or pilot projects to test large-scale feasibility. These agreements are not just about meeting sustainability targets they are critical financial instruments. By guaranteeing offtake volumes, airlines help de-risk multi-million-dollar SAF investments, ensuring producers have the financial stability to build and operate new facilities. This symbiotic relationship between producers and adopters illustrates how industry collaboration is accelerating SAF commercialization and making aviation's net-zero ambitions increasingly tangible.

### Hydrogen, Electrification, and Long-Term Aircraft Innovation

### The Emerging Hydrogen Aircraft Market

The global hydrogen aircraft sector represents one of the most promising frontiers in aviation's decarbonization journey. Estimated at USD 533.29 million in 2023, the market remains largely at the research and development (R&D) stage, with major players and startups alike pursuing hydrogen-based propulsion through either combustion engines or fuel cells (MarketsandMarkets, 2024). Hydrogen aircraft promise zero-emission flight, using hydrogen as a primary energy source that emits only water vapor when burned or used in fuel cells an innovation that could reshape the future of aviation. However, the technology faces significant challenges, including hydrogen storage, infrastructure development, and the high cost of green hydrogen production. Despite these hurdles, the industry's momentum is growing as leading aerospace manufacturers and clean-tech startups push hydrogen aviation toward commercial readiness.

### Airbus and the "ZEROe" Program

At the forefront of this transition is Airbus, headquartered in the Netherlands, which reported €58.76 billion in revenue in 2022 (Airbus, 2023). Airbus has taken a bold leadership role with its "ZEROe" concept, a suite of hydrogen-powered aircraft designs unveiled in 2020.

The project includes three primary models a turbofan, a turboprop, and a blended-wing body each engineered to demonstrate different pathways toward achieving net-zero flight by 2035. Airbus's investment extends beyond aircraft design to hydrogen infrastructure and fuel supply chains, recognizing that successful deployment depends on collaboration with airports, fuel producers, and governments to ensure global readiness.

Airbus has entered partnerships with energy companies such as Linde and Air Liquide to explore hydrogen logistics and fuelling systems at airports across Europe. The company is also coordinating with airport operators like VINCI Airports to pilot hydrogen refuelling technologies (Airbus, 2024). This holistic approach linking aircraft innovation to fuel infrastructure illustrates how Airbus is not merely building planes but constructing the ecosystem needed for a hydrogen-powered aviation era.

**Pioneering Startups: ZeroAvia, Universal Hydrogen, and H2FLY**

While Airbus dominates the large-scale vision, several startups are driving innovation at the technology level, focusing on retrofitting and modular systems to accelerate hydrogen adoption. Among the most notable is ZeroAvia, a U.S.-based startup developing hydrogen-electric powertrains for existing regional aircraft. The company has already conducted successful test flights using its ZA600 engine, which powers small aircraft like the Dornier 228 (ZeroAvia, 2024).

Though it does not yet generate revenue from aircraft sales, ZeroAvia has attracted significant venture capital and strategic investments from major airlines and industrial partners. Its funding exceeds USD 180 million, including investments from Alaska Airlines, United Airlines, American Airlines, and IAG (British Airways' parent company), signalling strong airline confidence in the technology's potential to meet future emission targets (Reuters, 2024).

Another major innovator is Universal Hydrogen, also based in the U.S., which focuses on developing hydrogen conversion kits for existing aircraft and a modular fuel logistics system that simplifies hydrogen delivery and storage. Its unique "hydrogen capsules" are designed to transport compressed hydrogen via standard freight systems, eliminating the need for costly airport infrastructure in the early stages of hydrogen adoption (Universal Hydrogen, 2024). The company has received backing from United Airlines and other investors and has begun flight testing a Dash 8 aircraft retrofitted with its hydrogen fuel system.


Universal Hydrogen Dash 8 aircraft

Germany's H2FLY represents another important player in Europe's hydrogen aviation R&D ecosystem. The company achieved a historic milestone by successfully flying the world's first piloted hydrogen-electric passenger aircraft, the HY4, in 2023 (H2FLY, 2023).


H2FLY

H2FLY's approach combines fuel-cell technology with advanced lightweight systems to maximize energy efficiency. The company collaborates with Deutsche Aircraft and has received EU and German government support to develop a 40-seat hydrogen-powered regional aircraft by 2028.

### Airline Investments and Early Adopters

The early adoption of hydrogen aviation is being catalysed by a wave of strategic airline investments that aim to secure technological advantage and future fuel supply. American Airlines has invested in ZeroAvia, signalling its commitment to hydrogen-electric propulsion as a long-term decarbonization strategy. Similarly, United Airlines has taken a dual-investment approach, supporting both ZeroAvia and Universal Hydrogen, thereby diversifying its exposure to competing hydrogen technologies (United Airlines, 2024). Alaska Airlines has partnered with ZeroAvia to retrofit regional aircraft in its fleet, while IAG, parent company of British Airways, has made equity investments in ZeroAvia to advance hydrogen aviation for its European routes (IAG, 2024).

European carriers such as Air France-KLM are also advancing hydrogen initiatives, albeit with a focus on the hydrogen supply chain rather than direct aircraft investment. Through partnerships with energy companies like TotalEnergies and participation in national hydrogen strategies, Air France-KLM is positioning itself within Europe's broader hydrogen infrastructure ecosystem (Air France-KLM, 2024). These collaborations are instrumental in ensuring that when hydrogen aircraft reach certification, a robust supply and distribution system will already be in place.

## Hydrogen's Path to Commercial Flight

Although the hydrogen aircraft market remains nascent, momentum is unmistakable. The involvement of Airbus gives the field industrial legitimacy, while startups like ZeroAvia, Universal Hydrogen, and H2FLY bring agility and technological experimentation. The financial engagement of airlines, combined with public-sector R&D funding from the EU and the U.S., suggests a gradual but steady path toward commercialization by the mid-2030s.

Hydrogen aircraft could fundamentally redefine regional and short-haul aviation, where the balance of range, payload, and fuel weight is most manageable. The ecosystem is still developing production costs for green hydrogen remain high, and certification pathways for hydrogen systems are complex but early evidence points toward rapid maturation. If successful, the sector could grow from its USD 533 million base in 2023 to a multi-billion-dollar industry by 2040, aligning aviation with global net-zero targets and ushering in a new era of sustainable, zero-emission flight.

Other strategies include hydrogen-fuelled aircraft (liquid hydrogen or hydrogen combustion), and in the longer term, zero-emission electric aircraft for short-haul routes. Hydrogen and fuel cells offer potential, especially for regional aircraft, although challenges remain around hydrogen storage, safety, and aircraft design changes.

Electrification (battery or hybrid-electric) is considered feasible for short regional hops; however, energy density limitations make full battery propulsion difficult for long-haul flights. Hence, aviation strategies typically see SAF and synthetic e-fuels as near- to mid-term solutions, with hydrogen and novel aircraft designs for longer term (post-2035-2040) deployment (DNV, 2024).

## Cost and Saving

Hydrogen aircraft, powered by combustion or fuel cell propulsion, represent one of the most promising solutions for long-haul and regional flights. Hydrogen offers three times the energy density of conventional jet fuel per kilogram, allowing for substantial performance advantages (Airbus, 2023). Major players such as Airbus (ZEROe), Boeing, and startups like ZeroAvia and Universal Hydrogen are already developing prototype aircraft, targeting commercial operations by the mid-2030s.

However, the cost of green hydrogen production—currently around US$4–6 per kilogram, compared to jet fuel's equivalent of US$0.80–1.00/kg—remains a major barrier. As renewable energy and electrolyser technologies advance, costs are projected to fall to US$1.50–2.00/kg by 2035 (IEA, 2024). Despite the high fuel cost today, hydrogen aircraft promise up to 25–30% lower lifecycle costs due to reduced maintenance, zero carbon taxes, and enhanced energy efficiency. Fuel cell systems have fewer moving parts than jet engines, which can cut maintenance costs by 40–50% over the aircraft's 25-year lifespan (McKinsey & Company, 2023). In terms of savings, a medium-range hydrogen aircraft flying 2,500 hours per year could save approximately US$600,000–800,000 annually in fuel and emission-related cost once hydrogen prices stabilize. For African nations investing in green hydrogen corridors—such as Namibia, Morocco, and South Africa—the regional production of hydrogen could significantly reduce import dependency, support clean aviation fuel exports, and create an estimated 200,000 jobs by 2040 (African Development Bank [AfDB], 2024).

### Electric Aircraft

The global electric aircraft market is valued at approximately $13.7 billion in 2025, reflecting a rapid acceleration in electrified aviation technologies and growing attention to sustainability within the aerospace industry. While much of this growth remains concentrated in prototypes and early-stage developments, the sector is being shaped by the twin forces of urban air mobility and regional decarbonization efforts. Governments and investors are increasingly channelling resources toward electric aviation, viewing it as a complementary pathway to hydrogen in achieving zero-emission flight (International Energy Agency [IEA], 2024). Electric aircraft leverage battery-electric or hybrid propulsion systems, enabling substantial reductions in carbon emissions and operational noise compared to conventional jet fuel-powered models. However, the market still faces challenges in battery energy density, certification standards, and large-scale commercialization (Roland Berger, 2024). Despite these barriers, the sector's funding trajectory and technological momentum underscore its critical role in reshaping the aviation landscape by the mid-2030s.

### Key Companies

### BETA Technologies

Several companies are at the forefront of developing electric vertical takeoff and landing (eVTOL) and electric conventional takeoff and landing (eCTOL) aircraft, representing the technological diversity within the emerging market. Among them, BETA Technologies (United States) stands out as a leading innovator in both eVTOL and eCTOL platforms. The company has conducted extensive test flights and raised substantial private capital to support development and certification.

BETA's flagship aircraft, the ALIA-250, aims to serve both cargo logistics and regional passenger transport markets, positioning the company as a future supplier of sustainable short-haul solutions (BETA Technologies, 2024).

### Archer Aviation

Similarly, Archer Aviation (United States) is developing eVTOL aircraft for urban air mobility (UAM) applications. Archer has entered into strategic partnerships and pre-order agreements with major airlines and logistics firms, signalling strong market confidence in the viability of electric air transport for congested metropolitan corridors.


The company's *Midnight* aircraft has been designed for short-range, high-frequency operations, and its collaborations with United Airlines and Stellantis highlight the growing intersection between aviation, automotive, and energy sectors (Archer Aviation, 2024).

### Leo Flight Corporation

Another example of electric flight innovation is Leo Flight Corporation, a U.S.-based aerospace startup developing the Leo Coupe, a two-seat electric vertical take-off and landing (eVTOL) aircraft designed for both personal and shared urban transportation. The Leo Coupe is envisioned as a futuristic "flying car," combining the agility of a helicopter with the efficiency and environmental benefits of electric propulsion. Since it can take off and land vertically, it removes the need for traditional runways, making it ideal for dense urban areas with limited space.

Fully powered by electric motors, the Leo Coupe offers zero-emission flight, contributing to global sustainability and clean mobility goals. Beyond its technical design, Leo Flight aims to democratize urban air mobility by creating an aircraft that is compact, cost-effective, and easy to operate. Its sleek design and versatile use cases ranging from personal air travel to air taxi services and emergency response reflect the company's broader mission to redefine electric aviation.

### Joby Aviation

Joby Aviation (United States) represents one of the most advanced developers in the field, having received a Part 135 Air Carrier Certificate from the U.S. Federal Aviation Administration (FAA) in 2022 an essential step toward commercial operations (Joby Aviation, 2023).

Joby's aircraft is designed to carry four passengers plus a pilot over approximately 150 miles on a single charge, catering to urban and regional mobility markets. Its progress toward certification and operational readiness has made it a benchmark for the broader eVTOL industry.

### Lilium

In Europe, Lilium (Germany) is developing a seven-seater electric jet optimized for regional air mobility. Unlike rotor-based eVTOLs, Lilium's ducted fan design offers higher cruise efficiency, making it suitable for short regional routes.

The company's modular architecture and partnerships with key infrastructure and energy providers reinforce its commitment to scalability and sustainability (Lilium, 2024). Meanwhile, Heart Aerospace (Sweden) focuses on the **ES-30**, a hybrid-electric regional airliner designed for 30 passengers. The company's approach blends conventional flight range with electric propulsion efficiency, appealing to regional carriers seeking lower-emission alternatives. Heart Aerospace's investments from **United Airlines** and **Mesa Air Group** underscore the growing commercial viability of electric regional aviation (Heart Aerospace, 2024).

### Major Adopters

On the demand side, airlines are increasingly positioning themselves as early adopters and investors, using strategic partnerships to influence technological pathways. United Airlines has invested in Heart Aerospace, aligning with its broader goal to reach net-zero carbon emissions by 2050. United's participation in electric aircraft development reflects its commitment to pioneering sustainable short-haul operations and building supply chain capacity for next-generation propulsion systems (United Airlines, 2024).

American Airlines has similarly invested in Vertical Aerospace, another eVTOL developer, indicating its belief in the future of urban and intra-city air mobility. Vertical Aerospace's VX4 aircraft is envisioned as a clean, efficient transport option for short-range commuter markets (American Airlines, 2023). Delta Air Lines has entered into a partnership with Joby Aviation, with plans to integrate eVTOL services into airport-to-city transfer operations creating a new multimodal travel experience for passengers (Delta Air Lines, 2023). Republic Airways, through its investment in Eve Air Mobility, also seeks to explore electrified regional operations, emphasizing sustainability and innovation within its service portfolio (Eve Air Mobility, 2024).

Collectively, these early investments and strategic alliances are not merely financial; they form a demand signal that supports regulatory acceptance, infrastructure development, and manufacturing scale-up. As airlines and mobility firms engage directly with developers, they help shape the ecosystem that will define the commercialization of electric aviation.

### Cost and Savings

Electric aircraft, powered entirely or partially by battery-electric systems, are redefining short-haul and regional aviation economics. Companies such as Heart Aerospace, Eviation (Alice), Pipistrel, and Rolls-Royce Electrical are developing aircraft capable of carrying 9–30 passengers for distances up to 500 km. While the capital cost of electric aircraft is currently 15–25% higher than comparable turboprop planes due to expensive battery systems, their operating costs are significantly lower (BloombergNEF, 2024).

Electric propulsion systems achieve energy efficiency levels exceeding 85%, compared to 35% for jet fuel combustion engines. With electricity costs averaging US$0.10–0.15 per kWh, versus US$0.80–1.00 per litre for aviation fuel, operators can achieve fuel savings of 70–80% per flight. Over ten years, this translates into US$2–3 million in savings per aircraft, depending on utilization and route length (IATA, 2024). Maintenance costs are also reduced by 50–60%, as electric systems eliminate complex gearboxes, oil systems, and turbine components.

For regional routes under 500 km common across Africa's fragmented aviation network electric aircraft can lower cost per seat-kilometre by 40–50%, improving route viability and access to underserved destinations. Furthermore, pairing electric aviation with renewable energy sources, such as solar-powered airports in Kenya or Morocco, can drive near-zero operational emissions, enhancing both economic and environmental sustainability. Although battery energy density remains a key limitation for long-distance electric flight, ongoing advancements in solid-state batteries and hybrid-electric architectures could extend aircraft range and reduce costs by another 30% by 2035 (IEA, 2024). Thus, while hydrogen is better suited for long-haul aircraft, electric propulsion offers immediate, scalable savings in regional aviation particularly for African markets seeking affordable, sustainable air mobility.

### Key Strategies in Shipping

#### Alternate Fuels: Ammonia, Methanol, Hydrogen & Biofuels

For shipping, the leading alternative fuel pathways include use of low-sulphur biofuels, LNG in some transitional applications, methanol, ammonia, hydrogen, and synthetic "green" fuels. Ammonia and methanol are particularly promising for larger vessels due to their higher energy density relative to hydrogen (on a volumetric basis) and the possibility of retrofitting certain engines or using dual-fuel systems (DNV, 2024). The International Maritime Organization (IMO) has set an Initial GHG Strategy aiming to reduce emissions intensity by 40% by 2030, and overall GHG emissions by at least 50% by 2050 compared to 2008 levels. It envisages that fuel switching (to ammonia, hydrogen, or biofuel), energy efficiency measures, and possibly carbon capture will be needed to meet those long-term goals (IMO Strategy, 2018).

### Ammonia in Maritime Decarbonization

As the shipping industry pursues deep decarbonization, ammonia has emerged as one of the most promising zero-carbon fuels provided it is produced sustainably (i.e. "green ammonia" from renewable hydrogen). What makes ammonia compelling is that it contains no carbon, meaning that when combusted or used in a fuel cell, its direct emissions do not include $CO_2$ (barring upstream production emissions) (ScienceDirect, 2024). That said, deploying ammonia in marine use requires innovations across vessel design, engines, bunkering infrastructure, and regulatory safety frameworks.

### Adopters and Vessel Operators

Leading shipping lines are now placing bets on ammonia-fuelled vessels to show leadership and align with future regulatory regimes. Trafigura, for example, recently shipped low-carbon ammonia from Louisiana to Europe showing its commitment to building ammonia supply chains for maritime use (Trafigura, 2025). The same company has also signed contracts for four medium-size gas carriers (MGCs) equipped with dual-fuel ammonia-capable engines, to be built at Hyundai Mipo Dockyard in South Korea, with delivery beginning in 2027–2028 (Trafigura, 2025).

Other shipping operators such as K Line and MISC (Malaysia International Shipping Corporation) also appear in strategic plans pushing toward ammonia use. For instance, MISC has ordered dual-fuel ammonia Aframax vessels under chartering arrangements (Reuters, 2024). MOL Coastal Shipping (a division of Mitsui O.S.K. Lines) is collaborating on a coastal ammonia carrier, and MOL more broadly is conducting ammonia ship-to-ship transfers and exploring ammonia-fuelled bulk carriers (Reuters, 2024). The role of adopters is pivotal: by committing to ammonia-capable vessels and operations, fleets help de-risk the demand side of the ammonia marine fuel value chain. These commitments are not just symbolic but critical to financing future plants and retrofits.

