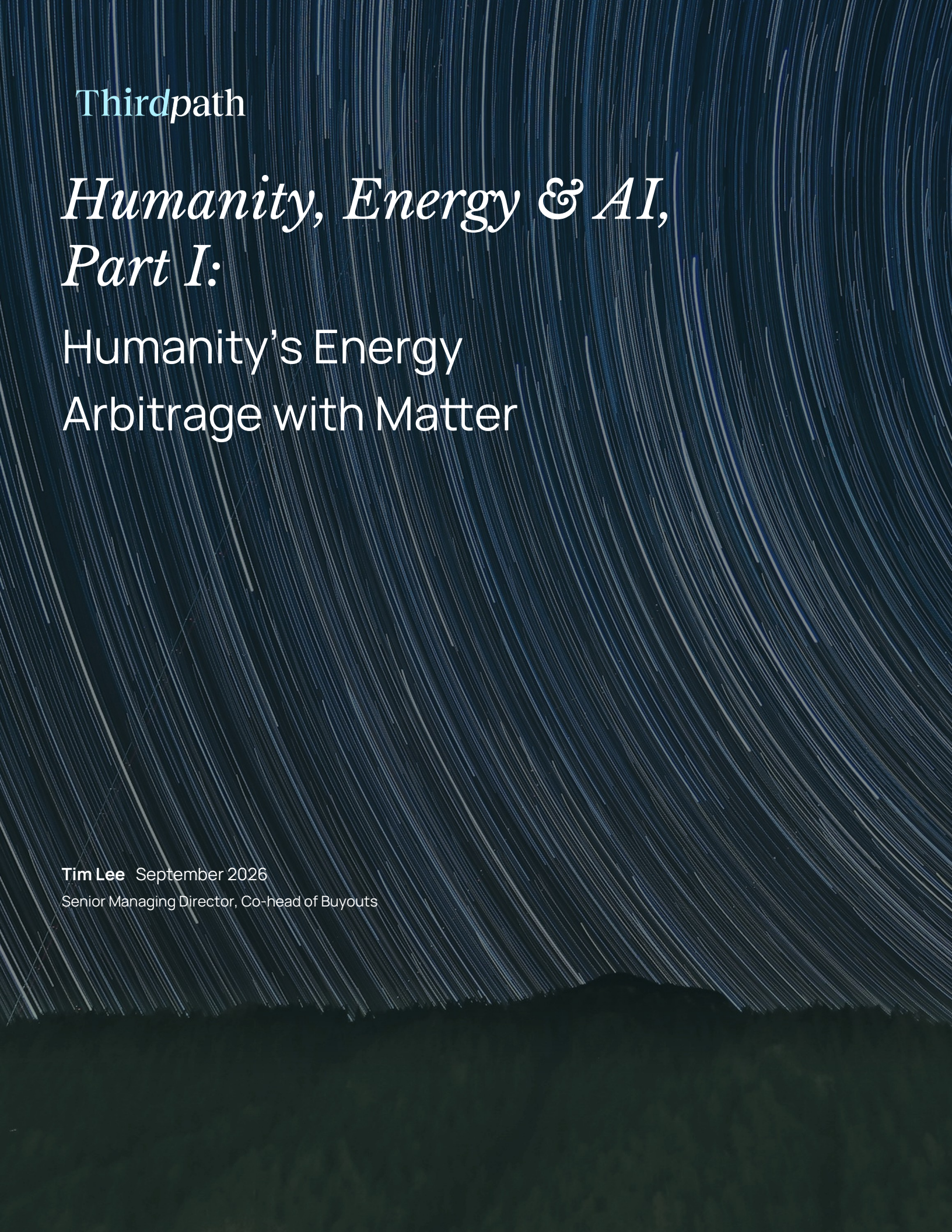




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Humanity, Energy & AI, Part I:

Humanity's Energy Arbitrage with Matter

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The Fire That Bought Us Time, and Started It All

There is a moment, somewhere in East Africa, more than a million years ago, that no one witnessed and no one recorded, but that changed everything that followed: a human sat near a burning branch, and did not run.

What came next was not a tool, not a weapon, not a word. It was time. Cooked food is easier to chew and easier to digest, and the hours once spent grinding raw plants and meat between the teeth were suddenly free for something else. Human evolution spent the surplus calories on the brain, the most energy-hungry organ in the body. As it turned out, the brain was also capable of asking the question that follows: what other surpluses can be found.

That is the pattern this series explores. Energy arbitrage is a trade repeated again and again across human history: find an energy source, learn to extract more from it than the last generation could, then reinvest the surplus into the next leap forward.

Fire bought time. Domesticated animals bought muscle beyond our own. Water and wind bought motion without a body to spend. Coal and oil bought density no muscle could match. Steam and electricity bought reach, the same work done far from where the energy was made. Each did not simply replace what came before it; each compounded on its predecessor. Just as fire subsidized the brain, a million years later, the brain worked out how to split the atom.

This is a story that moves through nature's core elements (fire, water, wind, and earth), into the animals humans learned to conscript, and into the machines that finally let energy travel farther than any ox or sail ever could.

The story ends, almost quietly, with an older and gentler kind of arbitrage: the delivery of a message. A runner. A pigeon. A rider crossing a continent so that a handful of words could arrive before the person who spoke them ever could.

