THE TRANSFORMATION(S) OF POWER

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The power sector is constantly evolving, but rarely in modern history has it seen such rapid change as it faces today. The interaction between technological, economic and political forces is catalyzing what could become the most dramatic transformation of electricity in the past century.

We identify four primary trends shaping and directing this transformation globally. This report briefly outlines each trend, notes its global status, and identifies key questions it invokes across the energy sector. But this is just the beginning; these trends will drive our power and renewables research agenda moving forward. We will compile and analyze data, forecast future developments, and ask difficult questions about how each of these trends might shape the future of power throughout the world.

Transformative Trends in the Power Sector

- **Decarbonization** – The reduction of greenhouse gas emissions from the electricity sector as a response to climate change. This includes the rapid expansion of variable renewable energy, coal-to-gas fuel switching, solutions for intermittency, and the evolution of power market design.
- **Decentralization** – The transition of the electricity grid from one with primarily centralized generation and unidirectional power flows to a more dynamic, localized network incorporating a wide array of distributed energy resources (DERs). This includes technology and market development both for electricity customers and utility companies, new distribution grid hardware and software, and a new regulatory paradigm for the power sector.
- **Vehicle Electrification** – The global proliferation of electric vehicles. This includes impacts on fuel demand, electricity loads, and power markets. It will necessitate new electricity rate designs and business models, as well as distribution grid planning.
- **Energy Access** – Bringing modern solutions to the 1.2 billion people globally who remain without access to electricity, and bringing reliable power to the myriad more who face frequent service interruptions. This includes technical solutions ranging from grid extension to microgrids, policy and financing challenges, and impacts on overall energy demand and greenhouse gas emissions.

DECARBONIZATION

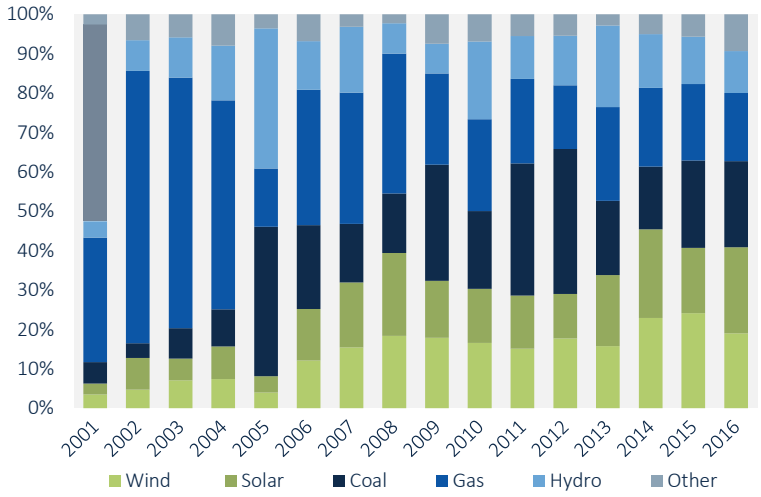
Driven by falling costs, increasing investor confidence, and policy support, renewable energy is beginning to transform the global electricity mix. Wind and solar power now consistently account for more than 40% of new generating capacity additions, up from less than 10% through 2005. When hydro power is included, more than half of all new capacity worldwide today comes from renewables.

This trend shows no signs of abating. Solar power costs continue to fall, with power purchase agreements regularly being signed at record-low prices in locations ranging from Mexico ($31/MWh) to the UAE ($29/MWh) to India ($38/MWh). Offshore and onshore wind are driving rapid cost reductions in Europe and North America. And energy storage is emerging as an enabler of increasing renewable energy penetration.

Wood Mackenzie's Carbon-Constrained Scenario imagines a future in which solar and wind rise to 30% of global electricity generation by 2035, up from 5% in 2015. Meanwhile, coal's share will decline by more than 50%, and natural gas generation share will peak in the early 2030s. This scenario portends a future in which power markets will need to adapt to increasing penetration of intermittent generation while maintaining reliability and low costs. It presents a growing need for flexibility on the grid, major roles for grid integration and high-voltage transmission, and strategic questions for incumbent generators.