### Engine Manufacturers & Technology Providers

The heart of deploying ammonia in shipping lies in engines capable of burning ammonia either as dual-fuel (ammonia + pilot fuel) or in dedicated ammonia combustion.

**MAN Energy Solutions** is among the leaders. It has developed a two-stroke, dual-fuel ammonia engine (the ME-LGIA) designed for marine propulsion, targeting retrofits of existing two-stroke engines or integration in newbuilds (Everllence, 2025). In January 2025, MAN announced that its full-scale ammonia engine was running at 100 % load in testing (Everllence, 2025). They also plan to deliver the first pilot engine to a shipyard in early 2026, potentially for Eastern Pacific Shipping’s vessels. Beyond two-stroke, MAN has also launched the AmmoniaMot 2 project to develop a four-stroke, medium-speed dual-fuel ammonia test engine (Everllence, 2025).

**Wärtsilä** is another key player. Its Wärtsilä 25 Ammonia engine is the first 4-stroke solution for ammonia fuel commercially offered to the marine sector (Wärtsilä, 2025). Extensive testing has demonstrated up to 90 % greenhouse gas reductions when using high shares of ammonia (e.g. 95 %) relative to conventional marine fuels, considering “well-to-wake” metrics. Also, Wärtsilä’s Ammonia Fuel Supply System (AFSS) handles storage, conditioning, bunkering, and delivery of ammonia to engines, supporting both liquid and gaseous ammonia modes (Wärtsilä, 2025). Wärtsilä is also contracted to supply ammonia fuel systems and bunkering technology to EXMAR’s six dual-fuel vessels under construction in South Korea.

Other engine and system players in this space include Caterpillar Marine and Yanmar, which are developing engine modules or retrofits to handle ammonia or ammonia blends (though publicly less visible). Their involvement is essential to broaden technology options, particularly for smaller vessels or auxiliary engines.

### Shipbuilders & Vessel Construction

Designing and building ships capable of safely handling ammonia requires shipbuilders to integrate ammonia tanks, piping, safety systems, and dual-fuel ngines.

Hyundai Mipo Dockyard (South Korea) is a prominent example: it has secured contracts to build ammonia dual-fuel vessels, such as the Trafigura MGCs noted above (World Economic Forum, 2024). The Korean shipbuilding complex is central to Asia's decarbonizing shipping ambitions. Dalian Shipbuilding Industry Company (China) is another major shipyard involved in contracts to build dual-fuel or ammonia-ready vessels, including Aframax vessels for MISC (Reuters, 2024).

These shipbuilders must incorporate robust safety features such as double-walled piping, ammonia containment, ventilation, sensors, scrubbers or catalysts for $NO_x$ and ammonia slip, and bunkering interfaces into the design. Integration of engines, fuel systems, and shipboard control systems is a complex engineering task, but essential for ammonia adoption at scale.

**Fuel Suppliers & Bunkering Infrastructure**

For ammonia to function as a marine fuel, bunkering supply chains must evolve rapidly. ITOCHU, a Japanese trading house, is one of the firms working to establish ammonia bunkering hubs and supply infrastructure. For instance, ITOCHU has partnered in planned ammonia bunkering development in Spain (Algeciras) via cooperation with Peninsula Petroleum.

Trafigura itself is also playing a fuel-supplier role having shipped certified low-carbon ammonia cargoes and executing **ship-to-ship ammonia transfers** to demonstrate the operational viability of future maritime bunkering. In January 2025, Trafigura completed a co-loaded ammonia-propane shipment, emphasizing flexibility and bunkering readiness. Classification societies and regulators, such as **Lloyd's Register (LR)**, have already approved designs for Trafigura's ammonia dual-fuel newbuilds, marking a milestone in regulatory acceptance.

Ammonia-based shipping holds enormous promise as a pathway to decarbonization especially for long-range, deep-sea vessels that are difficult to electrify. The active involvement of shipping lines, engine makers, shipyards, and fuel suppliers shows a coordinated push across the value chain. However, challenges remain significant: ammonia is toxic and corrosive, requiring strict safety systems; $NO_x$ formation and ammonia slip must be controlled with catalysis; the cost of green ammonia must fall; retrofits are complex; and global bunkering networks must scale. But the early signs are promising: first ship-to-ship transfers, contracted ammonia dual-fuel ships, and full-scale engine tests all indicate that ammonia as a marine fuel is moving from vision to reality.

## Cost and Saving

Ammonia ($NH_3$) is emerging as a frontrunner for deep-sea decarbonization because it contains no carbon, meaning that when produced from renewable energy ("green ammonia"), it emits zero $CO_2$ during combustion. Currently, the cost of green ammonia ranges between US$800–1,200 per tonne, compared to US$600–700 per tonne for marine gas oil (MGO) (IEA, 2024). However, as electrolyser efficiency improves and renewable capacity expands, production costs could fall to US$400–500 per tonne by 2035, making ammonia cost-competitive with fossil fuels (McKinsey, 2023).

A typical large container ship consuming 30,000 tonnes of fuel annually would initially face about US$9–12 million in higher annual fuel costs, but these costs would decline over time as technology matures and carbon pricing penalizes conventional fuels. With expected carbon levies of US$200–300 per tonne of $CO_2$, switching to ammonia could yield annual savings of US$6–9 million in avoided carbon costs alone (Lloyd's Register, 2023). Additionally, engine and maintenance savings of 10–15% are expected, as ammonia combustion produces fewer soot and carbon deposits compared to HFO. For African ports such as Lagos, Durban, and Walvis Bay, early investment in ammonia bunkering hubs could stimulate regional green trade and attract foreign vessels seeking zero-emission refuelling options.

## Methanol as a Marine Fuel

The maritime industry's transition toward cleaner propulsion has placed methanol at the forefront of alternative fuels due to its versatility, scalability, and lower carbon footprint compared to conventional marine fuels. Unlike ammonia or hydrogen, methanol can be stored and transported under ambient conditions, making it more compatible with existing port infrastructure and bunkering systems (Methanol Institute, 2023). As shipping companies seek to comply with the International Maritime Organization's (IMO) decarbonization goals cutting greenhouse gas emissions by 50% by 2050 methanol is emerging as a practical bridge fuel toward net-zero operations.

## Shipping Lines

A.P. Moller-Maersk has taken the lead in methanol adoption among global shipping lines. By 2023, the company reported that approximately 3% of its cargo shipments were powered by green fuels, primarily biofuel blends and new methanol-fuelled vessels (Maersk, 2024). The

Danish shipping giant began integrating methanol-capable vessels into its fleet as part of a broader decarbonization strategy targeting net-zero emissions by 2040. By late 2024, Maersk had six operational methanol-powered container vessels and numerous others on order, with the first dual-fuel container ship launched in 2023 signalling the start of large-scale commercial adoption (Clarksons Research, 2024).

Mitsui O.S.K. Lines (MOL) has also recognized methanol's strategic role in sustainable shipping. The Japanese conglomerate invested in HIF Global, a leading e-fuels producer, to secure a long-term supply of green methanol derived from renewable energy sources (HIF Global, 2024). This investment positions MOL to diversify its fuel mix and reduce exposure to carbon-intensive fuels. Collectively, these early adopters illustrate how shipping lines are integrating methanol into their decarbonization portfolios, balancing environmental compliance with economic viability.

### Engine Manufacturers

Methanol's growing appeal has spurred major engine manufacturers to develop compatible technologies. MAN Energy Solutions, one of the most active players, has commercialized the *ME-LGIM* dual-fuel engine capable of operating on methanol or conventional marine fuels (MAN Energy Solutions, 2024). This adaptability allows fleet operators to switch fuels based on availability and cost while maintaining regulatory compliance. Wärtsilä and Caterpillar Marine are also developing methanol-capable engines for both newbuilds and retrofits, expanding the technology's reach beyond container ships to include ferries, tankers, and offshore vessels.

The rollout of methanol engines aligns with the global effort to standardize green propulsion technologies, ensuring shipowners can transition without sacrificing operational reliability. The adaptability of methanol engines, combined with methanol's relatively straightforward handling compared to hydrogen or ammonia, makes it a key transitional fuel for maritime decarbonization.

### Shipbuilders

The demand for methanol-capable ships has catalysed innovation among global shipbuilders. HD Hyundai Heavy Industries and Samsung Heavy Industries, both based in South Korea, have emerged as industry leaders in designing and constructing methanol dual-fuel vessels (Lloyd's Register, 2024). Their designs feature optimized storage and fuel systems to handle methanol's specific combustion properties and safety requirements.

These shipyards are not only building new dual-fuel vessels but also exploring retrofit programs that convert existing diesel ships into methanol-compatible units. Retrofitting represents a cost-effective pathway for shipowners seeking to reduce emissions without investing in entirely new fleets. As a result, methanol-capable shipbuilding has become a competitive niche, with Asian and European yards racing to capture the growing green fleet market.

### Fuel Suppliers

The scalability of methanol adoption depends heavily on reliable fuel supply. Companies such as Liquid Wind are playing a pivotal role by developing *e-methanol* production facilities powered by renewable electricity and captured carbon dioxide. These facilities transform renewable energy into liquid fuels suitable for the shipping sector, providing a circular carbon solution (Liquid Wind, 2024).

In addition to Liquid Wind, several energy firms and port authorities are establishing green methanol bunkering hubs in key maritime corridors such as Northern Europe, Singapore, and the U.S. Gulf Coast. These initiatives aim to create a stable global supply chain capable of supporting long-distance methanol-fuelled voyages.

From a financial perspective, methanol adoption has begun to register in company performance metrics. While Maersk does not disclose revenue attributable specifically to methanol, its green fuel initiatives including methanol contributed to its $15.8 billion total revenue in Q3 2024 (Maersk, 2024). MOL, which invested heavily in HIF Global to secure methanol supplies, reported revenue of 435.9 billion yen (approximately $2.79 billion) in Q1 2024, reflecting steady returns amid its transition to low-carbon operations (MOL, 2024).

According to the Methanol Institute (2023), the average price of e-methanol stood at approximately $1,700 per ton, reflecting its premium over conventional methanol but highlighting cost-reduction potential as production scales. As economies of scale and renewable energy integration advance, costs are expected to fall, accelerating widespread adoption across the maritime sector.

### Cost and Savings

Methanol ($CH_3OH$) is currently one of the most commercially viable alternative marine fuels, with more than 250 methanol-powered vessels either in operation or on order (DNV, 2024). Green methanol produced from biomass or renewable hydrogen and captured $CO_2$ costs

US$900–1,200 per tonne, higher than conventional marine fuel, but conversion costs for existing engines are relatively low (US$1–3 million per ship), making it an attractive transitional fuel (IEA, 2024).

Fuel savings arise primarily from carbon credit avoidance and regulatory incentives. As carbon prices increase, methanol users could save US$2–4 million per ship annually compared to vessels still reliant on fossil fuels (McKinsey, 2023). Moreover, methanol's simpler storage and handling requirements being a liquid at ambient temperature significantly reduce infrastructure costs compared to hydrogen or ammonia. For African shipping routes, methanol offers an accessible entry point, as it can be produced locally from agricultural waste or natural gas reforming, helping countries like Nigeria and Egypt leverage existing feedstocks while cutting emissions by up to 70–90%.

### Hydrogen as a Marine Fuel

Hydrogen is increasingly emerging as a cornerstone of zero-emission strategies in the maritime sector. Its appeal lies in its potential to eliminate greenhouse gas emissions entirely at the point of use, offering a scalable pathway to meet the International Maritime Organization's (IMO) 2050 decarbonization targets. Hydrogen can be used in combustion engines or fuel cells, providing flexibility across different vessel types. However, the adoption of hydrogen as a marine fuel remains in its early stages, primarily limited to pilot projects and demonstration vessels. Among the pioneers, Norway stands out as a leader in integrating hydrogen technologies into its ferry and coastal shipping operations, setting global precedents for clean maritime transport (DNV, 2024).

### Shipping Lines

Norled AS, a Norwegian ferry operator, made maritime history by launching the world's first liquid hydrogen-powered vessel, the *MF Hydra*, in 2023. This landmark achievement positioned Norway at the forefront of green maritime innovation (Norled, 2024). The *MF Hydra* represents a significant milestone in clean propulsion, capable of operating on liquid hydrogen stored in cryogenic tanks and converted into electricity through fuel cells. The ferry, which operates in western Norway, demonstrates how hydrogen can power short-sea and inland waterway routes efficiently while achieving zero emissions.

Norled's adoption of hydrogen stems from Norway's broader governmental push for sustainable maritime transport, supported by Enova SF a Norwegian government agency funding clean energy technologies. The *MF Hydra* has since become a model project that other European and Asian ferry operators are studying as they assess the feasibility of hydrogen in their fleets. Its successful operation underscores hydrogen's promise in replacing diesel or liquefied natural gas (LNG) on routes where refuelling infrastructure can be centralized and managed efficiently.

### Engine Manufacturers and Developers

The *MF Hydra* project exemplifies how multiple technology providers collaborate to make hydrogen propulsion viable. Ballard Power Systems, a Canadian clean energy company, supplied the proton exchange membrane (PEM) fuel cells that convert hydrogen into electricity to drive the ferry's propulsion system (Ballard Power Systems, 2025). Ballard has long been an innovator in hydrogen fuel cell technologies across buses, trucks, and trains, and its expansion into maritime applications marks a crucial diversification of its product base.

Other engine manufacturers are following suit. Yanmar, Cummins, Kawasaki Heavy Industries, and Japan's Uyeno Group are actively developing hydrogen combustion and hybrid systems for marine propulsion (Kawasaki Heavy Industries, 2024). These companies are experimenting with dual-fuel and fuel-cell systems, targeting both new builds and retrofits for coastal and inland shipping. Cummins, for example, is developing modular hydrogen fuel cell systems suitable for ferry and tugboat applications, while Kawasaki is investing in hydrogen liquefaction and storage infrastructure, recognizing the fuel's potential role in future marine logistics.

These technological advances highlight a key theme: hydrogen propulsion is still evolving, with a strong focus on integrating safety, efficiency, and scalability. The lack of global bunkering infrastructure remains a constraint, but as demonstration projects succeed, investment in hydrogen-ready ports and refuelling networks is accelerating.

### Collaborators and Project Networks

Hydrogen maritime projects tend to rely on broad multi-stakeholder collaborations, as the *MF Hydra* initiative demonstrates. The project involved Ballard Power Systems (fuel cell supplier), Norled (operator), SEAM (integrator), LMG Marin (naval architect), Westcon Yards (shipbuilder), and Linde (hydrogen supplier) (Linde, 2024). This consortium approach was essential to solving the engineering and safety challenges of operating liquid hydrogen at sea. LMG Marin designed the ferry's unique propulsion layout, while SEAM coordinated the integration of power, control, and safety systems.

The collaboration also benefited from public funding and regulatory support from Norway's maritime authorities, which have been instrumental in creating standards for hydrogen safety at sea. These cooperative frameworks are increasingly being replicated in Europe and Asia, where hydrogen ferries and pilot vessels are now being planned for commercial routes. Such partnerships highlight how the hydrogen value chain spanning production, storage, distribution, and end-use requires coordination across multiple industrial actors to achieve technical and economic viability.

### Revenue Data and Market Outlook

While hydrogen shipping projects are still in their infancy, they represent a rapidly developing niche within the global maritime energy transition. Ballard Power Systems, for instance, does not disaggregate revenue by sector, but its fuel cell business which includes marine applications reported $14.1 million in revenue in Q2 2025 (Ballard Power Systems, 2025). These figures underline the early-stage nature of hydrogen propulsion technologies, where near-term profitability is secondary to long-term technological leadership.

### Cost and Savings

Hydrogen-powered vessels are gaining momentum for short-sea and coastal operations due to their zero direct $CO_2$ emissions and high efficiency in fuel-cell propulsion systems. Currently, green hydrogen costs around US$5–7 per kilogram, translating to US$150–200 per MWh, compared to about US$70/MWh for marine fuel oil (IEA, 2024). However, with scaling and renewable deployment, hydrogen could reach US$1.50–2.00/kg by 2035, cutting fuel costs by more than 60%.

A 1,000-TEU vessel operating 5,000 hours annually could reduce its annual fuel expenditure from roughly US$10 million to US$4 million once hydrogen prices stabilize (Lloyd's Register, 2023). Maintenance costs could also fall by 40% due to the simpler mechanics of fuel cells. In Africa, where nations such as Namibia, Morocco, and South Africa are investing heavily in green hydrogen export projects, the maritime sector can benefit from local hydrogen production, improving energy security and reducing dependence on imported fossil fuels.

## Biofuels in the Maritime Sector

### Shipping Lines: Adopters and Users of Marine Biofuels

The maritime industry's growing adoption of biofuels is a critical step toward decarbonizing shipping operations, and several major lines are leading this transition. Samskip, a Dutch logistics and shipping company, has been a notable adopter of sustainable marine biofuels, incorporating biofuel blends into its container vessels to reduce lifecycle emissions without modifying existing engines (Samskip, 2024). Similarly, A.P. Moller–Maersk, one of the largest shipping conglomerates globally, continues to power portions of its fleet using biofuel bunker blends. By 2023, approximately 3% of Maersk's total cargo shipments were powered by green fuels, including advanced biofuels derived from waste oils and biomass residues (Maersk, 2024). These efforts are aligned with Maersk's broader ambition to achieve net-zero greenhouse gas emissions by 2040, demonstrating how early integration of biofuels can serve as a bridge toward fully renewable propulsion systems.