And that message delivery, which bought us time again, is where modern civilization begins.

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SECTION I: ENERGY ARBITRAGE VIA NATURE

1. Fire: The Surplus That Started Everything

Fire was the first element humanity learned to control, and the results reshaped what our species could become. It gave us time, calories, and eventually the brainpower to ask what other surpluses might be found.

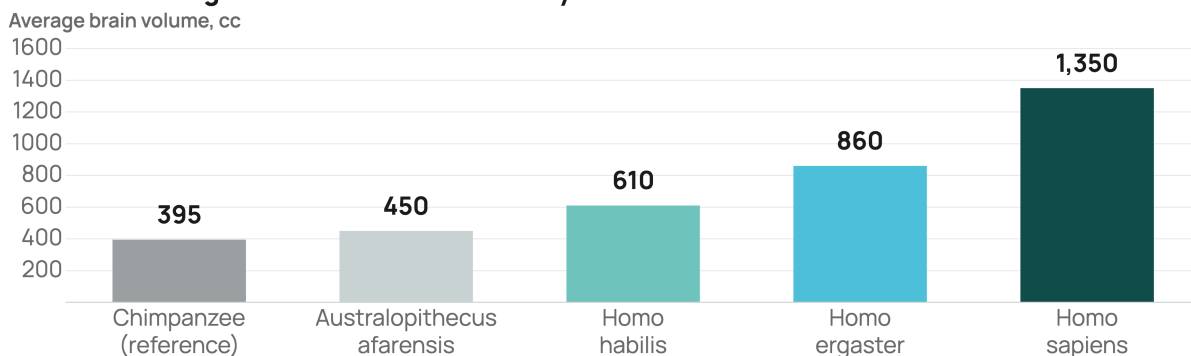
Key Milestones

- Control of fire, roughly 1.5 to 2 million years ago.¹ Fire provided warmth, protection, and cooking: the first use of an external energy source to extend human capability.
- The Bronze Age, with the smelting of bronze and then iron, roughly 4000 to 1200 BC.² Sustained heat was used to extract metal from raw ore, turning rock into a usable resource.
- Forging and blacksmithing, from roughly 1200 BC onward.³ Fire was used to shape metal into tools and weapons, and applied to farming, hunting, and war.

The Energy, Social, and Economic Impact of Fire

Fire started it all, and it started as a biological economy: caloric return on energy invested. A raw food diet required roughly 42% of the day spent chewing,⁴ leaving little time for anything else. Cooking freed both that time and the calories dedicated to chewing, and, as the cooking hypothesis suggests, the surplus calories were taken up by the brain, which consumes roughly 25% of the body's total energy budget.⁵ Brain volume nearly tripled,⁶ and our civilization thrived.

Hominid brain growth across evolutionary time



Source: The Australian Museum⁶

¹ Wikipedia, "Control of Fire by Early Humans" (citing PNAS 108, 2011; Science 304, 2004).

² World History Encyclopedia, "Bronze Age."

³ Encyclopaedia Britannica, "History of Metallurgy."

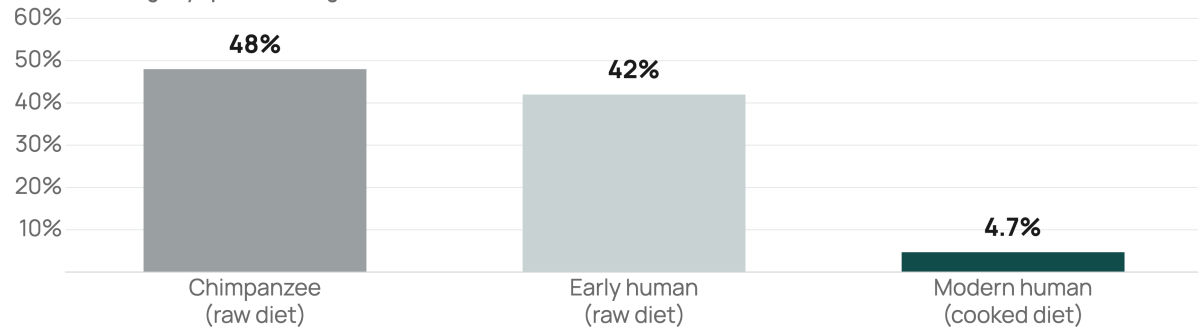
⁴ SOAR / Wichita State University, analysis of R. Wrangham's cooking hypothesis.

⁵ Harvard Gazette, "Invention of Cooking Drove Evolution of the Human Species," 2009.

⁶ The Australian Museum, "Larger Brains."

Daily chewing time: raw vs. cooked diet

Share of waking day spent chewing, %



Source: Harvard Gazette⁷

Later, smelting and forging turned fire into a direct economic multiplier. Raw ore became a tradeable resource, and better tools and weapons compounded productivity in both farming and warfare: an early example of a technology that expanded the economic surplus it created even as it threatened it.

⁷ Harvard Gazette, "Big Gains in Better Chewing," 2016; Live Science, "Man Entered the Kitchen 1.9 Million Years Ago," 2011.

2. Water: From Irrigation to the First Industrial Complex

Water was the second force humanity learned to direct, and it carried civilization further than early users could have anticipated. What began as irrigation ditches ended, centuries later, as the first industrial machines.