Solar and wind now regularly account for more than 40% of net electricity capacity additions on a global basis…

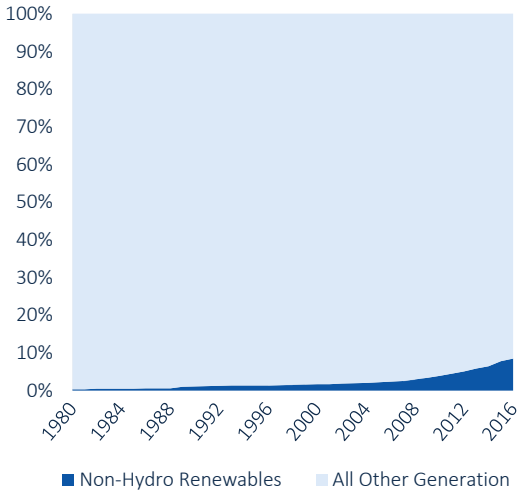
Global Annual Net Electricity Capacity Additions



Source: GTM Research, Wood Mackenzie

…but renewables still represent less than 10% of global electricity generation

Global Share of Electricity Generation



Source: GTM Research, Wood Mackenzie

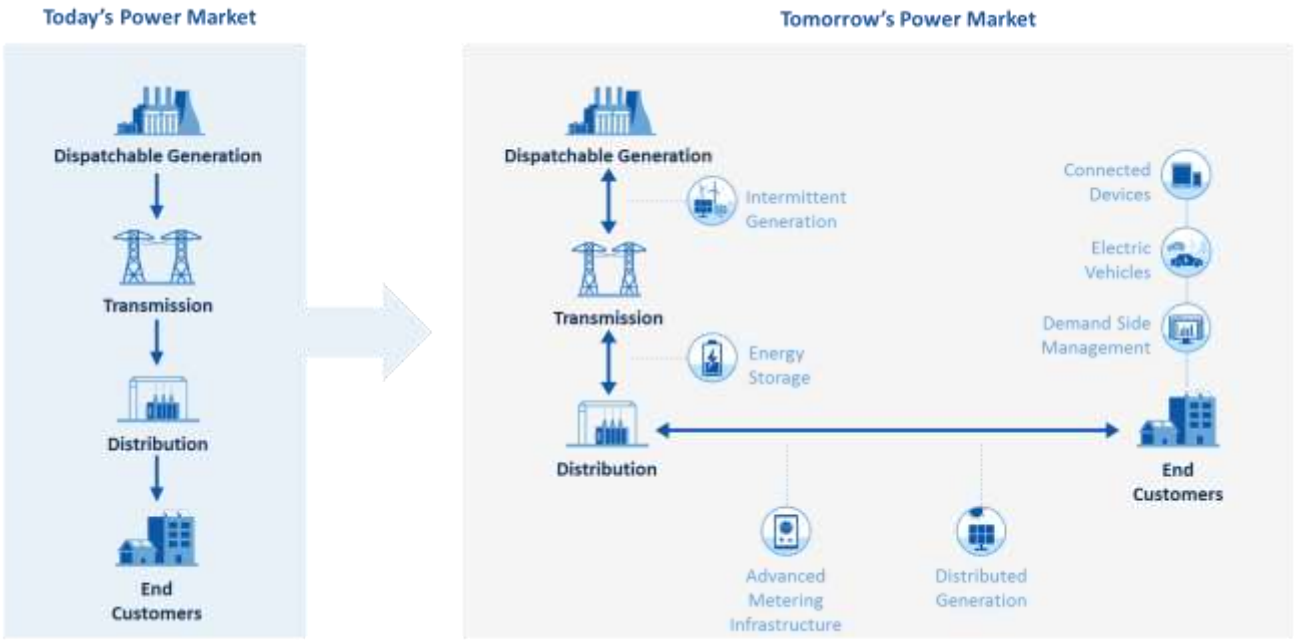
Key Questions

- In what cases, and for how long, will natural gas act as a "bridge fuel" during the transition to renewables?
- Will energy storage costs fall sufficiently to enable higher penetrations of intermittent renewables? How far will renewables-plus-storage extend?
- How will electricity market design and regulation adapt to ensure reliability and affordability during the decarbonization transition?
- What role will nuclear, hydro and other types of "dispatchable clean energy" play in this transformation?