Another major adopter, NYK Line, has integrated biofuel trials into its operational routes, reporting a 155% growth in biofuel-related revenue during the first half of 2025 (NYK Line, 2025). While exact financial figures were not disclosed, this expansion reflects both rising demand from customers seeking greener logistics and the increasing availability of sustainable biofuel supplies. Likewise, CMA CGM, which reported total revenue of $55.5 billion in 2024, has also expanded its low-carbon shipping options by combining liquefied natural gas (LNG) and biofuel use across its global fleet (CMA CGM, 2024).

### Engine Manufacturers: Technological Enablers of Biofuel Adoption

The successful deployment of marine biofuels depends not only on adoption by ship operators but also on technological innovation from engine manufacturers. Companies such as Wärtsilä, Hyundai Heavy Industries (HHI), and Mitsubishi Heavy Industries (MHI) have invested heavily in research and development of biofuel-compatible engines. Wärtsilä has conducted extensive trials using hydrotreated vegetable oil (HVO) and other second-generation biofuels in its marine engines, confirming that biofuels can serve as a “drop-in” solution requiring minimal technical modification (Wärtsilä, 2023). Hyundai Heavy Industries has also announced collaborations with global fuel suppliers to develop flexible fuel engine platforms that can run efficiently on biofuels, supporting South Korea’s maritime decarbonization strategy (HHI, 2024).

Mitsubishi Heavy Industries has pursued similar projects, emphasizing modular engine designs that can transition from conventional fuels to biofuel blends or even synthetic alternatives in the future (MHI, 2024). These advancements significantly lower the barrier to adoption by existing fleets, enabling shipowners to reduce emissions while avoiding the high costs of engine replacement or retrofitting.

### Fuel Suppliers: Building the Biofuel Value Chain

A key element driving this transformation is the emergence of specialized biofuel suppliers such as GoodFuels and the Biomass Technology Group (BTG). GoodFuels, based in the Netherlands, has positioned itself as a pioneer in sustainable marine biofuels by producing low-carbon fuels derived from waste feedstocks such as used cooking oil and agricultural residues. In partnership with BTG, the company announced a joint investment in a biorefinery project aimed at scaling production capacity for sustainable marine fuels (GoodFuels, 2024). This collaboration underscores the industry’s shift from small pilot projects to commercial-scale production, enhancing the availability of certified biofuels that meet the International Maritime Organization’s (IMO) decarbonization standards.

Other suppliers are entering the market, further expanding the global biofuel infrastructure. European ports such as Rotterdam and Antwerp have already established biofuel bunkering hubs, facilitating direct refueling for shipping lines operating across regional and intercontinental routes (BTG, 2024).

### Revenue and Market Dynamics

While specific biofuel revenue reporting remains limited due to the nascency of the market, available data indicate substantial growth potential. NYK Line’s 155% increase in biofuel-related revenue during 2025 highlights rising commercial momentum, while major players like Maersk and CMA CGM incorporate biofuel costs and credits within broader sustainability strategies (NYK Line, 2025; Maersk, 2024). GoodFuels’ partnership with BTG represents a move toward vertical integration, which could eventually translate into stronger profit margins as economies of scale lower production costs.

Globally, biofuels are considered one of the most immediately scalable alternatives for maritime decarbonization because they can be blended with conventional marine fuels without extensive retrofitting. Although challenges remain including high feedstock costs and limited global availability the consistent growth of supply partnerships and the entry of major fuel suppliers suggest a maturing market that will continue to expand in the near term.

### Cost and Savings

Sustainable biofuels, including biodiesel, hydrotreated vegetable oil (HVO), and bio-methanol, offer an immediate drop-in solution for existing ships with minimal engine modifications. Currently, biofuels cost US$1.10–1.40 per litre, slightly higher than marine diesel (~US$0.90/litre), but lifecycle emissions are 70–90% lower (BP, 2024). For a medium-sized vessel consuming 20 million litres annually, switching to biofuel could yield carbon penalty savings of US$3–5 million per year, assuming carbon prices of US$200–250 per tonne of $CO_2$.

In Africa, biofuels provide a dual economic and environmental advantage. Countries such as Nigeria, Kenya, and Ghana possess abundant biomass and agricultural residues (e.g., cassava waste, palm kernel shells, sugarcane bagasse) that can be converted into biofuels. Local production can save up to 20–25% in logistics costs and generate rural employment, aligning maritime decarbonization with economic development. Over a 15-year vessel lifecycle, operators can expect total cost savings of 10–15%, particularly when factoring in future carbon taxes and fuel import reductions (IEA, 2024).

In all, the electrification of transport and deployment of low-carbon mobility solutions are central to the decarbonisation agenda they reduce fossil fuel dependency, slash emissions, and generate measurable cost savings. Globally, light-duty electric vehicles (EVs) are becoming mainstream: about 17 million EVs were sold in 2024, representing around 20 % of global passenger vehicle sales. As these vehicles replace internal combustion engine (ICE) cars, they offer direct carbon savings for example, in 2022 EVs enabled roughly 80 Mt $CO_2$-eq of net avoided emissions, with projections reaching nearly 700 Mt by 2030 under stated policy scenarios. From a cost perspective, BEVs typically consume ~0.3 kWh per mile (~0.19 kWh/km), and assuming electricity at US$0.12/kWh versus diesel at US$0.80/gal and ~12 mpg, the fuel cost per mile for an electric van is approx. US$0.036 compared to US$0.067 for diesel, giving ~US$1,550 annual fuel savings per vehicle at 50,000 miles/year, without accounting for maintenance improvements. Extrapolate over larger fleets and the savings multiply substantially.

In heavy-duty freight and long-haul mobility, cost savings are also compelling. For example, battery-electric trucks with lower operating costs (fuel + maintenance) may achieve total savings of US$180,000–250,000 per truck over ten years, offsetting higher upfront cost. Particularly when electricity cost is low and diesel price high, the economics favour EVs. For fleets using managed charging and off-peak electricity, per-mile cost can drop from ~US$0.70 to ~US$0.26 per mile.

Regionally, adoption is accelerating in Asia (especially China) and Europe, while Africa is still early stage but presenting major opportunity. In Nigeria, for instance, the federal government approved contracts worth N151.9 billion (~US$100 million) for electric buses, tricycles and charging infrastructure in the Northeast in 2025. Lagos State and private firms are also targeting deployment of 12,000 electric buses, with estimated economic cost savings of US$2.6 billion for Lagos state's transport system. Practical cost comparisons in Nigeria show e-bus fleets can realise lower total cost of ownership: for example, a 10-year lifetime e-bus fleet study indicated savings up to US$44,200 annually in fuel + maintenance compared with diesel equivalents. At a more fleet-operator level, Nigeria's transport policy drives electrification, and early adopters of e-hailing or corporate fleets switching from petrol/diesel (petrol ~₦960/litre ~US$0.67) can save significantly per vehicle.

When aggregated, these savings become profound: fuel cost reductions of 60–70 % or more, maintenance cost reductions of 20–30 %, annual operational savings per light EV of US$2,000–4,000 or more, and fleet-level savings in the hundreds of thousands to millions of dollars regionally. As electric fleets scale, these cost shifts translate into not only cleaner air and lower emissions but also improved business viability and lower transport system costs. The Nigerian case shows what can be achieved even in emerging-market contexts when policy, infrastructure, and financing align. The result: by combining electrification, smart charging, fleet transformation and infrastructure rollout, transport decarbonisation is delivering both environmental benefit and robust economic returns.

Electrifying transport and advancing low-carbon mobility have already begun to redefine how societies move, proving that cleaner alternatives can outperform fossil-based systems in efficiency, cost, reliability, and environmental impact. What started with electric vehicles has now expanded into a global transformation touching every mode of transportation from battery-electric and hydrogen-powered cars, to fully electric buses and rail systems, to emerging low-carbon aviation technologies such as electric and hybrid aircraft, and even green-fuel innovations reshaping the future of shipping through ammonia, hydrogen, and advanced battery propulsion. Across road, air, and sea, the transport revolution is lowering emissions, reducing national fuel import burdens, improving air quality for millions, and driving new industrial value chains. The momentum is unmistakable: mobility is becoming smarter, quieter, cheaper to operate, more energy-secure, and significantly more climate-aligned, marking one of the most profound shifts in the global clean energy transition. Yet transport is only one part of the broader decarbonisation puzzle.

The next decisive leap lies in transforming the sectors that shape how we produce, build, and live. The upcoming section on Decarbonising Industry and Buildings examines how innovative technologies from green hydrogen and heat pumps to smart materials and energy-efficient design are reshaping heavy industry and the built environment. Together, they carry the potential to deliver some of the deepest and most lasting emissions reductions across the global economy.

# Section 4

# Decarbonising Industry, Buildings Sectors

## Decarbonising industry, and buildings

Decarbonisation of the global economy requires tackling relatively straightforward low-hanging fruit (electrifying buildings, switching light-duty transport to electricity) and the much tougher task of eliminating emissions in sectors where energy use and chemical processes are intrinsically carbon-intensive. Industry and long-distance transport together account for a very large share of global emissions: heavy industry (notably iron & steel, cement, and chemicals) alone contributes several billion tonnes of $CO_2$ per year as in 2022 these industries combine contributed a total of 6 billion tonnes (Gt) of (CO2), comparable in magnitude to road transport emissions, and shipping and aviation are among the fastest-growing transport emission sources if unchecked (). These sectors are often termed “hard-to-abate” because their emissions arise from (a) process chemistry ($CO_2$ released as an inherent by-product of the production reaction), (b) the need for very high temperatures, (c) requirements for high energy density fuels (long-range mobility), and (d) long asset lifetimes that risk locking in high emissions if early retirement or retrofit is uneconomic.

## Why some sectors are “hard to abate” — a typology of challenges

1. **Process emissions vs. energy emissions.** In many materials industries, $CO_2$ is emitted not just by burning fuel but by the chemical reactions that make the product. For example, calcining limestone to make cement releases $CO_2$ directly from the decomposition of $CaCO_3$; in conventional blast-furnace steelmaking, coke both provides heat and acts as a reducing agent, itself releasing $CO_2$. These process emissions cannot be eliminated by

simply decarbonising the energy input; they require alternative chemistry (e.g., hydrogen reduction), material substitution or carbon capture.

2. **High temperature and energy density requirements.** Some industrial processes require sustained temperatures well above the reach of conventional electric heating or heat pumps (e.g., 1,000°C+ for clinker production or smelting). The scale and continuity of heat demand make electrification technically and economically difficult in some applications; alternatives include direct-electrification (resistive or induction heating), plasma/process electrification, or fuels such as green hydrogen and bio-derived gases.
3. **Energy-dense, long-range transport fuels.** Aviation and deep-sea shipping demand fuels with high energy per unit mass/volume. Batteries are impractical for long-haul flights or very large vessels today because of weight and volumetric constraints; hence decarbonisation will likely rely on sustainable aviation fuels (SAF), synthetic e-fuels, ammonia, methanol, or hydrogen-based fuels each with its own scaling, cost and lifecycle challenges.
4. **Capital intensity and long asset lifetimes.** Industrial plants, ships, aircraft, and large pieces of process equipment have lifetimes measured in decades. Early investments in low-carbon alternatives are costly and risky; conversely, delaying action risks asset lock-in. This makes policy and financing critical to narrow investor risk and align private incentives with long-term climate goals.
5. **Scale and supply-chain constraints.** Transition pathways (hydrogen, CCUS, bioenergy, e-fuels) require enormous build-outs of upstream capacity electrolyzers, renewable power, $CO_2$ transport and storage, sustainable biomass supplies and new fuels infrastructure. Siting, permitting, and raw-material constraints (e.g., minerals for catalysts, construction metals) complicate rapid scale-up.

### What counts as "hard-to-abate" — the canonical sectors

While definitions vary across agencies, a consistent list emerges in major roadmaps: **iron & steel, cement (and other non-metallic minerals), chemicals & petrochemicals**. These sectors combine large, persistent emissions and limited short-term technical substitutes for fossil carbon. The IEA and other bodies emphasize that heavy industry and long-distance transport together represent a central obstacle to achieving net-zero by mid-century.

### Sector snapshots: core challenges and mitigation levers

#### Steel (iron & steel)

The iron and steel industry represents one of the most carbon-intensive sectors globally, contributing approximately 7–8% of total anthropogenic carbon dioxide ($CO_2$) emissions (International Energy Agency [IEA], 2023). This high carbon footprint stems largely from the conventional steelmaking route, which combines the blast furnace (BF) and basic oxygen furnace (BOF) processes. In these systems, metallurgical coal or coke serves both as a fuel and as a chemical reductant to extract iron from iron ore. The chemical reduction of iron oxide inherently produces large quantities of $CO_2$, making deep decarbonisation of the sector particularly complex (Material Economics, 2019). In addition to direct process emissions, the intensive heat requirements for smelting further elevate the sector's energy demand, particularly in regions reliant on fossil fuels.

To mitigate these emissions, the steel industry must undergo a technological transformation toward low-carbon production methods. One of the most promising decarbonisation pathways involves the electrification of steelmaking through electric arc furnaces (EAFs). Unlike traditional BF-BOF systems that depend on coal, EAFs primarily use electricity to melt recycled scrap steel, significantly reducing both energy consumption and $CO_2$ emissions (World Steel Association, 2022). The environmental performance of this route depends heavily on the carbon intensity of the electricity source. When powered by renewable or low-carbon electricity, EAFs can achieve reductions of up to 80–90% in direct emissions compared to conventional blast furnaces (Hasanbeigi & Springer, 2019). However, the transition to EAF-based production is constrained by the availability of scrap metal, which varies widely between developed and developing economies. For instance, mature industrial economies such as the United States, Japan, and those in the European Union possess abundant end-of-life scrap from decommissioned infrastructure and vehicles, enabling large-scale EAF adoption. Conversely, developing economies such as India or Nigeria often have younger infrastructure and lower scrap availability, making full reliance on scrap-based routes difficult (IEA, 2020).

Another transformative technology gaining momentum is hydrogen-based direct reduced iron (DRI) production. This process replaces carbon-based reductants with hydrogen to reduce iron ore into sponge iron, which is subsequently melted in an EAF to produce crude steel. When the hydrogen used is generated from renewable electricity via electrolysis referred to as "green hydrogen" the resulting steel can be nearly carbon-neutral (Vogl et al., 2018). Europe has become a global leader in pioneering hydrogen-based steelmaking, with flagship projects such as HYBRIT in Sweden and H2 Green Steel demonstrating commercial-scale feasibility (HYBRIT, 2022). HYBRIT aims to eliminate coal use entirely in ironmaking, replacing it with renewable hydrogen and renewable electricity, potentially reducing steel's carbon footprint by over 90%. Similarly, Germany's SALCOS project (Salzgitter Low $CO_2$ Steelmaking) integrates hydrogen DRI with renewable energy sources to achieve large-scale emission reductions (Salzgitter AG, 2023). These developments in developed economies showcase the potential of hydrogen to transform an otherwise carbon-intensive industry.

However, the deployment of hydrogen DRI in developing economies remains challenging. The production of green hydrogen requires abundant and affordable renewable electricity, along with significant infrastructure for hydrogen transport, storage, and handling conditions that are not yet widespread in many developing regions (Hasanbeigi, 2022). The high capital expenditure (CAPEX) associated with constructing new DRI-EAF plants also poses a barrier, especially in economies where steel demand is growing rapidly but financing mechanisms for clean technologies are limited. Moreover, even when hydrogen is available, its cost remains a critical constraint. As of 2023, green hydrogen costs between USD 3–6 per kilogram, compared to around USD 1–2 for hydrogen derived from natural gas (IEA, 2023). Reducing this cost gap through policy incentives, carbon pricing, and technological learning is therefore crucial for making hydrogen-based steelmaking competitive globally.

In regions where transitioning to hydrogen or EAF routes is not immediately feasible, carbon capture, utilisation, and storage (CCUS) present a near-term mitigation option. CCUS can be retrofitted onto existing blast furnaces or integrated steelworks to capture $CO_2$ emissions from both process and combustion sources. The captured $CO_2$ can then be stored underground or used as feedstock for other industrial processes (Fennell et al., 2022). For example, in the United Arab Emirates, the Emirates Steel Industries CCUS project captures around 800,000 tonnes of $CO_2$ annually from its steel operations for enhanced oil recovery (Abu Dhabi National Oil Company [ADNOC], 2021). Similarly, ArcelorMittal has initiated several CCUS projects in Europe and North America, including the Steelanol project in Belgium, which converts captured $CO_2$ into ethanol for use as transport fuel (ArcelorMittal, 2022). While CCUS can substantially reduce emissions, it is energy-intensive and costly, with capture costs ranging from USD 60–120 per tonne of $CO_2$ depending on the technology and scale (Fennell et al., 2022). Furthermore, suitable geological storage capacity and regulatory frameworks for $CO_2$ storage are limited in many regions, posing implementation challenges.

Despite the progress in technological innovation, multiple barriers hinder rapid decarbonisation of the steel industry. The first is the cost and scalability of low-carbon technologies. The upfront capital requirements for constructing new hydrogen-based DRI plants or CCUS facilities are substantial, and steel producers in competitive markets often face thin profit margins that discourage such investments without strong policy support (Material Economics, 2019). The second barrier is the limited availability of renewable energy and green hydrogen, particularly in emerging economies with underdeveloped power grids. The decarbonisation of steel is inherently linked to the broader energy transition, as low-carbon steelmaking requires abundant clean electricity for both EAFs and electrolysis. Third, raw material constraints including the availability of high-grade iron ore suitable for DRI pose another challenge, since not all ore types can be easily processed using hydrogen (IEA, 2023).