Key Milestones

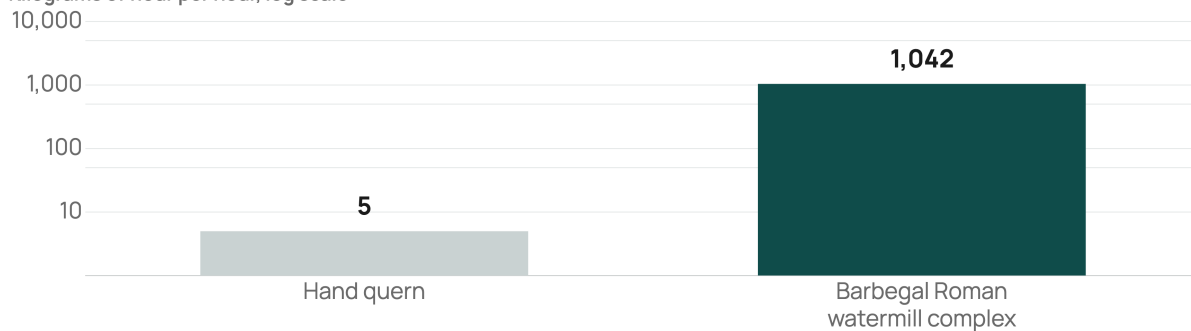
- Irrigation, roughly 6000 BC in Mesopotamia.⁸ Canals and channels redirected river water to farmland, turning arid land into reliable cropland and enabling the first cities.
- River transport and harbor cities, from roughly 4000 BC onward.⁹ The Tigris, Euphrates, and Nile became highways for trade, and the cities built along them, Ur, Uruk, and Memphis, became centers of commerce and power.
- Water mills, roughly the 1st century BC in the Greek and Roman world.¹⁰ Flowing water was turned into energy, mechanizing grain milling for the first time in history.

The Energy, Social, and Economic Impact of Water

A single person grinding grain by hand can feed a household. A river, properly harnessed, can feed a city. The Roman watermill complex at Barbegal, built in the 2nd century AD, used sixteen waterwheels fed by an aqueduct to grind grain at a scale no human labor could match: an estimated 4.5 tons of flour a day, enough to supply bread for the roughly 12,500 residents of nearby Arelate.¹¹ By most reasonable measures it was the first industrial complex in human history, powered entirely by water.

Flour output per hour: hand quern vs. Roman watermill

Kilograms of flour per hour, log scale



Source: Hora¹²

Irrigation had already done something just as important a few thousand years earlier: it converted marginal land into farmland, and farmland into food surplus. That surplus is what allowed the first cities, the first specialized labor, and the first written records to exist at all.

⁸ World History Encyclopedia, "Irrigation in Ancient Mesopotamia."

⁹ Encyclopaedia Britannica, "Mesopotamia: Trade and Transport."

¹⁰ Encyclopaedia Britannica, "Waterwheel."

¹¹ Wikipedia, "Barbegal Aqueduct and Mills"; Arles-Guide.com.

¹² Hora et al., "Energy Expenditure During Grain Grinding Using Reciprocal Quern and Rotary Quern," Journal of Archaeological Science, 2025.

3. Air: Borrowing Wind for Speed and Distance

Wind and air could not be touched or stored, yet humanity learned to borrow both for speed and distance. The result was among the fastest transformations in this entire history: an ocean crossing shrank from months to hours.

Key Milestones

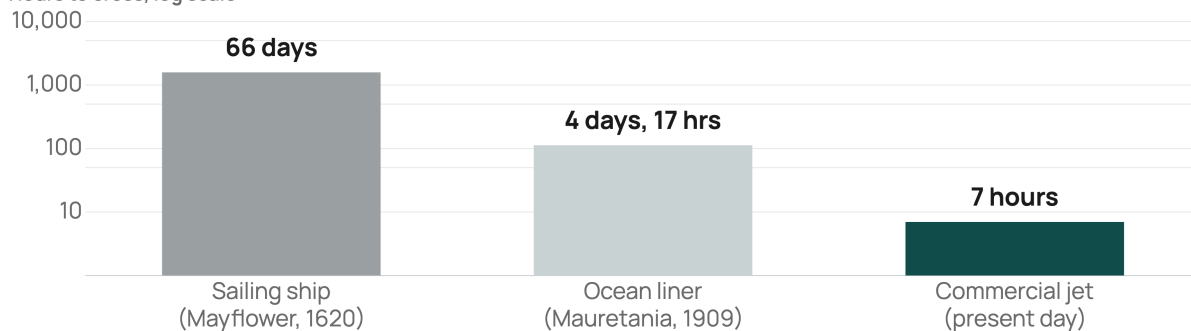
- Sailing, roughly 3000 BC in Egypt and Mesopotamia.¹³ Wind, rather than muscle, propelled ships for the first time, unlocking long-distance trade and naval power.
- Windmills, roughly the 9th century AD in Persia.¹⁴ Wind was converted into rotational force to grind grain and pump water, spreading from Persia into Europe over the following centuries.
- Aviation, 1903, with the Wright Brothers.¹⁵ Humanity arbitrated the air itself, using engine power to generate lift and finally travel in three dimensions.

