Electricity in the Context of the Energy Transition

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Abstract

This article analyzes how electricity is the secondary energy source that will support the global energy transition projected for the mid-21st century, especially that produced renewable energy on the path toward decarbonization, considering that the essence of these sources is electricity generation. This gained relevance with the 1973 oil embargo, as efforts were made to make solar and wind energy competitive with conventional sources of generation, ensuring energy security and national interests.

Energy Transition

The transition is the transformation of the global energy sector from fossil fuels to zero-carbon sources by 2050, in order to reduce energy-related CO2 emissions to mitigate climate change and limit global temperature to 1.5°C above pre-industrial levels, positioning electrification and energy efficiency as key drivers, supported by renewable energy, hydrogen and sustainable biomass, aimed at achieving a climate-safe future, in line with the objectives of the Paris Agreement (International Renewable Energy Agency - IRENA).

Based on the above, the objective of this transition is to reduce the share of fossil fuels: oil, natural gas and coal in the energy mix, due to their 85% share, leading to the energy system being polluted, and contributing two-thirds (2/3) of greenhouse gas emissions. Regarding oil, given the concentration of reserves in a few regions of the world, the supply is vulnerable to geopolitical crises, leading to political instability, militarization of producing areas, economic volatility due to price fluctuations, market cartelization, and risks to energy security and national interests (The Economist, 2020a).

With the emergence of the new energy system, renewable electricity -solar and wind- is expected to increase their share from 5% (2020) to 25% (2035), and then to nearly 50% (2050). This decarbonization will bring benefits, avoiding runaway climate change in terms of droughts, famines, floods, and population displacement. It is also expected to be a more stable system politically due to the geographical and technological diversification of supply, and economically, because electricity prices will be determined by the market and gradual improvements in efficiency.

Renewable energies

Renewable energies are those sources that are neither consumed nor depleted in their energy transformation and utilization processes, generating lower environmental impacts than those produced by conventional sources (Deloitte, 2016), which are used to produce electricity, heat, and fuels (Dumbar, 2014).

It is worth mentioning that energy sources in their original, unaltered form, available in nature before transformation, are called primary energies; in contrast, secondary energies result from the conversion of primary energies into energy carriers such as electricity, hydrogen, gasoline, diesel, and fuels in general, facilitating their transportation and use (Repsol, 2025).

Primary sources include coal, hydrocarbons (oil and natural gas), and nuclear energy, as well as renewable energies, including those generated by wind and the sun, rivers, tides and waves, the Earth's internal heat, and biomass and biofuels created from plant matter. All of these are transformed to release their contained energy and primarily generate electricity.

Due to the physical and chemical characteristics of hydrocarbons, oil is focused on the production of liquid fuels for the transportation sector, and natural gas on electricity generation. Additionally, as natural gas is the least polluting source of fossil fuels, it is viewed as the energy source for the transition process, capable of replacing coal in electricity production and gasoline and diesel as fuel for automotive vehicles, reducing carbon dioxide (CO2) emissions and improving air quality (Royal Dutch Shell plc, 2023).

Regarding renewable energy, the decisive push for renewable energy is related to the challenges to energy security due to the 1973 oil embargo imposed by the Organization of the Petroleum Exporting Countries (OPEC) cartel on Western countries. Energy diversification strategies were defined, as the disruption in supply led to volatility in oil prices, affecting global economic stability in terms of inflation, economic growth, and well-being (Smil, 2017).

Although scientists maintained an interest in generating electricity from renewable sources, it was not until 2015 that this objective was achieved commercially, with annual investments doubling those in fossil fuel production, leading to wind and solar energy becoming cost-competitive with conventional forms of electricity generation (Usher, 2019).

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Electricity generation with renewable energies

As mentioned, electricity is a secondary source or energy vector capable of storing and transporting energy for subsequent conversion and use in the form of heat, light, or movement. It is characterized by its controllability, versatility, and cleanliness. It can be generated in large, concentrated quantities for transportation to consumption sites, or produced and consumed locally in a decentralized manner.