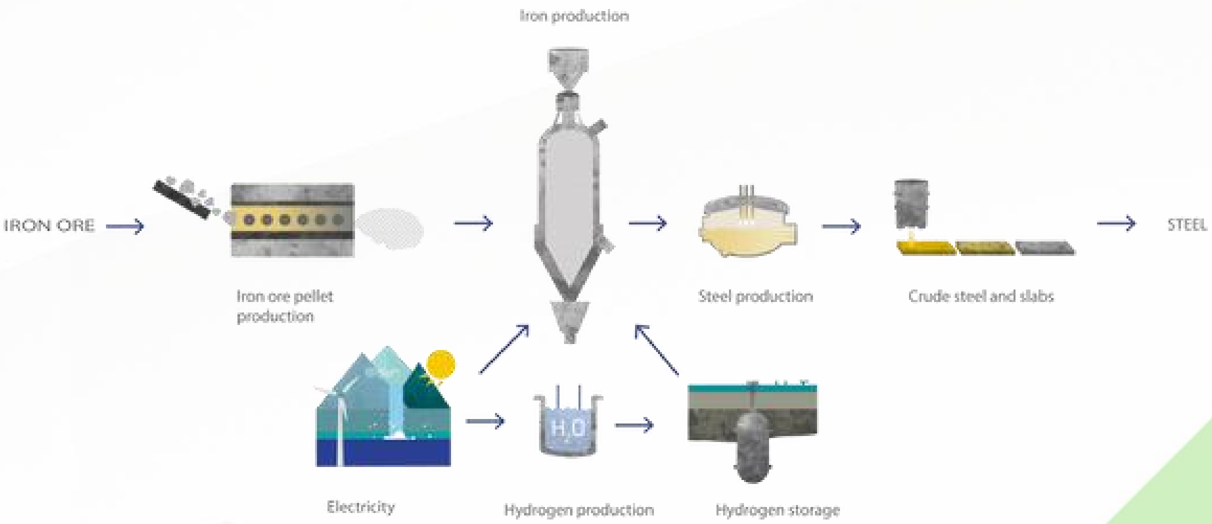
Policy frameworks in developed economies are already addressing some of these barriers. The European Union's Carbon Border Adjustment Mechanism (CBAM) aims to discourage carbon leakage and incentivise low-carbon steel production by levying tariffs on imported carbon-intensive steel (European Commission, 2023). Similarly, financial support mechanisms such as the EU Innovation Fund and Germany's H2Global programme are helping de-risk investments in green hydrogen and low-carbon industrial projects. In contrast, developing economies will require tailored transition pathways, emphasizing technology transfer, concessional finance, and regional cooperation. For instance, South Africa's Steel Master Plan integrates renewable energy development with local steel decarbonisation initiatives to maintain competitiveness while pursuing emission reductions (Department of Trade, Industry and Competition, 2022).

Ultimately, the decarbonisation of the global steel industry represents a multifaceted transformation requiring a combination of technological innovation, infrastructure investment, and policy alignment. While electrification through EAFs and hydrogen DRI offers promising long-term solutions, CCUS provides a necessary bridge for existing facilities. However, equitable transition pathways must ensure that developing economies where steel demand is growing fastest are not left behind due to financial and technological disparities. Achieving global decarbonisation in steel will therefore depend on international collaboration, knowledge sharing, and investment in scalable, cost-effective solutions that align with both industrial growth and climate objectives.

### Examples of Companies Championing the Decarbonisation of Steel

### SSAB & the Fossil-Free Steel Technology

SSAB-AB, a major Swedish steel producer, is one of the global forerunners in developing fossil-free steel via its HYBRIT initiative. HYBRIT (Hydrogen Breakthrough Ironmaking Technology) is a collaboration among SSAB, iron ore producer LKAB, and power company Vattenfall, aiming to replace coking coal with hydrogen (produced using renewable electricity) in the reduction of iron ore. This change in the primary raw material source can drastically reduce $CO_2$ emissions, since the traditional blast furnace method burning coal to reduce iron ore accounts for a significant share of steelmaking's carbon footprint. The HYBRIT pilot plant in Luleå has produced more than 5,000 tonnes of hydrogen-reduced iron, and pilot volumes of fossil-free steel have gone to customers for prototyping and limited use already. SSAB aims to scale to commercial deliveries by **2026** under HYBRIT (SSAB, Q3 2024 report).




HYBRIT initiative by SSAB

In terms of financial size, SSAB's revenue in 2024 was SEK 103.42 billion (approx. USD 9.4–9.9 billion depending on exchange rate), though this includes all its steel and specialty product lines, not just fossil-free steel. Operating profit in that year was SEK 7.86 billion, down from 2023, reflecting market headwinds, but also showing strong ongoing financial capacity to invest in the green transformation. SSAB's steel shipments and crude steel production saw modest declines year-on-year (5-6%) in 2024, in line with weaker demand in Europe, but the company continues to invest in strategic projects like the new mills in Luleå and Oxelösund to scale fossil-free and recycled steel capabilities.

### Adopters & Partnerships: Using SSAB's Fossil-Free Steel

A critical piece in SSAB's transition is demand-side partnerships: companies willing to adopt fossil-free steel even before volumes are large. SSAB has already signed multiple agreements with major industrial and automotive customers to begin integrating its fossil-free steel into real products.

- **Volvo Group**: One of SSAB's earliest partners. Volvo revealed in 2021 the first vehicle built using SSAB's fossil-free steel and is incorporating SSAB's HYBRIT steel in frames and components. This stands as proof of concept that fossil-free steel can meet the quality, strength, and safety demands of heavy equipment and automotive applications (SSAB, 2024).
- **Polestar**: The Swedish EV automaker is collaborating with SSAB via the *Polestar 0* project, aiming to develop a climate-neutral car by 2030. Steel from HYBRIT is intended to replace conventional steel in key structural components (SSAB, 2024).
- **Mercedes-Benz**: As part of SSAB's early portfolio of adopters, Mercedes-Benz has used or committed to using SSAB's fossil-free steel in prototype vehicle builds to explore how it can be integrated into traditional vehicle lines (SSAB, 2024).
- **Sandvik, Epiroc, Sjørring**: These companies in the manufacturing and mining machinery sectors have also become early customers of SSAB's pilot steel. For instance, Epiroc is using prototype hydraulic blocks made with fossil-free steel; Sandvik in loaders/trucks; Sjørring for attachments; these collaborations help test SSAB steel in real-world mechanical stresses and manufacturing processes (SSAB, 2024).

### Impacts, Challenges & Outlook

What stands out about SSAB's approach is that it is not purely technological it's systemic. By securing customer demand, SSAB ensures that its fossil-free steel is not a niche novelty but something with a path toward scale. Volvo's plan, starting in 2025, to incorporate "low-emission steel" (both recycled and fossil-free) into tens of thousands of its heavy truck frames (frame rails for Volvo FH & FM trucks), shows how demand can move from prototyping to serial production (Volvo Trucks, SSAB Zero program) (Volvotruck, 2024).

However, there are clear challenges: producing hydrogen at scale and cost-efficiently; building or adapting steel mills (like the ones in Luleå and Oxelösund) to handle hydrogen-based direct reduction; obtaining consistency and quality in strength, ductility, and performance matched to conventional steel; and making sure the cost premium of fossil-free steel can be absorbed by customers or offset with climate or regulatory incentives.

Yet, SSAB appears financially and industrially robust. With around SEK 103 billion revenue in 2024, and millions of tonnes of steel throughput, the company has the scale and resources to make the transition. Its strategy of combining recycled steel (where emissions can be lower) and hydrogen-reduced iron (via HYBRIT) provides flexibility. By 2026, it aims to supply fossil-free steel at commercial scale if hydrogen supply, permitting, energy cost, and customer demand align.

### H2 Green Steel

H2 Green Steel is a Swedish green-steel startup founded with a mission to decarbonise one of the hardest-to-abate industrial sectors: steelmaking. The company is building a large-scale green steel plant in Boden, in northern Sweden, that uses green hydrogen produced by electrolysis with renewable electricity. Rather than using coking coal in blast furnaces, H2 Green Steel will use hydrogen to directly reduce iron ore (i.e. a direct reduction process), producing what is known as hot direct reduced iron (HDRI) and hot briquetted iron (HBI). These feed into electric arc furnaces, allowing production of steel with up to 95% lower $CO_2$ emissions compared to conventional steel production methods (thyssenkrupp, 2023).

The planned initial capacity is to produce near-zero steel at a scale of 2.5 million tonnes per year once operations begin, with a ramp-up toward 5 million tonnes per year by 2030 (thyssenkrupp, 2023). The plant is intended to be fully integrated: hydrogen production (via electrolyzers), iron/steel equipment, and associated infrastructure (including long-term power purchase agreements) are being built in Boden, under full control of the project (Kobleco, 2022).

### Adopters & Offtake Agreements

A key part of H2 Green Steel's strategy is securing customer commitments in advance binding agreements that will assure demand for its green steel output. About half of the initial yearly volume already has binding 5- to 7-year customer contracts. Some of the announced adopters include carmakers and heavy industry players: Porsche, Mercedes-Benz, Scania, Cargill, among others (PRNewswire, 2024). These off-takers are willing to use steel produced via hydrogen reduction, even at a premium, because it helps reduce Scope 3 emissions in their supply chains and positions them as leaders in climate-conscious production.

These agreements help de-risk the project, allowing H2 Green Steel to plan production, financing, and infrastructure with reasonable certainty of market for their steel. They also send a signal to investors and policymakers that green steel demand exists, which is often one of the missing elements in scaling up clean-steel projects.

**Funding, Capital & Outlook**

While H2 Green Steel is not yet reporting significant revenue from steel sales (since production start is scheduled for mid-2025 / early 2026), it has raised very large amounts of funding to build the plant and associated infrastructure. As of early 2024, the company has secured almost €6.5 billion in total financing for its Boden facility. This includes approximately €4.2 billion in project debt, about €300 million in new equity, and a €250 million grant from the European Union's Innovation Fund (H2EG, 2025). The company expects its first steel production to begin in late 2025 / early 2026, with full commercial ramp-up following. The hydrogen electrolyzer capacity is large (several hundred megawatts), and by 2030 the facility aims to operate at ~5 million tonnes/year of green steel.

**Challenges & Strategic Significance**

While H2 Green Steel is making strong progress, there are still many challenges. A major one is cost green hydrogen is more expensive than coal or gas as a reducing agent, and there are infrastructural and permitting risks. Also, customers must accept paying a "green premium" for steel produced with lower emissions, which may limit how broadly green steel can compete without policy support like carbon pricing, subsidies, or regulatory mandates (Financial Times, 2024).

Another challenge is ensuring uninterrupted renewable electricity supply, and managing the technical complexities of scaling large electrolyzers and integrating hydrogen and direct reduction processes with electric arc furnaces. Given that many steel-making nations still rely heavily on coal-based blast furnaces, the shift requires major capital investment and often regulatory or policy frameworks that reward low $CO_2$ emissions more fairly.

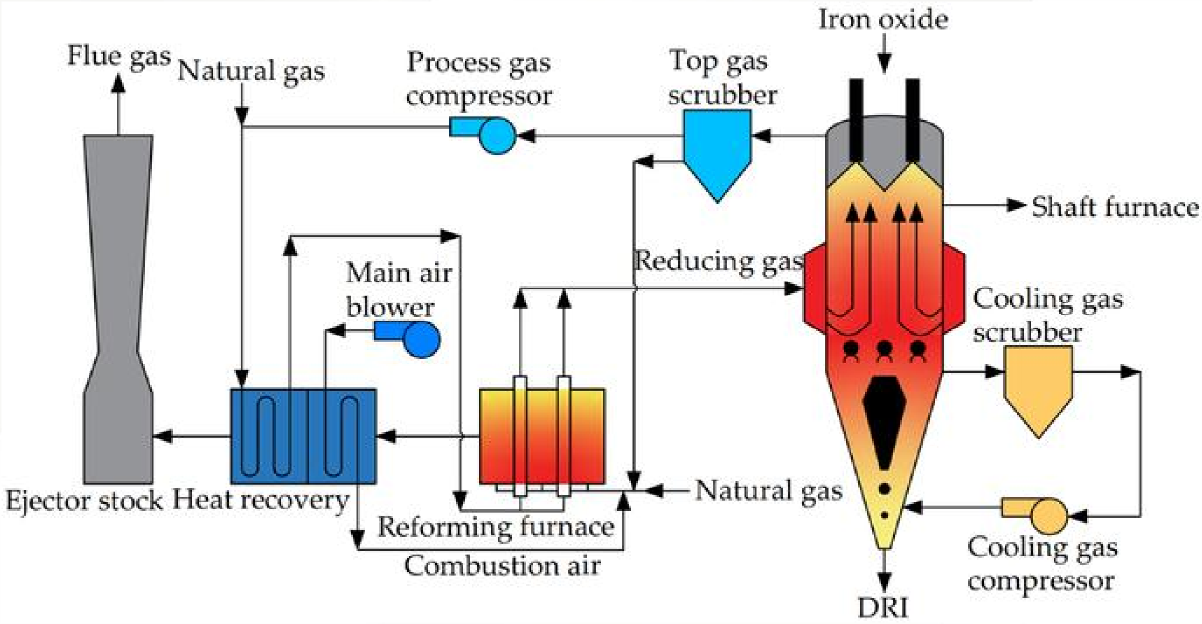
Despite that, H2 Green Steel represents one of the most advanced examples of industrial decarbonization to date. With funding nearing €6.5 billion, binding customer contracts for about half its initial output, and a very ambitious production target, it shows how the steel industry might transition from pilot projects to commercial scale. If successful, its model (green hydrogen + direct reduction + strong offtake commitments + large electrolyzer capacity + renewable power) could become replicable in other geographies with abundant renewable energy.

### ArcelorMittal's Decarbonization Journey

ArcelorMittal, one of the world's largest steel manufacturers, has been at the forefront of global efforts to decarbonize the steel industry. As of 2024, the company reported total annual revenue of $68.1 billion, underscoring its vast industrial footprint and influence across multiple regions and market segments (ArcelorMittal, 2024). Recognizing that the steel sector accounts for approximately 7–9% of global carbon dioxide emissions, ArcelorMittal has embarked on an ambitious pathway to drastically cut its emissions intensity. Its strategic roadmap focuses on leveraging hydrogen-based direct reduced iron (DRI) technology and electric arc furnaces (EAFs) both designed to reduce or replace the dependence on coal in steelmaking (World Steel Association, 2024).

### Hydrogen-Based DRI and Green Steel Production

A major component of ArcelorMittal's low-carbon strategy involves Direct Reduced Iron (DRI) plants that substitute hydrogen for natural gas or coal in the iron reduction process. Traditional blast furnaces rely heavily on coke, a carbon-intensive fuel, to reduce iron ore into molten iron. However, in hydrogen-based DRI, hydrogen serves as the reducing agent, producing water vapor instead of carbon dioxide as a by-product (International Energy Agency, 2023).

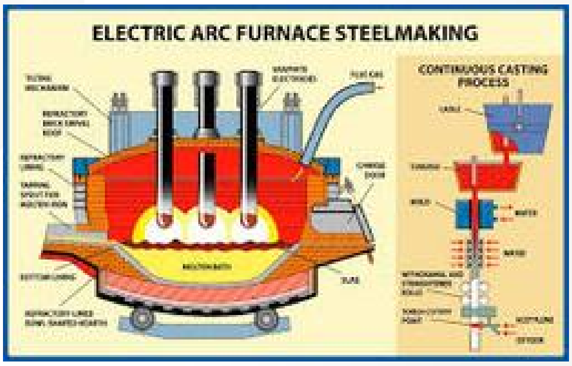



ArcelorMittal has made significant strides in implementing this technology, with pilot projects underway in Hamburg, Germany, and Gijón, Spain, where the company aims to transition from natural gas-based DRI to full hydrogen operation as renewable hydrogen becomes more available (ArcelorMittal, 2024).

The company's DRI programs are designed not only to reduce emissions but also to integrate seamlessly with Electric Arc Furnaces (EAFs). This combination is expected to cut emissions from steelmaking by up to 80% compared to conventional blast furnace–basic oxygen furnace (BF–BOF) routes. Such integrated processes represent the backbone of ArcelorMittal's commitment to achieving carbon neutrality by 2050, in line with the European Green Deal and the Paris Agreement targets (European Commission, 2023).

### Electric Arc Furnaces and Circular Production

ArcelorMittal is also heavily investing in the expansion of Electric Arc Furnace (EAF) technology, which melts scrap steel or DRI using electricity rather than coke. EAFs play a critical role in the circular economy model by allowing the reuse of steel scrap, drastically cutting raw material extraction and associated emissions. Between 2018 and 2024, the company invested over $1 billion in decarbonization projects, much of which has been channeled into constructing new EAF facilities in Spain and Germany (ArcelorMittal, 2024).




These investments align with the firm's XCarb® initiative, a proprietary brand dedicated to low-carbon steel products and technologies. Through XCarb®, ArcelorMittal markets green steel produced from recycled material and renewable energy sources. Although the company does not currently break out specific revenue for XCarb®, the brand has been widely adopted by automakers, construction firms, and renewable energy developers seeking to reduce their own emissions footprints (Reuters, 2024).

### Strategic Collaborations and Regional Projects

ArcelorMittal's decarbonization pathway extends across multiple continents, supported by collaborations with governments, technology providers, and research institutions. In Europe, the company's projects are bolstered by the European Union's Innovation Fund, which supports large-scale industrial decarbonization initiatives. In Spain, the Gijón project is a key focus, integrating hydrogen-based DRI with EAF steelmaking, while the Hamburg DRI project aims to produce the world's first commercial-scale fossil-free steel using hydrogen (Financial Times, 2024).