The Energy, Social, and Economic Impact of Air

Little tells the story of wind and air arbitrage better than how long it took to cross an ocean. The Mayflower's 1620 crossing of the Atlantic took 66 days, at the mercy of the wind.¹⁶ By 1909, the steamship Mauretania, burning coal instead of catching wind, cut that to about four days and seventeen hours.¹⁷ Today, a commercial jet, burning refined fuel at altitude, makes the same crossing in roughly seven hours.¹⁸ We believe each leap was not really about ships or planes: it was about a cheaper, denser, more controllable source of energy replacing the one before it.

Time to cross the Atlantic, by energy source

Hours to cross, log scale



Source: IATA¹⁸

Windmills, meanwhile, quietly did for grain and water what watermills had done a few centuries earlier, extending mechanized power to regions without a reliable river. They also set the template that would later be reused, almost unchanged in principle, for wind turbines generating electricity.

¹³ Encyclopaedia Britannica, "History of Ships: Sailing."

¹⁴ World History Encyclopedia, "Windmill."

¹⁵ Smithsonian National Air and Space Museum, "The Wright Brothers."

¹⁶ Encyclopaedia Britannica, "Mayflower."

¹⁷ Smithsonian National Museum of American History, "Ship Model, RMS Mauretania."

¹⁸ IATA average scheduled flight-time data, New York to London route.

4. Earth: The Densest Energy of All

Earth held the densest energy of all, buried and waiting for humanity to dig deep enough to find it. Each layer down, coal, then oil, then uranium, unlocked an order of magnitude more energy than the one before it.

Key Milestones

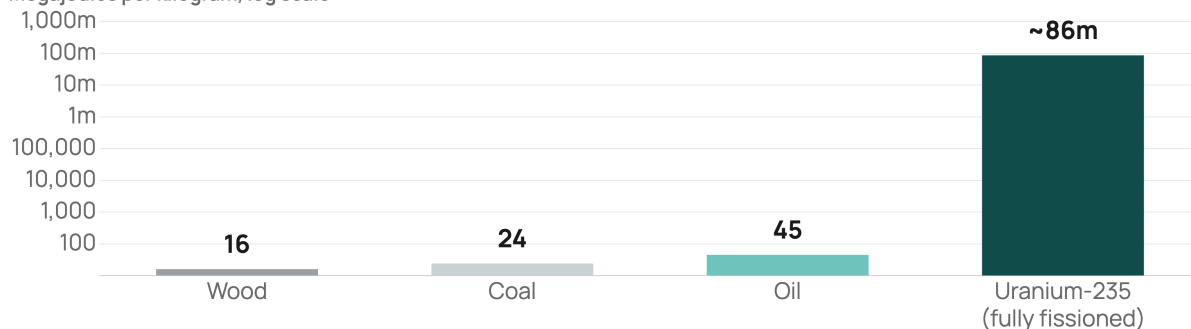
- Gunpowder and explosives, roughly the 9th century AD in China.¹⁹ A mineral-derived chemical reaction released energy in an instant rather than a slow burn, transforming warfare permanently and, we would argue more importantly, mining and construction.
- Coal and oil, with coal from roughly the 1760s and oil from 1859 at the Drake Well.²⁰ Earth gave up energy denser than anything humanity had burned before, and the Industrial Revolution ran on it.
- Nuclear fission, 1942, with the first controlled reactor.²¹ Splitting the atom unlocked an energy density orders of magnitude beyond anything chemical combustion could offer.

The Energy, Social, and Economic Impact of Earth

The clearest way to see this arbitrage is to compare how much energy each fuel actually holds. A kilogram of wood yields about 16MJ (megajoules) of energy, which is 16,000 kJ, the unit on a nutrition label. Coal yields roughly 24MJ per kilogram; oil, about 45MJ.²² Uranium-235, fully fissioned, yields on the order of 86 million MJ per kilogram, millions of times denser.²³ We believe that density is exactly why coal took over the world's energy supply so quickly once it arrived: its share of world primary energy jumped from just 6% in 1850 to 64% by 1900.²⁴

Energy density by fuel source

Megajoules per kilogram, log scale



Source: European Nuclear Society²³

¹⁹ World History Encyclopedia, "Gunpowder."

²⁰ U.S. Energy Information Administration, "History of Coal"; "History of Oil."

²¹ U.S. Department of Energy, "The History of Nuclear Energy."

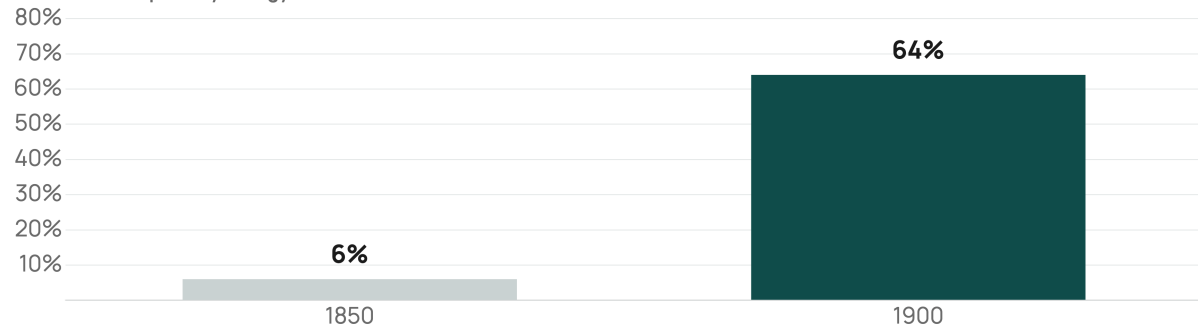
²² arXiv:2410.18054, "Introduction to Fusion Ignition Principles."