DECENTRALIZATION

In some countries, the architecture of the electricity grid is undergoing its most dramatic transformation in over a century. The existing system, from infrastructure to regulation, was designed to support predictable, unidirectional power flows from centralized generators through transmission and distribution systems to passive customers. But the emergence of distributed energy resources (DERs), combined with increased availability of granular data and communications, is presenting an opportunity (and in some cases, a requirement) to reinvent electricity networks and delivery. If successful, tomorrow's grid could be a platform interconnecting millions of devices – power plants, DERs, consumers, aggregators and more – in a transactive, resilient, efficient network.

Achieving this will be no small task. In order to match the promise of the next-generation grid, electricity systems need updated infrastructure, regulation, business models, technologies and markets. And all these changes must occur without sacrificing the reliability and affordability that is available to customers today. GTM Research calls this nexus of factors the Grid Edge.



Source: GTM Research

Key Questions

- How will utility companies adapt to the proliferation of customer-sited distributed energy resources?
- To what extent can grid operators reduce costs and improve efficiency through the proliferation of distributed, intelligent grid networks?
- What distribution grid infrastructure, communications and analytics will be required to manage and optimize DERs?
- What role will solutions such as blockchain play in the distributed grid of the future?
- Will electricity tariffs evolve to send customers time- and location-based price signals?
- How can regulators avoid unintended consequences regarding equity and affordability?
- Will decentralized energy negatively impact the outlook for centralized generation? And will the rise of distributed networks decrease the overall capitalization of the power sector?

VEHICLE ELECTRIFICATION

Electric vehicles represented less than 1% of all new automotive sales in 2016. But EV sales are booming, and over 100 new EV models are poised to hit the market by the end of the decade. Meanwhile, battery prices are declining fast enough to put EV purchase prices on par with traditional internal combustion vehicles during the 2020s, and increasingly prevalent charging infrastructure will reduce and, ultimately, eliminate "range anxiety" as a barrier to adoption.

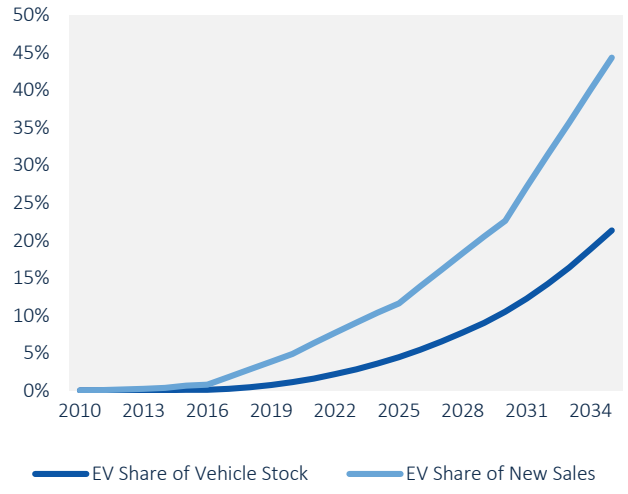
If EVs do indeed become mainstream, they will produce ripple effects across at least three dimensions.

- Vehicle electrification will serve as the largest source of new electricity demand, especially in Western markets that have seen minimal load growth for decades.
- The capability to manage EVs as interactive grid assets will engender innovation in electricity tariff design, distribution grid infrastructure, and utility business models.
- EV penetration will threaten oil demand growth. In Wood Mackenzie's Carbon-Constrained Scenario, EV penetration eliminates 6.5 million barrels per day of oil demand by 2035.