Beyond Europe, ArcelorMittal is exploring similar technologies in Canada and India, focusing on carbon capture and utilization (CCU) and bioenergy integration. The company's investment strategy emphasizes modular flexibility, allowing existing blast furnaces to be gradually phased out while scaling up green steel operations (IEA, 2023).

### Challenges and Economic Implications

Despite its progress, ArcelorMittal faces several challenges typical of heavy industrial decarbonization. Chief among these is the high capital cost of hydrogen infrastructure and renewable power supply. Producing hydrogen at scale through electrolysis remains expensive, and access to low-cost renewable energy varies across regions. Nevertheless, ArcelorMittal's phased approach combining transitional technologies such as natural gas–based DRI with eventual hydrogen substitution allows for economic and technical flexibility.

Moreover, the company's $1 billion decarbonization investment is not only an environmental strategy but also a competitive hedge. Global demand for green steel is expected to surge as sectors such as automotive, construction, and renewable energy transition to low-carbon materials. By building early capacity, ArcelorMittal positions itself to meet future supply chain requirements for fossil-free steel and to capture premium pricing in green markets (BloombergNEF, 2024).

### Cost and Savings

The iron and steel industry contributes about 7–9% of global $CO_2$ emissions, largely due to the use of coking coal in blast furnaces. Transitioning to hydrogen-based Direct Reduced Iron (DRI) and Electric Arc Furnaces (EAF) powered by renewables offers one of the most transformative decarbonisation pathways (IEA, 2024). The current production cost for conventional blast furnace steel is around US$500–600 per tonne, while green steel using hydrogen costs approximately US$800–900 per tonne. However, as the cost of green hydrogen falls to US$1.50–2/kg by 2035, green steel prices are projected to reach US$600–700 per tonne, narrowing the gap significantly (McKinsey & Company, 2023).

For a 1 million tonne-per-year steel plant, this could mean an additional US$200 million in fuel costs today, but potential savings of US$100–150 million annually by 2035 from lower hydrogen prices and carbon cost avoidance. Given that a carbon tax of US$100/tonne $CO_2$ would add roughly US$150–200 per tonne to coal-based steel, the shift to hydrogen-based production can yield annual carbon savings exceeding US$100 million (World Steel Association, 2024). In Nigeria and South Africa—where energy costs are high and coal supply is imported—electric arc furnaces using scrap and renewable electricity can already reduce production energy costs by 25–35%, translating to savings of US$60–80 per tonne of steel.

### Cement & concrete (non-metallic minerals)

The cement and concrete industry is one of the largest sources of industrial carbon dioxide ($CO_2$) emissions worldwide, responsible for approximately 7–8% of global anthropogenic $CO_2$ emissions (International Energy Agency [IEA], 2023). The primary source of these emissions lies in the production of *clinker* the key component of cement which is formed by heating limestone (calcium carbonate) and other raw materials in a rotary kiln at around 1,450°C. This process releases $CO_2$ through two main mechanisms: fuel combustion required to heat the kiln and the *calcination* reaction, where limestone decomposes into lime (CaO) and $CO_2$. The latter accounts for roughly 60% of total emissions from cement production and is inherently tied to the chemistry of clinker formation, making full decarbonisation technically challenging (Scrivener, John, & Gartner, 2018).

Moreover, cement demand continues to rise, particularly in developing regions such as Africa, South Asia, and Latin America, driven by rapid urbanisation, population growth, and infrastructure development (Andrew, 2019). In sub-Saharan Africa, for example, cement demand is projected to more than double by 2050, exacerbating global emissions unless low-carbon alternatives are adopted (IEA, 2023). In contrast, developed economies such as those in the European Union (EU) and Japan have seen relatively stable or declining cement demand, offering more flexibility for decarbonisation investments and policy-driven innovation (GCCA, 2022). Thus, the global cement sector faces a dual challenge: reducing emissions while meeting the construction needs of developing economies.

One of the most effective strategies for reducing emissions in the cement sector is material efficiency and design innovation. By optimizing structural design, engineers can reduce the quantity of cement required per unit of construction output. High-performance concretes, which achieve superior strength and durability, allow for thinner and lighter structures without compromising safety (Scrivener et al., 2018). Additionally, prefabrication and modular construction techniques improve material utilization and minimize waste, further reducing embodied carbon (Pomponi & Moncaster, 2017). Developed economies have begun to integrate these strategies through green building codes and sustainability certification systems such as LEED and BREEAM, which encourage the use of resource-efficient materials and circular construction models. However, in developing economies, the widespread adoption of such techniques remains limited due to cost constraints, lack of technical expertise, and informal construction practices (Cement Sustainability Initiative [CSI], 2019).

Another major lever is clinker substitution, which involves partially replacing energy- and carbon-intensive clinker with *supplementary cementitious materials (SCMs)* such as fly ash (a by-product of coal combustion), ground granulated blast furnace slag (GGBS, from steel production), and calcined clays. These materials possess pozzolanic or latent hydraulic properties that contribute to concrete's strength and durability while reducing $CO_2$ emissions per tonne of cement (Habert et al., 2020). For instance, substituting 30–50% of clinker with SCMs can lower carbon intensity by up to 40%. In the EU, the average clinker-to-cement ratio has already fallen to around 70%, compared to a global average of 75–80% (IEA, 2023).

However, SCM availability poses a significant challenge, especially in developing economies. The decline of coal-fired power generation in many regions has reduced fly ash supply, while slag availability is linked to steel production, which is itself undergoing transformation toward low-carbon pathways (Andrew, 2019). As a result, attention has turned to calcined clay and natural pozzolans as alternative SCMs. The *Limestone Calcined Clay Cement* ($LC^3$) initiative, pioneered by researchers at the École Polytechnique Fédérale de Lausanne (EPFL) and partners in India and Cuba, demonstrates that blending clinker with calcined clay and limestone can achieve up to 40% $CO_2$ reductions with comparable performance to ordinary Portland cement (Scrivener et al., 2018). India's implementation of $LC^3$ has shown that this approach can be cost-competitive and scalable, particularly in regions with abundant clay deposits and limited access to industrial by-products ($LC^3$ Project, 2021).

Fuel switching and electrification also play an important role in lowering emissions from the energy-intensive kiln operations. Cement kilns traditionally rely on coal, petroleum coke, or natural gas as fuel. Transitioning to *alternative fuels* such as biomass, waste-derived fuels, and refuse-derived fuels (RDF) can significantly reduce fossil fuel emissions (IEA, 2023). For example, Heidelberg Materials in Germany and Holcim in France have achieved fossil fuel substitution rates of over 60% by co-processing municipal solid waste, biomass residues, and industrial by-products (Reuters, 2022). In developing economies, however, fuel switching faces logistical and infrastructural challenges. Many regions lack reliable waste management systems or biomass supply chains, limiting the availability of suitable alternative fuels. Furthermore, while electric kilns powered by renewable electricity represent a long-term decarbonisation option, this technology is still at an early stage of development and may require breakthroughs in high-temperature electric heating (GCCA, 2022).

Given that process emissions from limestone calcination are unavoidable through fuel switching alone, carbon capture, utilisation, and storage (CCUS) is increasingly recognised as a crucial pathway for achieving near-zero emissions in cement production. Several large-scale demonstration projects are currently underway in developed economies. For instance, the

*Norcem Brevik* project in Norway operated by Heidelberg Materials aims to capture 400,000 tonnes of $CO_2$ annually from cement kiln exhaust gases, with permanent geological storage under the North Sea (IEA, 2023). Similarly, the *LEILAC (Low Emissions Intensity Lime and Cement)* project, funded by the EU, is testing direct separation technology that isolates process $CO_2$ for capture without altering kiln operation (GCCA, 2022). These projects demonstrate the feasibility of integrating CCUS into existing cement plants, though at significant cost and energy penalties.

The implementation of CCUS in developing economies remains limited, primarily due to high capital costs, lack of $CO_2$ transport and storage infrastructure, and limited access to finance (Reuters, 2022). In many African and Asian countries, the economic viability of CCUS is further constrained by the lower price of conventional cement and weaker regulatory frameworks for carbon management. Nonetheless, there are emerging collaborations aiming to bridge this gap. For example, Nigeria's Dangote Cement has initiated feasibility studies on $CO_2$ capture and reuse, while India's Dalmia Cement is exploring low-cost carbon capture technologies compatible with regional energy systems (Habert et al., 2020).

Despite these technological advancements, several barriers continue to impede large-scale decarbonisation of the cement industry. The first is feedstock availability for SCMs and alternative fuels, which is often region-specific and influenced by broader industrial trends. The second is retrofitting costs, as existing cement plants have long lifetimes (often exceeding 40 years) and adapting them for new technologies such as CCUS or electrified kilns requires substantial capital investment. Finally, the high energy intensity and cost of carbon capture at cement scale estimated at USD 60–120 per tonne of $CO_2$ poses a major challenge, especially in price-sensitive markets (IEA, 2023).

In all, achieving deep decarbonisation in the cement and concrete sector will require a multifaceted approach that combines process innovation, material efficiency, fuel diversification, and large-scale deployment of CCUS. Developed economies are leading in pilot projects and policy frameworks, while developing economies where cement demand is growing most rapidly must prioritise cost-effective solutions such as clinker substitution and material efficiency. Global cooperation, technology transfer, and targeted financing mechanisms will be essential to ensure that the cement industry transitions toward carbon neutrality without compromising infrastructure development and economic growth.

## Examples of Companies Decarbonising Cement & Concrete

### Holcim

Holcim, one of the world's largest building materials companies, is pushing forward in reducing carbon emissions in its core businesses of cement and concrete production through multiple levers. Its decarbonization strategy includes improving energy efficiency in its manufacturing processes; increasing the use of alternative fuels that replace coal or pet coke; boosting the use of Supplementary Cementitious Materials (SCMs) (like fly ash, slag, calcined clay, etc.) to reduce clinker content; and investing in Carbon Capture, Utilization and Storage (CCUS) to mitigate emissions that are difficult to remove in conventional cement plants. Key to its strategy are its branded products: ECOPact, low-carbon concrete, and ECOPlanet, its low-carbon cement line, which integrate many of these technologies and materials to reduce the $CO_2$ footprint of construction projects (Holcim, 2024).


Holcim's approach also emphasizes circular construction recycling construction and demolition materials and scaling up its use of its proprietary ECOCycle® platform to integrate waste materials and reduce reliance on virgin raw materials. This is complemented by efforts to use more low-carbon energy, improve process optimization, and develop near-zero cement varieties supported by CCUS investments in Europe (Holcim, 2024).

### Adoption & Market Penetration

Holcim's low-carbon branded solutions are gaining traction in its markets. In the first half of 2024, the share of ECOPact concrete in Holcim's ready-mix concrete business rose to 28% of net sales, up from around 19% previously, showing rapid uptake among customers seeking white-labeller or certified low-carbon materials. Similarly, its ECOPlanet cement achieved roughly 26% of net sales in Holcim's cement businesses in that period, also up from 19% the year before. These increases reflect growing demand from construction firms, developers, infrastructure projects, and sustainability-oriented clients implementing green building standards (Holcim, 2024).

Holcim has positioned ECOPact and ECOPlanet not as niche offerings but as mainstream components of its product portfolio. The growth in sales of these low-carbon products is supported by favourable regulatory regimes (e.g. public infrastructure requiring low-carbon materials), rising awareness among customers, and Holcim's ability to scale manufacturing and distribution. Moreover, in markets like Latin America, low-carbon cement and concrete products (especially ECOPlanet) now account for a notably high share of cement revenues, showing regional leadership in demand for green building solutions (Holcim, 2024).

### Financials & Revenue Implications

Holcim's overall financials indicate that its decarbonization strategy is contributing meaningfully to its performance. In H1 2024, the company achieved net sales of CHF 12,813 million, up 1.6% year-on-year in local currency. Recurring EBIT for that period rose about 12.7% in local currency, reaching CHF 2,210 million. Holcim noted that its ECOPact and ECOPlanet products accounted for about 28% and 26%, respectively, of their ready-mix concrete and cement net sales in that half-year period. The fact that low-carbon product lines make up more than a quarter of those product categories suggests a multi-billion-dollar contribution to Holcim's revenues, though the company does not break out exact revenue numbers per product line in all reports (Holcim, 2024).

For full-year 2024, Holcim reported CHF 26,407 million in net sales, with advanced branded products (which include ECOPact, ECOPlanet, Elevate, etc.) increasing to 36% of total net sales, up from 30% in 2023. ECOPact reached 29% of ready-mix net sales, and ECOPlanet 26% of cement net sales by the end of 2024. These figures confirm not only growing market penetration but also the scaling up of Holcim's decarbonized product lines as a core business driver (Holcim Full Year 2024 Results).

### Heidelberg Materials

Heidelberg Materials has committed itself to one of the most ambitious decarbonization programs in the building materials sector. Central to its approach is carbon capture, utilization

& storage (CCUS), exemplified by its Brevik cement plant in Norway, which is now operating the world's first industrial-scale CCUS unit integrated in a cement plant. The evoZero® product line stems from this project: evoZero cement achieves a net-zero $CO_2$ footprint by capturing approximately 400,000 tonnes of $CO_2$ annually at Brevik roughly 50% of that plant's emissions. The captured $CO_2$ is shipped for permanent storage under the sea via Norway's Longship project (Heidelberg Materials, 2024).

Beyond CCUS, Heidelberg is using other levers: increasing the use of alternative fuels, reducing the clinker ratio (the portion of high-emission material in cement), deploying supplementary cementitious materials (like calcined clay and biomass), and improving energy efficiency in plants. The company also emphasizes circularity, product innovation, and sustainability branding through its evoBuild® and evoZero® ranges.

### Products & Revenue Targets

While Heidelberg does not yet disclose exact revenue numbers solely attributable to its low-carbon product lines, recent results provide good insight into the scale and momentum of its sustainable offerings. In Q2 2025, sustainable products accounted for about 37% of revenue, a sizeable share that shows how evoZero, evoBuild, and related lines are no longer niche.


Under its Strategy 2030, Heidelberg aims to have over 50% of its revenue from sustainable products by 2030. The company also targets reducing its specific net $CO_2$ emissions to below 400 kg per tonne of cementitious material by then, alongside raising the rate of alternative fuels used above 50% and lowering clinker content (clinker ratio) to about 64% in its cement products. The Brevik evoZero plant itself has capacity of slightly over one million tons of cement annually, about half of which will be “carbon-captured net-zero cement” under evoZero (i.e., products capturing $CO_2$ in line with the Brevik project) beginning in 2025. The fact that the company pre-sold all evoZero product slated for 2025 suggests strong market demand for these premium sustainable materials (Heidelberg Materials, 2024).

### Adopters & Implementation

Adoption of Heidelberg Materials’ sustainable products has come from large-scale infrastructure and commercial building projects, especially in Europe, where environmental regulations, green building standards, and customer demand favour lower-emissions materials. evoZero, being functionally the same in performance to conventional cement but differentiated by its carbon footprint, is being selected for projects where sustainability is central.

The company is also advancing implementation through multiple CCUS projects beyond Brevik. These include the ANRAV project in Devnya, Bulgaria (which involves full value chain CCUS, pilot scale); Padeswood in the UK; Geseke in Germany, Slite in Sweden, and other plants in Europe that are part of Heidelberg’s rollout of CCUS and sustainable fuel programs.

Holistically, Heidelberg has managed to integrate its CCUS facility into existing operations (especially in Brevik) without disrupting cement production, underlining its engineering and logistical feasibility. The mechanical completion of the Brevik CCS unit in late 2024 was a major milestone, paving the way for delivery of evoZero cement to customers starting 2025.

### CarbonCure

CarbonCure Technologies is a cleantech company founded in 2012, based in Halifax, Canada, that has developed a concrete carbon utilization solution. Its core technology injects captured $CO_2$ into fresh concrete during mixing. The $CO_2$ mineralizes (reacts and becomes a stable mineral form) inside the concrete mix, permanently storing that $CO_2$, while also enabling the concrete producer to reduce cement content without compromising compressive strength. This reduces both embodied carbon (from the concrete itself) and the emissions associated with producing cement, which is one of the highest-carbon components in concrete (CarbonCure Media Kit, 2025).

The strategy is to make this technology “drop-in” or retrofittable to existing concrete plants, so that adoption can scale without needing entirely new infrastructure. Part of the value proposition is that producers can save on cement, which is expensive and carbon-intensive, while also generating carbon credits for the $CO_2$ saved and mineralized. CarbonCure’s model thus combines environmental impact with economic incentives, helping concrete producers make lower-carbon concrete with measurable performance benefits (strength, durability) and financial upside (credit revenue, cost savings).

### Adopters, Credits & Funding

Though concrete is a commodity product, CarbonCure has attracted attention from large companies and funders concerned about climate impact and embodied carbon. It has sold carbon credits to firms like Shopify and Stripe, among others in the tech and commerce sectors, who buy credits to offset their emissions and support innovative low-carbon solutions (CarbonCure, 2022).

In terms of funding, CarbonCure has secured backing from a number of climate-focused investors. Notably, it raised $80 million USD in an equity round led by Blue Earth Capital in mid-2023, which also involved investors like Breakthrough Energy Ventures, Amazon’s Climate Pledge Fund, Microsoft’s climate innovation programs, and others. The funding is intended to scale the deployment of its carbon mineralization systems globally, expand its product roadmap, and increase the supply of high-quality carbon credits (CarbonCure, 2023).