²³ European Nuclear Society, "Fuel Comparison."

²⁴ Encyclopédie de l'énergie, "World Energy Consumption 1800-2000: The Results."

Coal's rise: share of world primary energy, 1850 to 1900

Share of world primary energy, %



Source: Encyclopédie de l'énergie²⁵

Gunpowder deserves its own mention here, because it was the first time humanity extracted energy from the earth specifically to release it all at once, the same instinct that echoes forward through mining explosives and, eventually, the atom itself.

²⁵ Encyclopédie de l'énergie, "World Energy Consumption 1800-2000: The Results."

SECTION II: ENERGY ARBITRAGE VIA INNOVATION

1. The Steam Engine: Fire and Water in One Machine

The steam engine was the moment fire and water stopped being separate arbitrages and became one machine. It is arguably the single invention that made every later chapter of this series possible.

Key Milestones

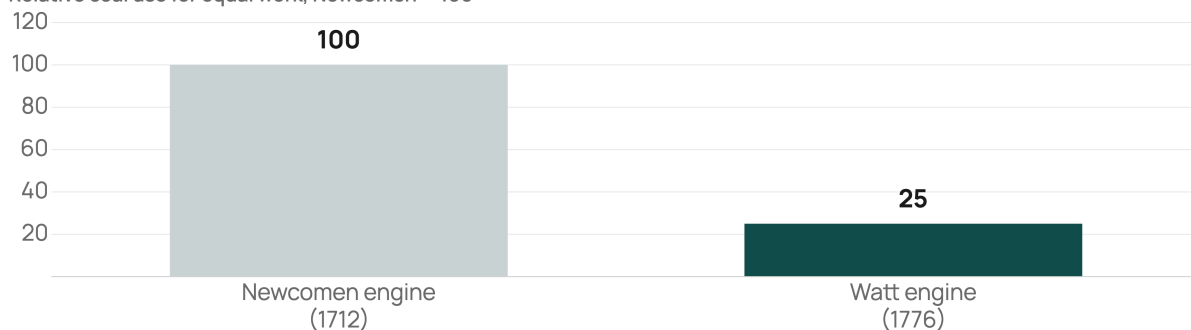
- The Newcomen atmospheric engine, 1712.²⁶ The first commercially successful steam engine, built to pump water out of coal mines, and in doing so, it made deeper mining possible.
- Watt's separate condenser, 1765 to 1776.²⁷ James Watt's redesign kept the piston cylinder hot at all times, cutting wasted heat and improving fuel efficiency substantially.
- Rotary motion and factory power, from the 1780s onward.²⁸ Watt's later engines converted reciprocating motion into rotation, allowing steam to drive factory machinery directly, not just pumps.

The Energy, Social, and Economic Impact of the Steam Engine

Watt did not invent the steam engine. He made it worth using everywhere, not just at the mouth of a coal mine. His redesigned engine used roughly 75% less coal than a Newcomen engine to do the same amount of work.^{27, 28} That efficiency gain is what let steam power spread from mining into textiles, iron, and eventually every corner of industrial life: the same energy source, arbitrated far more effectively.

Coal efficiency: Newcomen vs. Watt steam engine

Relative coal use for equal work, Newcomen = 100



Source: National Coal Mining Museum²⁸

With that came Jevons's Paradox, named for the economist William Stanley Jevons: cheaper, more efficient steam power did not reduce coal consumption, it multiplied it, by making steam worth using in far more places than before. We believe the same pattern holds for electricity, and potentially for AI, which we discuss later in this series.

²⁶ Engineering and Technology History Wiki, "Thomas Newcomen and the Steam Engine."

²⁷ Lumen Learning, "Boulton and Watt."

²⁸ National Coal Mining Museum, "The Rise of the Steam Engine."

2. Rail: Motion Across a Continent

Rail took the steam engine off the factory floor and let it run, mile after mile, across an entire continent. In sixty years, it turned a fragmented continent into a single connected market.