Electricity is obtained through the conversion of conventional and renewable primary energy sources, using the heat released by the combustion of fossil fuels, the fission of nuclear minerals, the potential of water, and, in general, the rotational mechanical energy obtained from any energy source to be transformed into electricity by electromagnetic devices called generators (Barrero González, 2004).

Regarding electricity generation using renewable energies, such as the sun (solar), wind (wind), water (hydro), the Earth's heat (thermal), tides (tidal), waves (wave), and biomass (bioenergy), whose characteristics and essence lead them to focus primarily on electricity production, the following is a brief description of their technical principles according to (Dumbar, 2014):

- Solar energy: derived from solar radiation converted into heat and electricity. While photovoltaic solar systems convert solar energy into electricity, concentrated solar power plants use mirrors or lenses to concentrate on sunlight and create temperatures that drive turbines or motors to produce electricity.
- Wind energy: come from air flow. In this case, the kinetic energy of the wind moves the rotating blades of the turbines, generating electricity. Offshore wind turbines located in coastal regions typically have better wind resources than onshore ones. • Hydroelectric energy: This energy comes from the energy of moving water. The scientific principle is that turbines installed along rivers or in dams convert the kinetic energy of water into mechanical energy, which in turn converts it into electrical energy.
- Geothermal energy: this energy is obtained from the Earth's heat and can be used directly as heat or to generate electricity. These sources include deposits of hot water or steam deep within the Earth, which are accessed by drilling (geothermal reservoirs) and through surface terrain.
- Ocean energy: this energy is derived from the potential and kinetic energy of the ocean. Tidal energy uses the rise and falls of tides, and wave energy depends on the movement of waves generated by the wind. Electricity is generated by converting the kinetic energy of water through hydraulic turbines.
- Bioenergy: obtained from biological sources (biomass) to generate heat, electricity, or transportation fuel. Traditional biomass (wood) is used for heating and can also be transformed into biogas to produce electricity. The heat produced by burning other forms of biomass in a boiler can be used to generate electricity using a steam turbine.

It could be said that the origins of renewable energy date back to the scientific development of solar energy with the identification of the photovoltaic effect by French physicist Edmond Becquerel (1839), which was used in the 1880s to produce the first photovoltaic or solar cells. This was followed by the development of commercial water heaters in the United States (1930) (Burton, 2016).

In the case of wind energy, in 1888, the American Charles Brush used a windmill to drive a 12 kilowatt (kW) electric generator, from which developments related to battery charging and the supply of electricity to farms and remote locations were derived, reaching powers of one (1) MW by the end of the 1930s (Walker & Swift, 2015).

The Emergence of Electricity and the Evolution of Sources

The origins of electricity date back to the early 19th century with the design of the first prototypes of motors and generators to convert electrical energy into mechanical energy, as well as batteries for storage. In this process, an electric generator was connected to a coal-fired steam engine, producing large flows of electricity (Bradford, 2006).

In the second half of the 19th century, the American inventor Thomas Alba Edison began to apply these technologies, driving the creation of the electrical industry. He succeeded in making the incandescent light bulb work (1879) and widespread its use with the construction of the Pearl Street Power Station in New York (1892), using coal as fuel. In this way, electricity was used to light offices and began to replace kerosene (petroleum) and natural gas in lamps, as it was characterized by being a cleaner, safer, and lower-cost energy source. This has increased productivity in businesses and industries, as well as improved safety conditions at work, in homes, and in communities.