CarbonCure also shares carbon credit revenue with its concrete producer partners. As of 2024, credit revenue from ready-mixed concrete producers globally is approaching USD 5 million (for credits generated over several years) in markets such as North America and overseas, though this is part of a broader revenue stream rather than being tied exclusively to one product line (CarbonCure, 2025).

### Impact, Revenue & Scaling

On the impact side, CarbonCure has made several visible milestones. As of late 2024, the company’s solutions have saved over 500,000 metric tons of $CO_2$ globally via more than 7.5 million truck-loads of concrete produced with its systems. This reflects widespread deployment hundreds of systems across dozens of countries, supplying concrete for green building projects around the world (CarbonCure, 2024). In addition, over 750 carbon mineralization systems have been installed in concrete plants globally; the number of truck-loads of concrete using CarbonCure mixes has grown rapidly, and cumulative volumes are in millions (truck-loads) as the company scales (CarbonCure, 2023).

As for revenue, while there is mention in some public company-data profiles that CarbonCure's annual revenue is about USD 40.7 million in 2025, I was not able to verify that exact figure from reliable primary sources or company filings in what I checked. It may include income from licensing, carbon credits, services, and other business lines rather than direct sales of "green concrete" per se. What is clear is that CarbonCure's business model includes multiple revenue streams: licensing its technology to concrete producers, sharing in cost savings via reduced cement usage, and earning from carbon credits and voluntary carbon markets. These multiple levers help its partners offset the cost of adopting the technology, making the transition more economically viable (CarbonCure Media Kit, 2025).

### Cost and Savings

Cement manufacturing is the single largest industrial emitter of $CO_2$, accounting for around 8% of global emissions, mainly from limestone calcination and fossil fuel combustion (IEA, 2024). The cost of producing traditional Portland cement averages US$75–100 per tonne, while low-carbon cement made with alternative binders, supplementary cementitious materials (SCMs) like fly ash or slag, and carbon capture technologies costs around US$120–150 per tonne today (Global Cement and Concrete Association [GCCA], 2023).

Despite higher initial costs, operational savings are achievable through fuel efficiency, renewable heat integration, and carbon avoidance. Carbon pricing at US$100 per tonne of $CO_2$ could make carbon-captured cement cheaper than conventional cement by 2030. For a 5 million tonne cement plant, adopting waste heat recovery and SCM substitution (30–40%) can save US$20–30 million annually in fuel and carbon costs. Additionally, substituting biomass or hydrogen for coal can reduce fuel expenditure by 15–25%, or approximately US$10–15 per tonne of product. In Africa, where cement demand is growing by 5–7% annually, introducing clinker substitutes from local agricultural residues (e.g., rice husk ash, pozzolans) could cut both production costs and emissions. A typical Nigerian cement factory producing 2 million tonnes annually could save around ₦15–20 billion (US$12–15 million) per year through lower fuel imports and improved efficiency.

### Chemicals & petrochemicals

The chemical and petrochemical industries constitute one of the most energy-intensive and carbon-intensive segments of the global economy. They are essential for producing the materials that underpin modern society plastics, fertilizers, solvents, synthetic fibers, and countless other intermediates yet their heavy reliance on fossil fuels and feedstocks presents profound challenges for decarbonisation. According to the Intergovernmental Panel on Climate Change (IPCC, 2022), the sector accounts for approximately 5–8% of total global $CO_2$ emissions, both from the combustion of fuels to generate heat and from the chemical transformation of hydrocarbons into products that embed carbon within their molecular structures. The International Energy Agency (IEA, 2023) highlights that this dual dependency on fossil fuels as both an energy source and as a feedstock complicates decarbonisation efforts compared with sectors that primarily consume energy for heat or electricity alone.

### Challenges in Decarbonising the Chemical and Petrochemical Sector

The primary challenge lies in the intrinsic nature of chemical production. Many processes rely on hydrocarbons such as naphtha, natural gas, and oil not only to provide high-temperature heat but also as a source of carbon atoms incorporated into products such as polyethylene, polypropylene, methanol, and ammonia. For example, ammonia production through the Haber–Bosch process depends on hydrogen derived from natural gas via steam methane reforming (SMR), which emits substantial amounts of $CO_2$ (IEA, 2022). Similarly, ethylene and propylene core building blocks of plastics are produced via naphtha or ethane cracking, which involves high-temperature pyrolysis and results in direct emissions from fossil fuel combustion (Worrell et al., 2019).

Furthermore, the chemical sector is highly diverse, comprising thousands of processes, each with different feedstock requirements, reaction mechanisms, and energy demands. This complexity means there is no universal decarbonisation pathway; rather, multiple tailored approaches are required depending on the product and region. Compounding this challenge is the sector's integration within industrial clusters, where multiple facilities share feedstocks, energy systems, and by-product streams (Material Economics, 2018). This interdependence makes transitioning to low-carbon alternatives logistically and economically complex.

### Electrification of Heat and Processes

One major decarbonisation lever is electrification, particularly the use of renewable electricity to provide process heat and drive electrochemical transformations. Traditional chemical processes such as ethylene cracking or methanol synthesis require extremely high temperatures often exceeding 800°C traditionally supplied by fossil fuel combustion. Advances in electric heating technologies, including plasma-assisted and resistive heating, offer potential alternatives that can be powered by renewable energy sources (Lechtenböhmer et al., 2016). For example, pilot projects in Europe are testing electrified steam crackers capable of producing ethylene with nearly zero direct $CO_2$ emissions when powered by renewable electricity (IEA, 2023).

Electrification also extends to electrochemical and photochemical pathways that can synthesize chemicals directly from $CO_2$ and water using renewable electricity. Although still at the pilot stage, these technologies have the potential to disrupt conventional feedstock dependence on fossil resources. However, barriers remain: the high capital costs of retrofitting plants, the need for stable renewable electricity supplies, and the challenge of achieving the high temperatures and reaction efficiencies required for large-scale chemical synthesis (IEA, 2022).

### Green Hydrogen as an Energy Carrier and Feedstock

Hydrogen plays a dual role in the chemical industry as a reducing agent in ammonia and methanol production and as a potential low-carbon energy carrier. Currently, around 95% of industrial hydrogen is produced from natural gas or coal through processes that emit roughly 900 million tonnes of $CO_2$ annually (IEA, 2023). Transitioning to green hydrogen produced via water electrolysis using renewable electricity can drastically reduce these emissions.

Green hydrogen is especially critical for ammonia production, where it replaces fossil-derived hydrogen in the Haber–Bosch process. Similarly, methanol can be synthesized using green hydrogen combined with captured $CO_2$, offering a potential carbon-neutral pathway for both fuel and chemical feedstock production (IRENA, 2022). The use of hydrogen-based processes can also enable synthetic hydrocarbons for downstream products, effectively closing the carbon loop if $CO_2$ is captured and reused.

However, large-scale deployment of green hydrogen faces economic and logistical hurdles. Electrolyzer technologies remain costly, renewable power generation must expand significantly to meet industrial hydrogen demand, and transport and storage infrastructure need development (Bazzanella & Ausfelder, 2017). Despite these challenges, pilot projects in Europe, Japan, and Australia demonstrate that industrial-scale green hydrogen can be viable under supportive policy frameworks and declining renewable energy costs.

### Circularity and Feedstock Switching

Another cornerstone of chemical-sector decarbonisation is circularity the design of systems that minimize waste, maximize recycling, and reuse carbon already in circulation. Currently, less than 15% of global plastic waste is recycled, and only a fraction of that is reused for high-quality applications (Geyer et al., 2017). Scaling up mechanical and chemical recycling can significantly reduce the need for virgin fossil feedstocks. Mechanical recycling reprocesses plastic waste into secondary materials, while chemical recycling breaks polymers down into their original monomers or feedstock molecules for reuse in petrochemical production (IEA, 2023).

In parallel, bio-based feedstocks derived from agricultural residues, algae, or biomass offer renewable carbon sources for producing bioplastics and other chemicals. However, bio-based production must balance land-use impacts, feedstock availability, and potential competition with food supply (Material Economics, 2018). Moreover, $CO_2$-based feedstocks using captured $CO_2$ as a carbon input for producing methanol, urea, or synthetic fuels represent a promising pathway to circular carbon use. While these routes remain energy-intensive and technically complex, they align with broader strategies for achieving net-zero industrial emissions.

### Carbon Capture, Utilization, and Storage (CCUS)

Given the chemical sector's reliance on carbon-based feedstocks, CCUS is indispensable for managing residual emissions that cannot be eliminated through electrification or green hydrogen alone. CCUS can capture $CO_2$ from process streams, such as ethylene crackers or ammonia reformers, and either store it permanently in geological formations or reuse it as a feedstock for chemical synthesis. For instance, methanol and urea plants can integrate $CO_2$ utilization as part of their production cycle, reducing net emissions (IEA, 2023).

Nevertheless, CCUS deployment in chemical and petrochemical clusters faces technical and economic barriers. These include the integration of capture systems into existing plants, the availability of storage sites, and the costs of $CO_2$ transport infrastructure (IPCC, 2022). The long payback period for CCUS investments also deters private-sector adoption unless supported by strong carbon pricing mechanisms or government incentives.

### Barriers and Pathways Forward

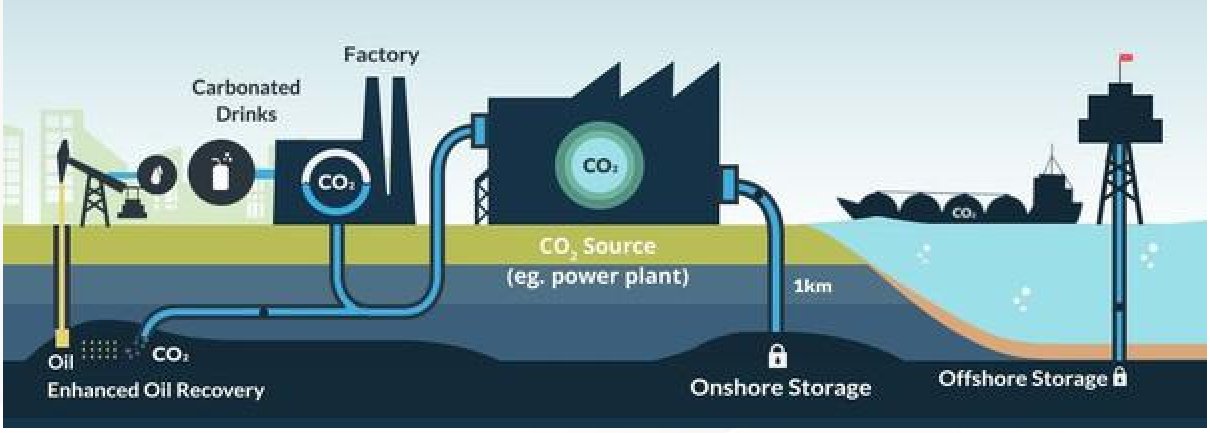
Decarbonising the chemical sector requires overcoming several systemic barriers. Feedstock availability remains a challenge for both bio-based and recycled materials, particularly in regions lacking advanced waste management systems. The economics of recycling versus virgin production often favour new plastics due to lower fossil fuel prices and established supply chains (Geyer et al., 2017). Integrating CCUS and hydrogen infrastructure within dense industrial zones also requires coordinated investment, shared pipelines, and robust policy support (IEA, 2022).

Ultimately, a combination of technological innovation, circular economy principles, and enabling policy frameworks will be necessary to decarbonize the chemical and petrochemical industries. Governments must incentivize low-carbon investments through carbon pricing, green public procurement, and research funding. Industry collaboration is equally critical, as shared infrastructure and industrial symbiosis can reduce costs and accelerate the adoption of cleaner technologies.

As global demand for chemicals continues to grow especially in emerging economies balancing industrial development with decarbonisation imperatives will determine whether the sector contributes to or hinders the world's net-zero transition.

### Carbon Capture, Utilisation, and Storage (CCUS)

For industrial processes that inherently produce $CO_2$ such as cement calcination or chemical reforming carbon capture, utilisation, and storage (CCUS) is one of the few available mitigation pathways. CCUS technologies capture $CO_2$ from flue gases or directly from the atmosphere and either store it in geological formations or reuse it in products such as synthetic fuels, plastics, or building materials (IEA, 2022). The IEA's Net Zero by 2050 roadmap highlights CCUS as critical to achieving deep decarbonisation, particularly for industries where emissions stem from process chemistry rather than fuel combustion.




CCUS operations (Global CCS Institute)

Practical deployments illustrate both promise and challenge. Norway's Longship project, which includes the Northern Lights $CO_2$ storage facility, represents a significant milestone in cross-sector collaboration, integrating cement and waste-to-energy sources for carbon capture and offshore storage (IEA, 2023). Similarly, in Texas, the Petra Nova project demonstrated post-combustion capture from a coal-fired power plant, although economic volatility limited its continuity (Global CCS Institute, 2022). The key challenges include high capital costs, energy penalties associated with capture processes, and public acceptance of $CO_2$ storage. Moreover, in developing economies, CCUS deployment is hindered by limited geological data, weak regulatory frameworks, and high financing risks. Nonetheless, international cooperation through mechanisms like the Clean Energy Ministerial's CCUS Initiative can facilitate knowledge transfer and cost-sharing.

**Circularity, Material Efficiency, and Demand Reduction**

A circular economy approach seeks to minimize resource extraction and emissions by keeping materials in use for as long as possible through reuse, recycling, and design efficiency. Material efficiency strategies such as lightweight construction, modular design, and improved product durability can substantially reduce demand for emissions-intensive materials like steel, cement, and plastics (Material Economics, 2020). Recycling steel scrap through electric arc furnaces can cut emissions by up to 75% compared to primary steelmaking (IEA, 2023). Similarly, substituting clinker in cement with industrial by-products such as fly ash or slag can lower both process and energy emissions.

Circularity is also critical in the chemical sector, particularly for plastics. Chemical recycling technologies can convert waste plastics into feedstock for new production, reducing reliance on virgin fossil feedstocks. The Ellen MacArthur Foundation (2021) reports that scaling circular plastics strategies could cut annual global emissions by 40–50 Mt $CO_2$e by 2040. In developing economies, strengthening waste collection and informal recycling sectors presents a dual opportunity improving livelihoods while reducing environmental impacts.

Demand reduction complements circularity by tackling consumption patterns directly. For example, using alternative building materials like timber and promoting car-sharing or modal shifts in transport reduce aggregate demand for high-emission products and fuels. A study in *Nature Sustainability* found that demand-side measures could lower required carbon removal volumes by up to 40% by 2050 (Creutzig et al., 2022).

**Policy and Finance to De-Risk Transitions**

The technological solutions described above will only succeed if underpinned by coherent and well-designed policy and financial frameworks. Industrial decarbonisation involves long-lived assets, high capital intensity, and uncertain market signals making government intervention essential to de-risk private investment. Carbon pricing mechanisms, such as the EU Emissions Trading System, create long-term pric signals for emission reductions. Meanwhile, public procurement policies that favour low-carbon materials can generate “first-mover” markets for green steel, cement, and hydrogen (IEA, 2023).

Financial instruments, including concessional loans, green bonds, and blended finance, play a crucial role in mobilising capital, especially in emerging economies. The World Bank’s Climate Investment Funds and the African Development Bank’s Sustainable Energy Fund for Africa have begun supporting industrial decarbonisation projects across developing regions (AfDB, 2023). Additionally, regulatory standards such as zero-emission vehicle mandates and lifecycle carbon intensity thresholds create predictable demand for clean technologies.

Ultimately, systemic transformation in hard-to-abate sectors hinges on integrating technology, finance, and governance. The transition must balance climate ambition with economic competitiveness and social inclusion, ensuring that workers and communities dependent on carbon-intensive industries are supported through retraining and social protection programs. Coordinated international frameworks like those fostered under the Paris Agreement and the

Mission Innovation initiative can accelerate learning, cost reduction, and equitable participation in the global decarbonisation effort (UNFCCC, 2023).

### Examples of Companies Decarbonising

#### BASF SE

BASF SE is one of the world's largest chemical companies, headquartered in Ludwigshafen, Germany. In 2023, its revenue was approximately €68.9 billion (or about USD 73.1 billion) according to official reporting.

BASF is actively investing in electrification, renewable feedstocks, and circularity to decouple chemicals production from fossil inputs. A flagship initiative: in 2025, the company's Intermediates division converted its entire European amines portfolio to manufacturing using 100% renewable electricity, which is expected to reduce $CO_2$ emissions by about 188,000 tons annually (versus 2020 levels). In its Performance Materials division, BASF achieved a full switch to renewable electricity at all European sites (covering engineering plastics, polyurethanes, specialty polymers) as of January 1, 2025. This shift conforms with BASF's goal of greener internal operations to set the foundation for greener products.

The company also launched an electric steam cracker furnace in Ludwigshafen one of the first industrial-scale efforts to replace fossil-fuel heating with electric resistance heating in a chemical cracker. Though the feedstock remains fossil-derived, the move demonstrates electrification of energy-intensive processes.

Moreover, BASF has secured public funding support for innovations in low-carbon feedstock production. For instance, in 2024, the U.S. Department of Energy selected BASF for negotiations to receive up to USD 75 million to pilot electrified syngas production (from recycled chemical byproduct streams) at its Freeport, Texas site part of its broader strategy toward circular chemistry.

Even as BASF charts a robust pathway, it faces significant challenges. The chemical industry is highly energy-intensive, so the cost and availability of renewable electricity and green feedstocks remain critical constraints. Scaling electrified processes (like the electric cracker) is technically demanding and capital-intensive.