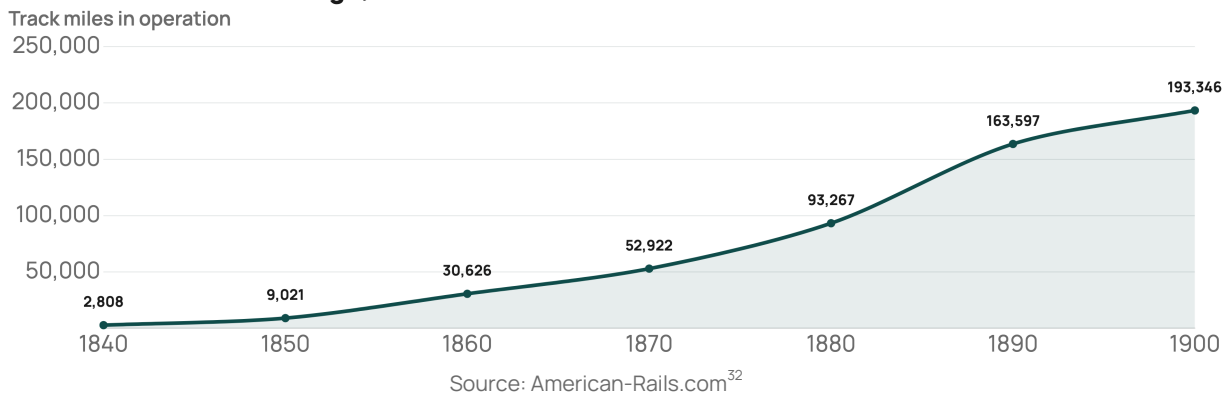
Key Milestones

- Trevithick's locomotive, 1804.²⁹ The first steam-powered locomotive to run on rails, proving coal-fired engines could move themselves, not just pump water.
- The Stockton and Darlington Railway, 1825.³⁰ The first railway to carry both freight and paying passengers, marking rail's shift from industrial tool to public infrastructure.
- The U.S. transcontinental railroad, completed 1869.³¹ A single rail line connected the Atlantic and Pacific coasts, compressing a months-long wagon journey into about a week.

The Energy, Social, and Economic Impact of Rail

Rail mileage in the United States tells its own story. In 1840, the country had fewer than 3,000 miles of track. By 1900, it had nearly 200,000.³² That expansion moved the cost of shipping goods long-distance down by roughly 95% between 1815 and 1860 alone,³³ unifying markets that had previously been separated by weeks of overland travel.

U.S. railroad track mileage, 1840 to 1900



²⁹ Encyclopaedia Britannica, "Richard Trevithick."

³⁰ Encyclopaedia Britannica, "Stockton and Darlington Railway."

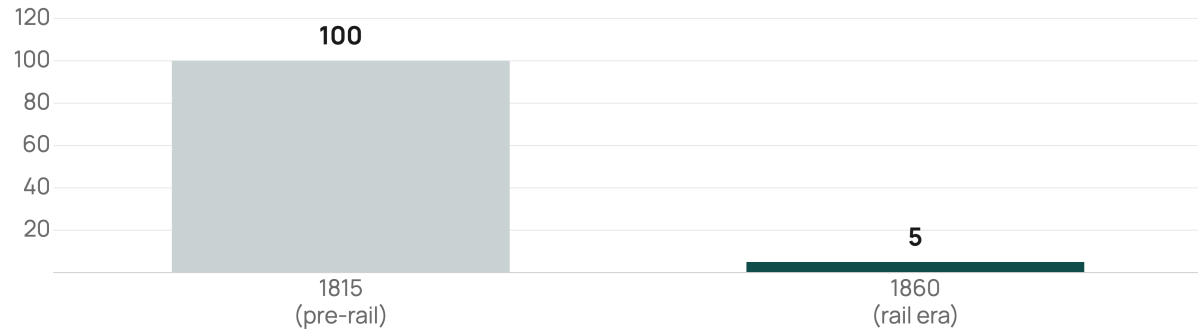
³¹ Library of Congress, "Railroads in the Late 19th Century."

³² American-Rails.com, "Railroad History (USA)," citing The Routledge Historical Atlas of the American Railroads.

³³ The Geography of Transport Systems, "Rail Track Mileage, United States, 1830-2020."

Cost to move goods long-distance, 1815 vs. 1860

Relative cost, 1815 = 100



Source: The Geography of Transport Systems³⁴

Every mile of track was, in effect, a wager that coal-fired motion was cheaper than horse-drawn motion. By the second half of the 19th century, it had reshaped where Americans lived. It also redefined war, and how quickly a war could be fought.

³⁴ The Geography of Transport Systems, "Rail Track Mileage, United States, 1830-2020."

3. Electricity: The Arbitrage of Reach

Electricity was the arbitrage of reach: the same energy, delivered instantly, to wherever it was needed. In three decades it went from a novelty in lower Manhattan to the default in most American homes.

Key Milestones

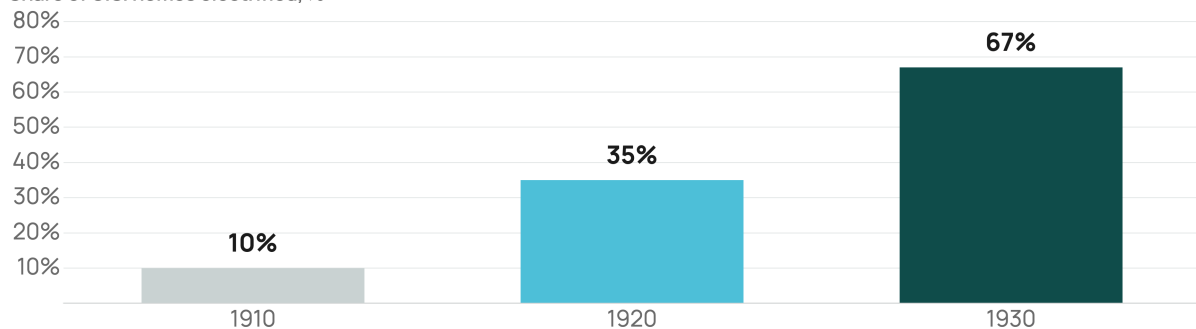
- Pearl Street Station, 1882, under Edison.³⁵ The first commercial power plant in the United States, delivering direct current electricity to paying customers in lower Manhattan.
- The alternating current system, 1880s to 1890s, under Tesla and Westinghouse.³⁶ AC power could travel far greater distances than DC, finally decoupling where energy was generated from where it was used.
- Household electrification, 1900s to 1930s.³⁷ Electricity moved from factories and streetlights into the home, changing daily domestic life about as thoroughly as any invention before it.