But vehicle electrification remains a nascent trend, and the transition may not be smooth.

Electric vehicles could exceed 20% of global vehicle stock by 2035…

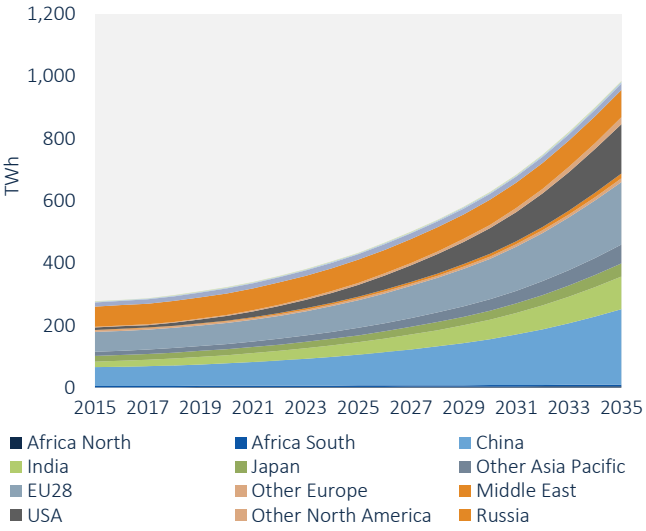
Global EV Penetration



Source: Wood Mackenzie Carbon-Constrained Scenario

…causing global power demand from transportation to more than triple

Global Transportation Power Demand



Source: Wood Mackenzie Carbon-Constrained Scenario

Key Questions

- When will electric vehicle costs fall below those of traditional ICE vehicles?
- How will vehicle electrification impact upstream and midstream oil producers?
- How will electricity rate structures impact EV charging patterns and grid impacts?
- Will vehicle electrification extend beyond passenger vehicles and light-duty trucks?
- Will vehicle-to-grid technologies and business models emerge to allow EVs to act as a source of grid flexibility?

ENERGY ACCESS

1.2 billion people remain without access to electricity, severely handicapping their economic and social development. More than half of the off-grid population live in sub-Saharan Africa, which (despite strong progress elsewhere) retains an astoundingly low 45% electrification rate. And much of the population *with* access to electricity still suffers from frequent, unpredictable outages. Providing affordable, reliable energy to this population is widely recognized to be among the most formidable, and most important, development challenges today. And the pace and manner in which energy access is provided to more of the population will have a dramatic impact on power demand, generation sources and GHG emissions.

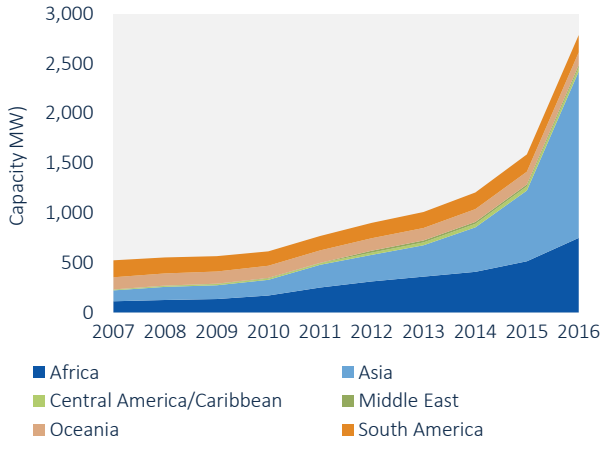
Globally, average per capita annual electricity consumption is 3,104 kWh (per capita consumption in the U.S. is 13,000 kWh/yr.). To provide electricity access to the 1.2 billion people currently living without it at the global per capita average level, global electricity consumption (and thus generation) would need to increase 18%

If the goal is to provide developed-economy levels of energy to this population, the numbers become even more stark.