**SABIC** (Saudi Basic Industries Corporation)

SABIC is one of the world's major petrochemicals companies, based in Saudi Arabia and majority-owned by Saudi Aramco. In 2023, SABIC reported full-year revenue of SAR 141.54 billion (roughly US$ 37.74 billion) amid a challenging global chemicals market (SABIC, 2024). SABIC has begun pushing initiatives to reduce its greenhouse gas emissions, recognizing that the petrochemicals industry is energy- and feedstock-intensive. The company is investing in electrification, carbon capture, utilization, and storage (CCUS), and alternative feedstocks as key levers for decarbonization. One example is SABIC's involvement in a project with BASF and Linde to build the world's first electrically heated cracker furnace, intended to reduce $CO_2$ emissions relative to conventional steam cracking technologies (SABIC, 2024).

Another major pillar is efficiency improvements and portfolio optimization: SABIC aims to optimize its plants, reduce energy intensity, and switch to zero- or low-carbon feedstocks where feasible. It has also joined national programs in Saudi Arabia, such as the Circular Carbon Economy National Program (CCE-NP), which supports large-scale CCUS infrastructure, with SABIC targeting capture of up to 2,000 kilotons of $CO_2e$ annually by 2030 via these efforts.

To support its decarbonization roadmap, SABIC is deploying capital and forming strategic partnerships. For example, the company is investing in the Fujian Petrochemical Complex in

China – a major joint venture involving SABIC, with downstream facilities for polymers and chemicals. While this is not purely a decarbonization project, it reflects SABIC's strategic investment footprint in growing capacity and applying advanced technology (SABIC, 2024).

SABIC has also made progress in partnerships for sustainability innovation. Collaboration with BASF and Linde on the electric cracker, participation in the chemicals recycling and circular feedstock efforts (e.g. ISCC+-certified polymers) are part of their strategy to reduce carbon intensity.

### Dow (United States)

Dow has adopted a "Decarbonize & Grow" strategy that combines aggressive investment in low-carbon technologies with expansion into higher-growth, sustainable product lines. A key component is its plan to build a world-scale carbonate solvents facility on the U.S. Gulf Coast, intended to support the battery and EV supply chain (specifically, electrolyte components for lithium-ion batteries). Crucially, this facility is designed to capture more than 90% of carbon dioxide emissions from its ethylene oxide manufacturing processes. It is part of Dow's move toward value-added, low-carbon derivative products (Dow, 2024).

Another flagship project is the net-zero carbon emissions ethylene and derivatives complex at its Fort Saskatchewan site in Alberta, Canada. This complex aims to decarbonize approximately 20% of Dow's global ethylene capacity, including a retrofit of existing assets, deployment of hydrogen / CCUS (carbon capture, utilization, and storage), and increased production of certified low- or zero-carbon polyethylene and related derivatives. The facility is expected to deliver a material reduction in greenhouse gas emissions while expanding Dow's output (Dow, 2024).

### Clean Energy, Electrification & Operational Improvements

Dow has also taken steps to shift its energy usage toward cleaner power sources. It has signed numerous renewable power purchase agreements (RPAs) across Europe, the Americas, and Latin America to move sites toward using renewable electricity. For example, in one round of agreements, Dow secured an additional ~132 MW of clean power, bringing its total access to more than 850 MW of clean energy from wind and solar (Dow, 2021). Dow also plans several infrastructure-level shifts: for example, its Seadrift, Texas site is under plans to be powered not only by renewables but also by advanced nuclear (via a partnership with X-Energy) so the site can reduce emissions associated with power and steam generation by hundreds of thousands of metric tons annually (Dow, 2024).

In its manufacturing operations, Dow is replacing older, less efficient assets with lower-carbon technologies. This includes early work on “e-cracking” (electric heating of cracking furnaces), fluidized catalytic dehydrogenation (FCDh), and more efficient process designs to reduce Scope 1 and 2 emissions. Dow aims to invest around $1 billion per year, averaged across economic cycles, in its asset base to reduce emissions, while targeting large gains in earnings (Dow, 2024). Dow’s focus on renewable electricity, hydrogen, CCUS, and possibly advanced nuclear indicates that a portion of its capex is being reallocated toward sustainability. External analyses (e.g. Planet Tracker) suggest that more than 60% of Dow’s capital expenditures in coming years will be devoted to projects with environmental sustainability drivers, including circularity and low-carbon technologies.

### Cost and Savings

The chemicals and petrochemicals sector is both energy- and feedstock-intensive, relying heavily on natural gas and naphtha for producing ammonia, methanol, and plastics. The pathway to decarbonisation involves green hydrogen, electrified steam cracking, and carbon capture, utilisation, and storage (CCUS) (IEA, 2024). Current production costs for conventional ammonia stand at about US$300–400 per tonne, while green ammonia costs around US$800–1,000 per tonne. However, with falling hydrogen prices, the cost is expected to drop to US$450–600 per tonne by 2035 (McKinsey, 2023).

Energy efficiency improvements in chemical plants such as electrification of heat processes and waste heat recovery can reduce energy use by 15–25%, translating to savings of US$20–40 per tonne of output. For a medium-sized petrochemical plant producing 500,000 tonnes annually, this equates to US$10–20 million in annual savings. Furthermore, carbon penalties (estimated at US$100–150 per tonne $CO_2$) could add US$50–100 million per year in costs for non-decarbonised producers costs that clean technology adopters would avoid. In the African context, especially in Nigeria, Egypt, and Algeria, integrating green hydrogen into existing ammonia and fertilizer production could substantially cut import dependency. Nigeria’s Dangote Fertilizer Plant, for instance, could reduce its natural gas consumption by 20–30%, saving US$50–70 million annually while improving energy security.

In all, decarbonising the industrial and building sectors is a cornerstone of global emissions reduction, as these sectors collectively account for nearly 40 % of energy-related $CO_2$ emissions. Across heavy industries such as steel, cement, chemicals, and petrochemicals, low-carbon technologies including electrification, hydrogen integration, energy efficiency improvements, carbon capture, and process optimisation have already demonstrated significant environmental and economic impact. For steel production, the shift from blast furnaces to electric arc furnaces powered by renewable electricity or green hydrogen has the potential to reduce direct emissions by 50–70 % per tonne of steel, while lifecycle energy costs can drop by 20–30 % in regions with low-cost renewable electricity. Similarly, in cement and concrete, fuel switching to biofuels or electrification of clinker production, combined with energy-efficiency retrofits, can cut emissions by 30–40 % and operating expenses by up to 25 %. In chemicals and petrochemicals, process electrification, heat recovery systems, and green hydrogen adoption reduce emissions intensity substantially, with global studies indicating potential cumulative savings of 200–300 Mt $CO_2$ per year by 2030 under moderate adoption scenarios.

Globally, capital deployment in industrial decarbonisation has surged, with estimates exceeding US$200 billion in renewable electrification, energy efficiency, and hydrogen projects across Asia, Europe, and the Americas. Asia leads in absolute capacity, leveraging low-cost renewables and high industrial density, while Europe has aggressively integrated industrial clusters with green hydrogen and electrification solutions, achieving measurable reductions in system-level carbon intensity. The Americas, particularly the U.S., have invested heavily in carbon capture retrofits and renewable-powered electrification in heavy industry. Africa and the Middle East remain early-stage adopters, with targeted investments focusing on pilot projects and green energy integration to offset diesel and fossil fuel dependence.

In Nigeria, industries and commercial buildings are increasingly transitioning to renewable energy sources, solar mini-grids, and energy-efficient retrofits, driven by rising electricity costs and the need to reduce operational expenditures. Companies adopting solar and hybrid solutions are reporting fuel savings of 60–75 %, translating to US$10,000–100,000 annually per medium-sized facility. Industrial pilot projects integrating green hydrogen and electrification have demonstrated both emissions reductions and long-term cost efficiency, indicating that even with high upfront capital costs, total cost of ownership declines over a 5–10-year horizon.

Collectively, these interventions have not only reduced carbon emissions across sectors but also generated substantial economic benefits. Globally, energy savings and operational efficiency gains in industrial and building sectors now represent billions of dollars annually, with cumulative $CO_2$ reductions measurable in hundreds of millions of tonnes per year. Nigeria's adoption, though nascent, signals that coordinated investment, technology deployment, and policy support can drive both environmental and economic returns, demonstrating that decarbonising industry and buildings is both feasible and financially rewarding.

Decarbonising industry and buildings offers one of the most powerful pathways for climate action, economic modernization, and long-term competitiveness. From low-carbon materials and electrified production to efficient, digitally managed buildings, cleaner technologies are proving more cost-effective, resilient, and future-ready. As this transformation accelerates, the next frontier becomes clear: unlocking the full power of Platform Capital to scale decarbonisation across Africa. The coming section will explore how innovative financing models, catalytic investment platforms, corporate-led capital deployment, and blended finance can accelerate technology adoption, deepen market penetration, and position Africa not as a late adopter, but as a global leader in the clean industrial and built-environment revolution.

# Section 5

# Platform Capital Driving Decarbonisation in Africa

### Platform Capital Driving Decarbonisation in Africa

Africa's decarbonisation journey extends far beyond the mere deployment of renewable technologies it fundamentally involves the creation of robust financial, infrastructural, and investment ecosystems that render clean energy and low-carbon solutions economically viable and scalable. Historically, high upfront capital requirements, grid limitations, and fragmented supply chains have constrained the adoption of green technologies across the African continent (IRENA, 2023). Platform Capital is strategically addressing these challenges through an innovation-driven investment model that reduces entry barriers, mitigates deployment risks, and accelerates commercial-scale adoption of decarbonisation technologies.

By leveraging mechanisms such as Power Purchase Agreements (PPAs), lease-based models, blended finance, and co-investment structures, Platform Capital allows businesses and public institutions to access solar, wind, battery storage, electric mobility, and green hydrogen solutions without incurring prohibitive upfront costs. This approach not only lowers the capital burden but also transforms energy expenditure from capital-intensive to operationally manageable, enabling adopters to benefit immediately from cost savings (McKinsey & Company, 2023). The impact is measurable across multiple dimensions. In the energy sector, industrial facilities switching from diesel to solar or hybrid systems can achieve fuel cost reductions of 50–70%, translating to annual savings of hundreds of thousands of dollars per medium-sized facility. In transport, electrified fleets benefit from lower fuel and maintenance costs, while grid-connected storage systems optimize demand charges and enhance reliability (IEA, 2024).

Beyond individual adopters, the systemic benefits include reduced grid stress, improved energy security, and lower carbon emissions, fostering sustainable economic growth.

In essence, Platform Capital is not only enabling technology deployment but is also creating an ecosystem where operatioal efficiency, cost-effectiveness, and sustainability converge. By doing so, it ensures that Africa's decarbonisation trajectory is economically rational, socially inclusive, and technologically ambitious, unlocking both monetary and developmental value for adopters and the broader society.

### Driving Cost Savings Through Technology and Capital Innovation

Across Africa, one of the biggest barriers to adopting clean technologies is the high upfront capital cost whether for electric vehicles, renewable energy systems, hydrogen infrastructure, or industrial retrofits. Platform Capital addresses this through innovative financing models such as Power Purchase Agreements (PPAs), leasing schemes, project bundling, and co-investment platforms that enable users to access technology without incurring large upfront expenses. This approach translates directly into cost savings and financial flexibility for adopters.

For example:

Through partnerships with emerging African e-mobility startups and fleet operators, Platform Capital has been at the forefront of driving the transition agenda in Africa, investing in battery-electric vehicles (BEVs), charging networks, and smart grid integration. By leveraging Zero Capex and pay-as-you-drive financing arrangements, fleet operators can adopt clean mobility solutions without the barrier of high upfront capital costs. Adopters pay only for the kilometres driven or the kilowatt-hours consumed, effectively reducing initial capital outlays by up to 70%, while still benefiting from substantial operational savings, including fuel and maintenance reductions typically amounting to US$3,000–4,000 per vehicle annually. Electricity costs in the region average US$0.08–0.12/kWh, compared with petrol prices of US$0.67/litre, allowing fleet operators to achieve fuel savings of around 65% and annual cost reductions of US$2,000–4,000 per vehicle. These operational savings, combined with lower maintenance requirements due to fewer moving parts and regenerative braking, significantly improve fleet economics, shortening payback periods and enhancing financial sustainability.

A prime example of Platform Capital's strategic advisory impact is its engagement with Metropolitan Electric Limited, which is establishing Nigeria's first Completely Knocked Down

(CKD) Electric Vehicle assembly plant. With Platform Capital's guidance, Metropolitan Electric successfully navigated financing, regulatory, and operational challenges while securing critical offtake partnerships with the National Union of Road Transport Workers (NURTW), Nigerian Police Force, Lagos State Government, and Oyo State Government. These agreements provide guaranteed market uptake, revenue certainty, and scalable deployment for EVs, demonstrating how strategic advisory and market linkages complement financial innovation to accelerate adoption.

Platform Capital's ambition does not end on the ground. With its investment in Leo Flight Corporation, a U.S.-based aerospace startup developing the LEO Coupe eVTOL aircraft, the company is taking the decarbonization agenda to the skies. The LEO Coupe represents a new era of electric vertical take-off and landing (eVTOL) technology, designed for urban and personal air mobility. Platform Capital's early involvement in this groundbreaking venture positions it at the frontier of sustainable aviation technology. This investment aligns with the company's mission to bridge global innovation and African advancement. By fostering partnerships with technology firms at the cutting edge of electrification, Platform Capital ensures that Africa is not a passive observer but an active participant in shaping the next wave of transportation innovation. The firm's role in promoting eVTOL technology signals its belief that Africa can leapfrog outdated models and directly integrate sustainable, clean technologies into its transport ecosystem.

By combining innovative financing, advisory support, and market development, Platform Capital not only reduces entry costs for adopters but also creates an ecosystem where clean mobility solutions can scale rapidly. This approach underscores that decarbonisation is not merely a technological challenge but a coordinated effort spanning capital innovation, infrastructure deployment, and institutional collaboration, delivering measurable financial and environmental benefits for private operators, public stakeholders, and the wider Nigerian economy (IRENA, 2023; IEA, 2023).

In renewable energy deployment, Platform Capital has emerged as one of the largest technology investors in Africa, with a portfolio spanning multiple sectors, including energy, transport, industrial solutions, and sustainability-focused innovations. Within the renewable energy space, Platform Capital has strategically deployed both capital and advisory resources to enable businesses, hospitals, educational institutions, and industrial facilities to transition from costly diesel-based power to clean solar and hybrid energy systems. These investments are designed to reduce operational expenditure, enhance energy security, and accelerate decarbonisation across the continent. Through its Sustainable Green Energy product, Platform Capital provides a Zero Capex pathway for companies seeking to adopt renewable energy. Under this model, adopters can leverage solar and hybrid systems without incurring large upfront costs, instead paying for energy as it is consumed. This approach effectively converts traditionally capital-intensive investments into manageable operational expenses, enabling fuel savings of 60–75%, which translates to annual saving that run to the tune of millions in dollars for medium-sized facilities depending on energy consumption patterns.

Platform Capital also invests in innovative energy companies such as Koko Networks and Sanivation, which are pioneering clean energy and waste-to-energy solutions in Africa. Koko Networks provides efficient, clean cookstove technology and distributed energy solutions, reducing reliance on conventional fuels, while Sanivation transforms organic waste into clean fuel briquettes for institutional and community use. By backing these companies, Platform Capital expands access to sustainable energy technologies and strengthens the broader clean energy ecosystem, demonstrating scalable and impactful solutions for energy-intensive sectors. In the industrial sector, Platform Capital has extended its investments to solar mini-grids and green hydrogen demonstration projects, enabling local manufacturers to reduce diesel dependence. Switching to solar or green hydrogen lowers energy costs from approximately US$0.25/kWh (diesel) to US$0.10–0.12/kWh, yielding annual savings of 40–60%. For a 1 MW industrial facility consuming 8 GWh annually, this translates into US$1 million in yearly savings. By financing and aggregating industrial demand through joint-venture frameworks, Platform Capital reduces financing costs and ensures economies of scale, making clean energy adoption financially viable and operationally impactful.

In collaboration with local manufacturing firms, Platform Capital is facilitating energy-efficient retrofits in steel, cement, and chemical sectors. By deploying electric arc furnaces, waste heat recovery systems, and green hydrogen pilots, industrial partners can achieve energy efficiency gains of 20–30%, resulting in savings of US$20–40 per tonne of product. Over a year, a medium-scale steel mill can save US$10–15 million in energy and carbon costs while positioning for green certification premiums in export markets.

Overall, Platform Capital's renewable energy initiatives through direct investments, advisory, and innovative financing models deliver substantial financial and operational benefits, enabling African adopters to cut fuel costs, reduce emissions, and secure a reliable energy supply. By combining capital innovation with strategic partnerships, Platform Capital continues to lead Africa's energy transition, proving that clean energy adoption can be both economically advantageous and environmentally transformative.

### Sustainable Construction and Industrial Transformation

In the construction sector, where emissions are driven by cement and concrete production, Platform Capital's strategy is informed by global best practices and local realities. Through research-driven partnerships and investments in low-carbon building technologies, the company supports projects that reduce reliance on high-emission materials and promote energy efficiency in construction. This approach mirrors what global industry leaders like Holcim and Heidelberg Materials are achieving through carbon capture and sustainable materials, but Platform Capital's distinctive contribution lies in local adaptation and financial structuring. By channelling investment into green building startups and sustainable materials research, the company ensures that Africa's urbanization inevitable and rapid unfolds in a way that respects both the environment and the economy.