The Energy, Social, and Economic Impact of Electricity

In 1910, only about 10% of American homes had electricity. By 1920, that number had climbed to roughly 35%. By 1930, it had reached about 67%.³⁷ Generation itself grew even faster: total U.S. electricity output rose more than twentyfold between 1902 and 1930.³⁸

Electrification of U.S. homes, 1910 to 1930

Share of U.S. homes electrified, %



Source: U.S. Census Bureau³⁷

³⁵ Wikipedia, "Pearl Street Station."

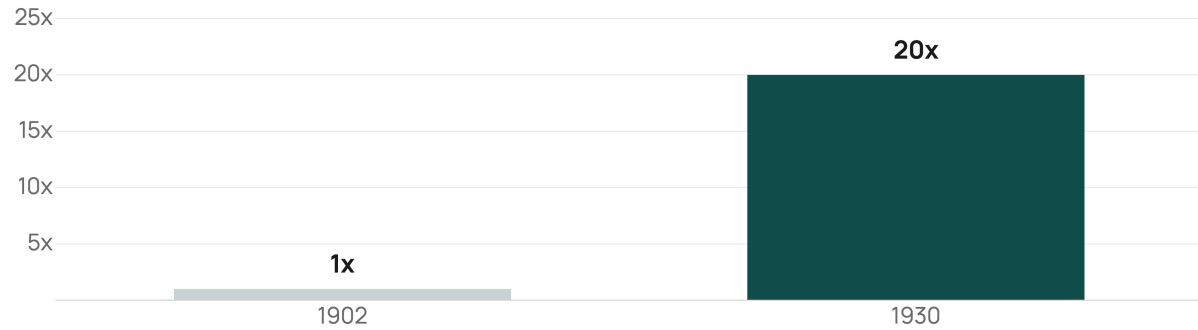
³⁶ Encyclopaedia Britannica, "Nikola Tesla"; "George Westinghouse."

³⁷ U.S. Census Bureau historical statistics, as reported in Federal Reserve Bank of Richmond, "Economic History," Econ Focus, 2020 Q1.

³⁸ Construction Physics, "The Grid, Part II: The Golden Age of the Power Industry."

U.S. electricity generation growth, 1902 to 1930

Generation index, 1902 = 1x



Source: Construction Physics³⁹

Electricity's real arbitrage was reach. Steam and coal had already unlocked enormous energy density; electricity simply let that energy travel, silently and instantly, to wherever it was needed, with no train tracks required.

³⁹ Construction Physics, "The Grid, Part II: The Golden Age of the Power Industry."

SECTION III: ENERGY ARBITRAGE VIA ANIMALS

1. Animals: Borrowed Muscle, the Oldest Multiplier

Long before humanity burned anything, it borrowed muscle, from oxen, from horses, from dogs, and multiplied its own strength many times over. It may be the most intuitive energy arbitrage of all, which is perhaps why it is so rarely counted as one.

Key Milestones

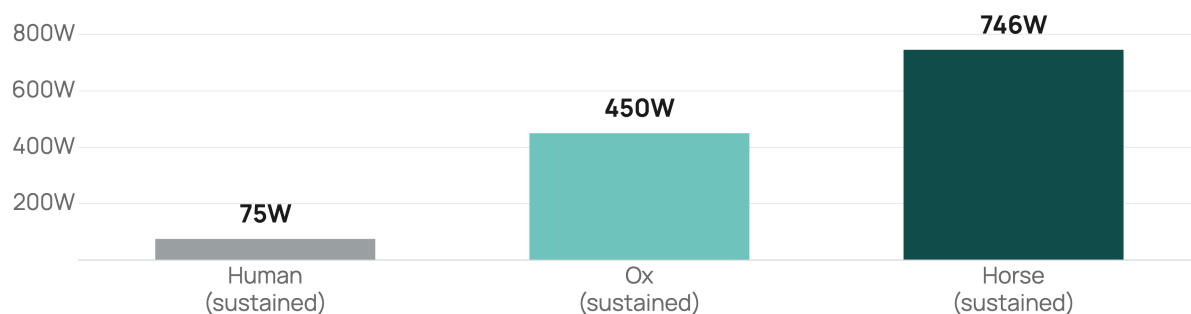
- Hunting, from roughly 15,000 BC onward.⁴⁰ Domesticated dogs extended human senses and speed, making hunting considerably more reliable as a food source.
- Farming, from roughly 4000 BC onward.⁴¹ Oxen and other draft animals pulled plows, multiplying how much land a single farmer could work.
- War and transport, from roughly 2000 BC onward with chariots.⁴² Horses turned soldiers into cavalry and messengers into relay riders, compressing both battle and distance.

The Energy, Social, and Economic Impact of Animals

The arbitrage here is simple physiology. A human can sustain roughly 75 watts of continuous power output over a full workday.⁴³ A medium-sized ox can sustain about 450 watts, and a horse about 746 watts, the literal origin of the term "horsepower," which James Watt coined by measuring a horse's steady work rate.⁴⁴ Every farmer who hitched an ox or horse to a plow was arbitraging that six-to-ten-fold gap in output, and civilization scaled accordingly.