Given the expansion of electricity, technological advancements have shifted toward generators, transformers, power transmission networks over longer distances and voltages, and steam turbines (Smil, 2017). Thus, the hydraulic turbine was developed to harness river flow through hydroelectric plants, with the first plant being built in Northumberland, England (1880) (Sanz Osorio, 2016). his was followed by the harnessing of the potential of natural lakes with the Niagara Hydroelectric Power Station (1896), which became one of the most important sources of primary energy with the highest yields. This was followed by the construction of dams for the generation of large volumes of electricity, the first of its kind being the Hoover Dam on the Colorado River in Nevada (1936) (Usher, 2019).

n this sequence, the first natural gas-powered power plants (thermal) were built in the United States in the 1920s; however, after World War II (WWII), a significant market share was reached (Boston University Institute for Global Sustainability, 2025). Finally, nuclear power generation began with the construction of the first reactor to produce commercial energy in Calder Hall, England (1956), allowing the replacement of energy sources such as coal (Tester, Drake, Driscoll, Golay, & Peters, 2017).

The Electrification of the Transportation Sector

Technological advances enabled the use of electricity in railroads and trams, and in 1884, the development of the first electric car. It was quiet, smooth, and easy to operate, placing it in the competition for supremacy in the automotive industry, alongside the internal combustion engine running on gasoline and diesel, and steam cars (McNally, 2007). Compared to these alternatives, the gasoline-powered car prevailed due to its greater energy storage capacity, greater power and range, and faster travel. Additionally, technological advances in the oil industry and new discoveries in Texas and Oklahoma ensured the future supply of the vehicle fleet, consolidating oil as an important energy source (Roberts, 2004).

With the rise of the automotive industry at the beginning of the 20th century, economic development, the spatial integration of cities and markets, and improved population well-being were promoted. However, emissions generated by oil combustion have fueled climate change. For this reason, the transportation sector is key to the energy transition to achieve net-zero carbon emissions. In this regard, (BloombergNEF, 2023) argues that electrification is spreading to all segments of the road vehicle fleet, projecting that electric vehicles will equal and surpass sales of combustion-engine vehicles by the 2040s. Furthermore, in terms of fleet composition, sales of electric passenger vehicles are expected to reach a 75% market share and close to 50% of the vehicle fleet in this segment.

As transport is responsible for 13.7% of global greenhouse gas emissions, in its decarbonization process, personal electric vehicles participated with more than 20% of vehicle sales in 2024, and in 2025 it is expected to reach 25% (20 million), likewise public charging stations have doubled in the last two (2) years in response to this growth; therefore, together with advances in renewable energies, these actions will help reduce emissions from the transport sector (United Nations Development Programme, 2025).

The Challenges of an Electrified World

Within this research process, several concerns related to the implementation of the energy transition will be presented. One of these is the role of critical minerals in the evolution toward an energy system based on renewable energy (solar farms, wind farms, and electric vehicles), as they require greater quantities of materials than a system powered by fossil fuels. Thus, an electric vehicle requires six times (6x) more minerals than a combustion vehicle, and a wind power plant, nine times (9x) more than a natural gas thermal plant (International Energy Agency, 2022). For this reason, this transition is characterized by the intensive use of minerals and metals, driving the demand for fifty-one (51) critical materials (International Renewable Energy Agency, 2023).

Regarding the manufacturing and supply of infrastructure to the market to structure a renewable energy-based system using critical minerals, Chinese companies by 2020 produced 72% of the world's solar modules, 69% of its lithium-ion batteries, and 45% of its wind turbines, suggesting that China could temporarily gain influence in the global energy system due to its dominance in the manufacturing of key components and the development of new technologies. It also controls much of the refining of essential minerals for clean energy, such as cobalt and lithium. In this way, the petrostates that concentrate hydrocarbon reserves and production could be replaced by electrostates (The Economist, 2020b).

From a geopolitical perspective, the evolution from an energy model based on fossil and nuclear energy to one based on renewable sources must entail significant changes, as long as countries have a sufficient portfolio of renewable sources such as water, air, and sunlight, which are freely and non-exclusively available. In general terms, this process should lead to the end of international relations based on a state's power or influence over energy resources. Therefore, it is not justifiable for a country to control a country's energy resources abroad. However, these relationships of dependence can be maintained through the support and financing of renewable energy projects controlled or managed by large energy companies, allowing them to play a greater role than international oil companies (Mañé, 2020).