### Leadership Through Partnership and Knowledge

Decarbonization is not a solo mission; it is a collaborative pursuit. Platform Capital's strength lies in its ability to build partnerships that blend global expertise with local insight. Through strategic collaborations with governments, private investors, research institutions, and international organizations, the company has cultivated an ecosystem that accelerates Africa's low-carbon transformation. These partnerships are built on trust, credibility, and shared purpose. The company's emphasis on capacity building and knowledge transfer ensures that Africa is not just a recipient of solutions but a producer of innovation. Platform Capital's involvement in sustainability-focused dialogues, climate finance forums, and green investment networks underscores its thought leadership and influence in shaping Africa's policy and investment direction.

### Financial Innovation as a Decarbonisation Enabler

Platform Capital's decarbonisation strategy in Africa goes beyond technology deployment; it is firmly anchored in innovative financial engineering and risk-sharing models that directly address the economic constraints faced by industries across the continent. One of the key pillars of this approach is carbon credit monetisation, whereby adopters can convert their verified greenhouse gas emission reductions into tradable carbon credits, creating an additional revenue stream that enhances project economics. By capturing the financial value of decarbonisation, companies can offset operational costs and accelerate the payback period on clean energy or low-carbon investments.

Another core element of Platform Capital's strategy is hybrid financing, which blends equity, concessional loans, and green bonds to reduce project risk and lower financing costs. By optimising the capital structure and leveraging concessional funding where available, adopters can reduce the effective cost of capital by up to 30%, making large-scale transitions such as solar, hybrid energy systems, hydrogen infrastructure, or electric vehicle deployment financially feasible. This approach is particularly impactful in Africa, where access to affordable project financing has historically been a barrier to clean technology adoption.

Platform Capital also places strong emphasis on local capacity development, training technicians, engineers, and operational staff to service and maintain deployed technologies. By reducing dependence on imported services and specialised foreign expertise, maintenance costs decline, system uptime improves, and operational resilience is strengthened. Combined, these financial and capacity-building interventions enable adopters to realise net-positive returns within **3–6 years,** a critical timeframe that fosters investor confidence and supports the scalability of clean technology projects. By linking capital innovation with practical operational support and monetisation mechanisms, Platform Capital demonstrates that decarbonisation in Africa is not only environmentally necessary but also economically compelling, creating a framework where sustainability and profitability reinforce one another (IRENA, 2023; IEA, 2023).

### Why Platform Capital is Africa's Most Prepared Decarbonization Partner

What distinguishes Platform Capital is not merely its investment capacity but its strategic foresight and integrated approach. While many organizations are just beginning to explore green transition, Platform Capital has already built a robust portfolio of climate-aligned investments that span multiple sectors energy, transportation, manufacturing, and aviation. Its expertise in sustainability financing, project structuring, and carbon asset management positions it as the most capable partner for governments and businesses seeking to transition responsibly. The firm understands the economics of decarbonization the balance between upfront investment and long-term gain, between environmental targets and financial viability.

Moreover, Platform Capital's zero-capex model is proof that financial innovation can unlock large-scale sustainability impact in emerging markets. By removing the cost barrier, it enables African industries to adopt renewable energy and carbon mitigation practices without sacrificing competitiveness. This practical, solutions-driven approach embodies the company's ethos: innovation that serves people and planet alike.

Africa stands at a historic crossroads. The continent can either follow the carbon-intensive trajectory of past industrial revolutions or leapfrog into a sustainable, inclusive, and prosperous future. The difference will be made by institutions like Platform Capital institutions that combine vision with execution, capital with conscience, and profit with purpose. Platform Capital's commitment to decarbonization is not a fleeting corporate agenda but a long-term developmental mission. Its investments are shaping the next generation of African industries cleaner, smarter, and more resilient. Its financing structures are redefining how sustainability is funded. Its partnerships are bridging the gap between ambition and action. While its leadership is proving that Africa can, and will, lead the global transition to a low-carbon economy.

The time for Africa is now and the engine driving that transformation is already in motion. With its proven expertise, expansive network, and unwavering vision, Platform Capital stands as the most prepared, most capable, and most visionary driver of decarbonization across Africa and Nigeria.

# Section 6

# Outlook: Africa, Nigeria, and the Next Decade of Decarbonisation

### Outlook: Africa, Nigeria, and the Next Decade of Decarbonisation

The coming decade will define how effectively economies reconcile climate imperatives with industrial competitiveness. For Africa and Nigeria in particular this moment presents a rare convergence of necessity and opportunity. Africa's emissions disparity is stark. With **18% of the world's population**, it contributes only **~3% of global annual $CO_2$ emissions** and **~3% of historical cumulative emissions**. Its per capita emissions average **~0.8 tonnes $CO_2$**, compared to the global average of **~4.7 $tCO_2$** and **~14 $tCO_2$** in North America. At the same time, Africa's rapid population growth, urbanisation, and industrial expansion mean that today's investment and technology choices will lock in either high-carbon vulnerability or low-carbon resilience for generations. The decisive question is not whether Africa will grow, but how.

The global pivot toward decarbonisation has made the carbon economy central to industrial strategy, risk management, and long-term value creation. Energy systems, transport networks, industrial processes, and buildings are being re-engineered around efficiency, electrification, and renewables, with over **$1.7 trillion** invested annually in the energy transition. For the oil, gas, and mining sectors—which contribute over **25%** of GDP and **~70%** of export earnings in several major African economies—the challenge is profound, but so is the opportunity. The future does not lie in abandonment, but in transformation: leveraging Africa's **40%** global reserve of critical minerals and vast solar potential to lower emissions, cut costs, and reposition these industries as competitive players in a carbon-constrained global economy.

Africa is uniquely positioned within the global energy and climate transition. The continent holds approximately 60 percent of the world's most competitive solar resources, alongside vast wind corridors, significant hydropower potential, and an abundance of critical minerals such as lithium, cobalt, manganese, and rare earth elements that underpin batteries, electric vehicles, and renewable energy technologies. This natural endowment creates a structural advantage that, if effectively harnessed, allows Africa to move beyond being a passive consumer of imported clean technologies to becoming an active producer and exporter within global low-carbon value chains. Nature-based solutions, renewable electricity, green hydrogen, and industrial decarbonisation initiatives collectively place Africa at the centre of emerging carbon markets and climate-aligned trade flows.

However, this potential remains largely unrealised because many African countries have yet to establish the regulatory, institutional, and market frameworks required for a functioning carbon economy. Carbon markets across the continent are fragmented, inconsistently regulated, and often lack credible measurement, reporting, and verification systems. In addition, the absence of clear carbon ownership rules, standardised registries, and alignment with international compliance mechanisms such as Article 6 of the Paris Agreement continues to limit Africa's ability to attract high-integrity climate finance and participate meaningfully in global climate-aligned trade.

As global demand for verified carbon credits and low-carbon products accelerates, the cost of inaction is rising. It is therefore imperative that African countries urgently develop coherent carbon market frameworks, strengthen institutional capacity, and harmonise policies across borders. Doing so will unlock investment, ensure credibility, and enable Africa to capture its fair share of value in the rapidly expanding global carbon economy.

Policy momentum is reinforcing Nigeria's decarbonisation outlook, but it is equally important to interrogate the adequacy of existing frameworks and the institutional gaps that continue to constrain effective implementation. Across Africa, Nationally Determined Contributions (NDCs) under the Paris Agreement have helped translate climate ambition into sectoral priorities, providing high-level direction for renewable energy expansion, low-carbon transport, and climate finance mobilisation. However, in many jurisdictions—including Nigeria—these commitments remain largely aspirational, with limited enforceability, weak coordination mechanisms, and insufficient linkage between policy intent and on-the-ground execution.

In Nigeria, the Energy Transition Plan (ETP) articulates a pathway toward achieving net-zero emissions by 2060 across five critical sectors: power, cooking, oil and gas, transport, and industry. The plan reflects an awareness of Nigeria's development realities, seeking to balance emissions reduction with energy access, industrial expansion, and job creation. While these objectives are commendable and directionally sound, the ETP remains modest when benchmarked against the ambition and scale of comparable frameworks emerging across other African economies. Notably, Nigeria's projected carbon market revenue of approximately US$2.5 billion under the ETP significantly underestimates the country's true potential. Peer African countries, leveraging more robust regulatory frameworks and clearer market integration strategies, are targeting carbon revenues in excess of US$6 billion. Given Nigeria's size, population, industrial base, natural capital, and emissions profile, its carbon economy potential should exceed, not trail, continental comparators. A realistic near-term target would place Nigeria's carbon market potential at approximately US$10 billion, with a more ambitious but achievable upside of US$15 billion. The current targets therefore signal a gap in strategic ambition rather than resource endowment. Furthermore, the ETP functions primarily as a policy roadmap rather than a binding legal or regulatory instrument. Its effectiveness is consequently dependent on supporting legislation, enforceable standards, credible carbon accounting systems, and institutional capacity—areas where material deficiencies persist. Without these enabling mechanisms, Nigeria risks underperforming in a rapidly evolving African and global carbon economy.

The Climate Change Act of 2021 and the subsequent establishment of the National Council on Climate Change (NCCC) were intended to provide this institutional backbone. While these steps signal political recognition of climate risk at the highest level, the current structure and operational design of the NCCC fall short of international best practices. In leading climate governance systems globally, climate councils or authorities are typically endowed with clear statutory powers, operational independence, dedicated technical capacity, and strong enforcement mandates. By contrast, Nigeria's NCCC remains heavily centralised, administratively constrained, and insufficiently insulated from political cycles. Its role is largely advisory and coordinative, with limited authority to compel compliance, enforce emissions targets, or systematically integrate climate objectives into fiscal, industrial, and energy policy.

Furthermore, the existing framework lacks granular, sector-specific implementation pathways, clear accountability mechanisms, and transparent monitoring, reporting, and verification (MRV) systems aligned with global carbon markets. This creates uncertainty for private investors, particularly those seeking to deploy capital into long-term decarbonisation assets such as renewable infrastructure, industrial retrofits, or carbon credit projects. Without a clear legal and regulatory signal, capital mobilisation remains fragmented and risk-weighted, slowing the pace of transition.

It is within this context that the proposed Decarbonisation Act assumes critical importance. Currently at its second reading at the House of Assembly, the Decarbonisation Act has been developed to address these structural deficiencies and move Nigeria from high-level ambition to actionable execution. Unlike existing policy instruments, the Act is designed to embed decarbonisation targets into enforceable law, establish clear institutional roles, and define measurable pathways toward achieving Nigeria's 2060 net-zero goal. Crucially, it seeks to align national climate objectives with international best standards in governance, transparency, and market integration.

The Decarbonisation Act is expected to provide sector-specific obligations, define emissions baselines and reduction trajectories, and strengthen MRV frameworks necessary for participation in global compliance and voluntary carbon markets. It also aims to enhance investor confidence by reducing regulatory ambiguity, enabling predictable carbon pricing mechanisms, and supporting innovative financing models such as zero-capex decarbonisation projects and carbon-linked investments.

In effect, the Act represents a shift from intent to implementation. It recognises that achieving net zero by 2060 will not occur through policy statements alone, but through legally grounded, institutionally robust, and economically coherent action. If effectively enacted and operationalised, the Decarbonisation Act has the potential to correct existing governance gaps, catalyse private capital, and position Nigeria as a credible leader in Africa's low-carbon transition.

Yet ambition alone is insufficient. Africa's primary constraints remain the high cost of capital, infrastructure deficits, and limited access to scalable green finance. These barriers can render otherwise cost-competitive renewable and decarbonisation technologies financially unattractive when risk premiums are high. Overcoming this challenge requires innovative financing structures, credible measurement and verification frameworks, and platforms capable of blending local execution with global capital. This is where private-sector leadership becomes decisive.

Platform Capital's outlook is grounded in the conviction that decarbonisation in Africa must be commercially viable, industrially relevant, and locally anchored. The firm's approach recognises renewables, storage, and carbon solutions not as peripheral ESG add-ons, but as strategic tools for cost reduction, operational resilience, and long-term competitiveness. Across power generation, mobility, industry, and buildings, clean technologies are already outperforming fossil-based systems on operating cost, reliability, and scalability particularly in markets where grid instability and fuel price volatility are structural challenges.

In the extractive and industrial sectors, the transition is accelerating through hybrid solar systems, battery storage, energy efficiency, and low-carbon process technologies. These solutions reduce diesel dependence, stabilise energy supply in remote locations, and significantly lower emissions intensity. Zero-capex and power purchase agreement models are removing upfront financial barriers, enabling firms to decarbonise without constraining balance sheets. At the same time, the integration of carbon credits both compliance and voluntary creates additional revenue streams and risk-hedging mechanisms, positioning African projects as suppliers of high-integrity climate outcomes to global markets.

Carbon markets will be a defining pillar of this future. Rising global demand for verified carbon credits driven by regulatory compliance, corporate net-zero commitments, and investor scrutiny places Africa's nature-based and industrial decarbonisation assets at the centre of future value creation. However, meaningful participation requires more than project development. It demands robust governance, transparent monitoring and verification, and the ability to structure bankable projects at scale. Platform Capital's role as an enabler providing strategic advisory, financial engineering, and access to capital addresses precisely these gaps.

Nigeria exemplifies both the urgency and the promise of this transition. Chronic power shortages, high diesel costs, and growing industrial demand have made renewable energy not only an environmental choice, but an economic imperative. Corporates and manufacturers are increasingly adopting solar, storage, and hybrid systems as cost-reduction strategies, while electrification of transport and buildings offers further savings and emissions reductions. With the right capital structures and policy alignment, Nigeria can leverage its market size to become a regional hub for clean energy deployment, low-carbon manufacturing, and climate finance.

Looking ahead, Platform Capital's outlook is anchored on three interlinked priorities. First, scaling Africa-based decarbonisation and carbon credit projects through partnerships that span clean energy access, regenerative agriculture, circular waste systems, and industrial emissions reduction. Second, mobilising capital into bankable transition pathways across oil, gas, mining, and manufacturing integrating renewables, storage, zero-capex financing, and credible offset mechanisms. Third, deepening Africa's participation in global carbon governance by equipping corporates and governments with the tools to engage effectively in international frameworks, including Article 6 of the Paris Agreement.

The broader vision is clear: African industries should not remain passive buyers of imported technologies or offsets, but become active suppliers, innovators, and thought leaders within the global green economy. Achieving this will require transparency, skills development, and technology adoption at scale areas where platform-based investment models offer a decisive advantage. The green transition is no longer optional; it is inevitable. The winners will be those who move early, structure intelligently, and collaborate across capital, policy, and technology.

In this context, Africa and Nigeria in particular stands at a defining crossroads. With visionary leadership, strategic investment, and credible execution, the continent can leapfrog carbon-intensive development and emerge as a global reference point for climate-smart industrialisation. Platform Capital positions itself at the forefront of this transformation, ensuring that Africa's industries do not merely survive the coming shift, but thrive within it building environmental resilience, industrial competitiveness, and inclusive prosperity for decades to come.

# Conclusion

The story of Africa's decarbonization is not merely a tale of environmental necessity; it is a story of economic opportunity, technological empowerment, and social transformation. It is a story that reflects the ingenuity, resilience, and entrepreneurial energy of a continent poised to define the future of sustainable growth. Within this narrative, Platform Capital emerges as both an architect and an accelerator, leveraging its technical, financial, and institutional expertise to build a greener and more prosperous Africa.

Platform Capital's integrated approach to investment combining Zero-Capex Solar Solutions, carbon credit monetization, and climate financing innovation embodies what the new African economy should look like: financially sustainable, socially inclusive, and environmentally responsible. By investing in renewable energy infrastructure, sustainable mobility, and low-carbon industrial processes, the company is addressing the dual imperatives of economic competitiveness and climate resilience. What sets Platform Capital apart is its ability to transform complexity into opportunity. While others see the cost of transition, Platform Capital sees the value in carbon. While others focus on compliance, it focuses on innovation. And while many institutions are still theorizing about sustainability, Platform Capital is building the structures, systems, and partnerships that make decarbonization a practical reality across sectors.

Through its portfolio investments from Metropolitan Electric Limited's local EV assembly and Koko Networks' clean energy distribution to Leo Flight's electrified aviation technology the company is not only investing in industries but in the future of African lives. It is helping communities gain access to cleaner air, more affordable energy, and sustainable livelihoods. This community-centred impact reinforces Platform Capital's belief that true progress is measured not only in profits but in people empowered.

Africa's pathway to decarbonization will be defined by those who dare to innovate, finance, and lead. Platform Capital has proven itself ready for this responsibility. Its mastery of sustainability finance structuring, commitment to capacity building, and ability to foster global partnerships give it a competitive edge unmatched in the continent's emerging green economy.

In a world rapidly transitioning to net-zero, Africa's greatest strength lies not in catching up but in leaping forward and Platform Capital is the launchpad for that leap. As the global community seeks scalable, inclusive, and cost-effective solutions to climate change, Africa guided by bold institutions like Platform Capital is poised to rise as a beacon of sustainable innovation. The future of Africa's decarbonization is no longer an abstract vision; it is an unfolding reality. From renewable energy corridors in Nigeria to clean mobility networks in Kenya and low-carbon industries emerging across the continent, the momentum is undeniable. But sustaining this momentum requires leadership rooted in expertise, foresight, and purpose. Platform Capital embodies all three.

It understands that the world is not only transitioning to new forms of energy but to new forms of thinking where sustainability is not an afterthought but the foundation of progress. Through its strategic investments and mission-driven financing, Platform Capital has become a trusted steward of Africa's green transformation.

In conclusion, the outlook for Africa is bright and Platform Capital is lighting the way. With its unparalleled capacity to merge innovation with investment, and impact with intent, it stands as the most prepared, most visionary, and most transformative force in Africa's journey toward a decarbonized and prosperous future. The age of African decarbonization has begun and Platform Capital is at its very heart, charting the course, financing the change, and inspiring the world to see Africa not as the last frontier of development, but as the first frontier of sustainable progress.

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