Sustained power output: human vs. domesticated animals

Sustained power output, watts



Source: Tillers International⁴⁴

Unlike fire or coal, animal power is intuitive enough that it rarely gets credited as an energy technology at all, but it was humanity's primary energy multiplier for thousands of years, right up until steam finally offered something even a horse could not match.

⁴⁰ World History Encyclopedia, "Domestication of Animals."

⁴¹ Encyclopaedia Britannica, "History of Agriculture: Animal Traction."

⁴² World History Encyclopedia, "Chariot."

⁴³ Wikipedia, "Horsepower" (sustained human and historical horsepower figures).

⁴⁴ Tillers International, "Animal-Driven Shaft Power Revisited" (Goe & McDowell, 1980), draft-animal power tables.

Conclusion: What Compounds

We began with a hominid who did not run from a fire. In the ages since, the same trade played out again and again, in wood, in water, in wind, in ore, in muscle, and in steam: find an energy source, extract more from it than the last generation could, and reinvest the surplus into the next leap.

Nature offered the first four sources, fire, water, air, and earth, each one denser and more useful than the last. Mechanical innovation then taught those raw sources to travel: the steam engine converted fire and water into motion, rail carried that motion across a continent, and electricity finally let energy move without a single mile of track. And running alongside both, quietly and for far longer than either had existed, was the oldest arbitrage of all: an ox, a horse, a dog, multiplying human strength long before anyone thought to call it energy.

What should stand out is not any single invention, but the compounding.

Fire subsidized the brain. The brain built the plow, the mill, the sail, the engine, and eventually, the reactor. Every gain in this paper made the next one more likely, not less, and each new energy source did not simply replace the one before it, it built on top of it.

And running underneath all of it, the whole time, was a different kind of arbitrage entirely: not the movement of matter, but the movement of messages. That story is worth telling on its own.

Postlude: An Alternative Arbitrage, Moving Messages Rather Than Matter

Somewhere on the Persian Royal Road, around 500 BC, a runner hands off a message to another waiting at a relay station, then rests while the news keeps moving without him. The system amazed the Greek historian Herodotus, who marveled that neither snow, rain, heat, nor darkness could slow it down.⁴⁵

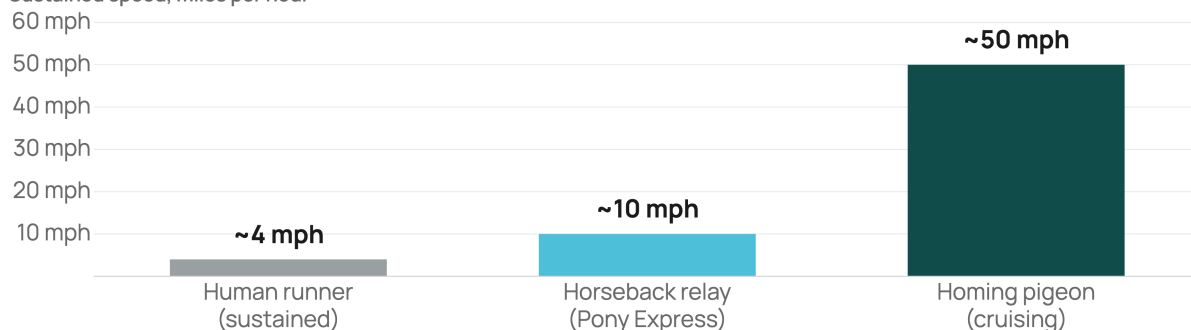
Egypt had already found an even faster courier: homing pigeons, domesticated for messaging as early as 3000 BC, needed no relay at all, just an uncanny sense of where home was, and could cover fifty miles in a single clear-sky hour.⁴⁶

By 1860, the relay had a new engine: the horse. A young rider named Johnny Fry reportedly carried the first Pony Express pouch out of St. Joseph, Missouri, swapping horses every ten to fifteen miles so no single animal ever had to cover the whole 1,900-mile route, the same relay logic the Persian Royal Road had already proven centuries earlier.⁴⁷

Lined up together, the arbitrage is clear. A human messenger sustains roughly 4 miles an hour on foot. A horse relay sustains closer to 10. A pigeon, needing no relay at all, cruises at 50 or better.⁴⁸ Each represented a faster energy source, applied to information delivery.

Speed of message delivery, pre-electric era

Sustained speed, miles per hour



Source: The Donut Whole⁴⁸

None of it was really about the cargo. What mattered was the energy spent getting information somewhere faster than humans could manage on their own.

Part II picks up exactly there: the telegraph, the radio, and the internet, each one a further arbitrage of the same problem those early messengers were solving on foot and on horseback, leading to what we believe may be the most consequential arbitrage of all: energy spent not on carrying information, but on replicating knowledge and judgment itself.

Fire bought us time. Pigeons bought us reach. What comes next, we believe, buys us thought.

⁴⁵ World History Encyclopedia, "Persian Royal Road."

⁴⁶ World History Encyclopedia, "Homing Pigeon."

⁴⁷ National Park Service, "Pony Express National Historic Trail"; "The First Ride on the Pony Express."

⁴⁸ The Donut Whole, "How Far Can a Messenger Pigeon Travel in a Day?"

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