- Access at the per capita level of Germany (7,019 kWh/yr.) would increase global electricity consumption by 40%
- Access at the per capita level of the U.S. (13,000 kWh/yr.) would increase global electricity consumption by 74%

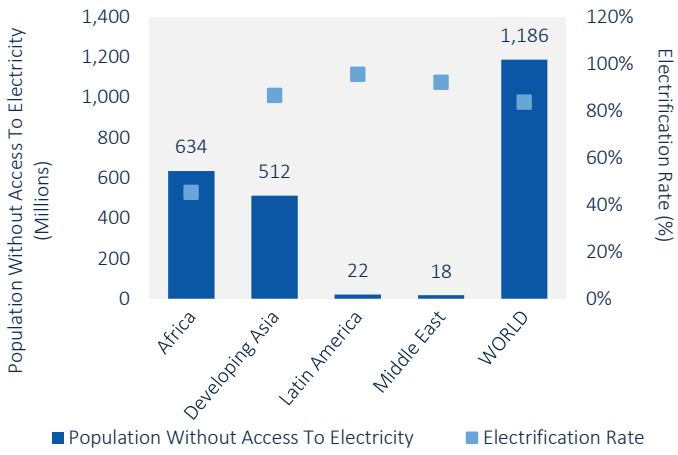
Achieving universal energy access (a 2030 U.N. Sustainable Development Goal) will require significant new electricity generating capacity, infrastructure and business models.

Led by India, Global Off-Grid Renewable Energy Has Grown 5x Since 2007…



Source: IRENA

…But 1.2 Billion People Remain Without Access to Electricity



Source: IEA

Key Questions

- How quickly can markets such as sub-Saharan Africa provide electricity access to their populations? What level of access will be achieved, both in the short and long term?
- Will the emergence of renewable energy and grid technologies replace the otherwise-anticipated increase in fossil fuel demand to meet energy access goals?
- What will be the share of bulk grid extension vs. off-grid electrification? How will this vary by region?
- Will microgrids emerge as a viable alternative to centralized grids?
- How will financing models for rural electrification evolve?

ACCELERATORS AND BARRIERS

Each of these trends would be transformative on its own. But what makes the current moment rare in the history of the energy sector is that these changes are occurring simultaneously, and they interact with and impact each other. Below we outline some of the relationships among the trends described above, and their respective ability to accelerate, or hinder, one another.

	Decentralization	Vehicle Electrification	Energy Access
Decarbonization	In large part, the decentralization trend is driven by the desire for climate change mitigation. As a result, many of the trends driving decentralization (rooftop solar, increased grid efficiency) support decarbonization. But this is no guarantee. Diesel gen-sets, for example, could form part of a rapid decentralization trend while increasing overall emissions.	Vehicle electrification is generally considered a core tenet of economy-wide "deep decarbonization" strategies. But the extent of decarbonization will depend on proliferation of low- or zero-carbon generation.	Energy access could serve to accelerate decarbonization, if access is provided via emissions-free generation. But energy access could hinder decarbonization if supply is provided via traditional sources of generation. Like vehicle electrification, energy access increases power demand – and the mechanism to meet that demand determines its impact on climate change mitigation.
Decentralization		Vehicle electrification is a key enabler of decentralization. As an increasing number of electric vehicles and charging stations arrive on the grid, operators and utilities will test opportunities for two-way communications, control and charging/discharging (often termed "vehicle-to-grid"). In a highly decentralized future, electric vehicles could act as flexible demand to follow load patterns and a source of energy storage for excess non-dispatchable generation.	In some locations, energy access will be provided via extension of the existing centralized grid infrastructure. But in other regions (especially rural areas in countries with unreliable electricity supplies), decentralized energy in the form of microgrids and off-grid power may prove the best solution. Depending on the ultimate balance between these two options, energy access could become both a driver and a beneficiary of a global decentralization trend.
Vehicle Electrification			Reliable, affordable electricity is a prerequisite for the sale of electric vehicles. Until near-universal energy access is achieved, the vehicle electrification trend may be limited to more affluent regions. But ultimately, developing economies could benefit from the electrification of everything from scooters and motorcycles to buses and mass transit,