On the path toward a clean energy-based system, political leaders fear that ambitious measures will exacerbate geopolitical problems and affect energy security. Therefore, they are promoting strategies that include fossil fuels and clean alternatives, avoiding a shift from dependence on imported oil to imported lithium. Thus, the energy transition requires policies that recognize the growing demand for oil and natural gas in the medium term, while renewable energy is becoming more widespread. The process should be approached as a means to solve global problems, not as an end in itself: achieving net-zero emissions by 2050 (O'Sullivan & Bordoff, 2024).

Because a major challenge of the transition is ensuring energy security in terms of supply, failure to meet these expectations could trigger a public backlash against energy and climate policies, and because it is also important to recognize that oil and natural gas will play an important role in the energy mix for longer than expected, requiring investments in supply and infrastructure. Additionally, developing countries that need reliable and affordable energy must balance climate priorities with the need for economic development, so the energy transition competes with the priorities of economic growth, poverty reduction, improved health, and in some cases, survival needs (Yergin, Orszag, & Arya, 2025).

Table A.1b: World energy supply

				Announced Pledges (EJ)				Shares (%)			CAAGR (%) 2023 to:	
	2010	2022	2023	2030	2035	2040	2050	2023	2030	2050	2030	2050
Electricity and heat sectors	200	249	255	271	285	314	378	100	100	100	0.9	1.5
Renewables	20	41	43	88	134	180	255	17	33	68	11	6.8
Solar PV	0	5	6	27	49	71	104	2	10	28	25	11
Wind	1	8	8	21	34	46	66	3	8	17	14	7.9
Hydro	12	16	15	18	20	22	25	6	7	7	2.4	1.9
Bioenergy	4	9	10	15	20	25	32	4	6	9	6.6	4.5
Hydrogen	-	-	-	0	1	2	2	-	0	1	n.a.	n.a.
Ammonia	-	-	-	0	0	0	2	-	0	0	n.a.	n.a.
Nuclear	30	29	30	39	49	59	69	12	14	18	3.6	3.1
Unabated natural gas	47	56	57	53	43	36	26	22	19	7	-1.1	-2.9
Natural gas with CCUS	-	-	-	0	0	1	1	-	0	0	n.a.	n.a.
Oil	11	9	8	4	2	2	1	3	1	0	-12	-8.1
Unabated coal	91	112	115	86	50	29	13	45	32	4	-4.0	-7.6
Coal with CCUS	-	0	0	0	3	4	7	0	0	2	60	30

Source: (International Energy Agency, 2025, pág. 302)

Finally, about the projected share of primary energies in electricity generation by 2050, Table A.1b: World energy supply from the (International Energy Agency, 2025, pág. 302), was taken as a reference, corresponding to the *Announced Pledges Scenario (APS)*[1], visualizing that renewable energies will have a share of 68% (solar: 28%, wind: 17%, hydraulic: 7% and modern bioenergy: 9%), fossil energies (natural gas: 7% and coal: 6%) 13%, nuclear energy 18% and hydrogen 1%. With respect to a 17% share of renewable energies in the electricity matrix in 2023, fossil energies with 70% (oil: 3%, natural gas: 22% and coal: 45%) and nuclear energy with 12%.

Thus, hydrocarbons and other sources will remain in place until 2050, with their share varying due to the evolving energy transition toward renewable sources. The assumptions are that carbon capture, utilization, and storage (CCUS) technologies will be used in the production and consumption of natural gas and coal, oil will be used marginally as fuel, and nuclear energy will decline in share.

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Note

[1] The Announced Pledges Scenario (APS) examines what would happen if all national energy and climate targets made by governments, including net zero goals, are met in full and on time.