Energy and Information: A Framework for Human Progress

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Foreword

"For we cannot command nature except by obeying her." – Francis Bacon, *Novum Organum*

At Castleforge, we have often found ourselves drawn to questions that sit beyond the conventional remit of a real estate investment business. Not because we imagine we have some special mastery of them, but because investing forces you to engage with a world that does not stand still. Narrow sector analysis will only get you so far. To allocate capital well, you need a view on technology, politics, economics, society, history and the deeper forces that shape how people live, organise, produce and prosper – even if, like everyone else, you do not always get that view right.

We have also learned that one of the best ways to understand a market is not to begin with the market itself, but with the wider system in which it sits. Real estate does not exist in a vacuum, but instead reflects how people work, how firms coordinate, how states govern, how technologies evolve and how capital responds to all of that. The built environment is often a lagging physical expression of deeper currents. In a previous paper, we looked at how human population has organised itself across the planet since prehistory as a way of thinking about one of the most important drivers of value in the built environment: the movement of people and their needs.

But population movement is not the only force that reshapes real estate demand. Technological change can do the same. The rise of industrial and logistics is an obvious example. Not long ago, it was widely overlooked and often treated as marginal by institutional investors. Today it sits at the centre of many portfolios, because e-commerce and adjacent technologies changed the economy around it. Entire sectors can move from peripheral to core when the underlying system changes.

This paper takes on another of those deeper currents. It asks one of the biggest questions of all: what has actually driven human progress across time?

That is, on its face, an absurdly ambitious thing to try to answer. It moves from prehistory to artificial intelligence; from agriculture to industrialisation; from anthropology to engineering; from the first settled communities to the modern data centre. It compresses thousands of years of uneven, contingent and morally complicated human experience into a framework built around two ideas: energy and information. We do not claim to be the first to connect energy, technology, information, and control. But we have found relatively little work that treats history explicitly as a contest shaped by the changing balance between energy mastery and information mastery, or that asks which of the two is the tighter binding constraint in different eras. Some readers will be drawn to that ambition. Others will be sceptical of it. Both reactions are fair.

What follows is not a final theory of everything, or a treatise on techno-energy determinism. It is not an argument that culture, institutions, geography, war, disease, religion, legitimacy, politics or chance somehow do not matter. Of course they do. We have read enough Mackinder, Marx, Mahan and Tilly to know that no narrowly geographic, economic, naval or militaristic framework is going to explain the whole course of history on its own. Human development is too jagged, too contested and too path-dependent for that.

What this paper actually tries to do is something more modest, but I would argue more useful: it offers a lens. Its claim is not that energy and information are the only things that matter, but that they are among the deepest and most persistent constraints on what societies can achieve, and that many of history's great leaps can be understood as moments when one or both of those constraints loosened. That is of course a strong claim, but it is not the same thing as saying everything else doesn't matter.

Nor does the paper pretend that “progress” is a simple or uncontested idea. Agriculture increased carrying capacity, but also hierarchy, disease and coercion. Writing enabled extraction and surveillance as well as coordination and learning. Industrialisation brought misery and pollution alongside abundance. Artificial intelligence may yet prove transformative, but it may also produce manipulation, tremendous social imbalances or even the end of humanity as we know it from the forces of Skynet. Productive capacity and human flourishing are related, but they are not the same thing, and history offers plenty of examples of societies becoming more capable before they became more humane. The same applies to institutions. Energy may expand the frontier of what is physically possible, and information the frontier of what is cognitively and organisationally possible, but institutions still determine how much of that potential is realised, by whom, and to what end. To my mind, though, that does not weaken the framework. It strengthens it. Institutions do not float above material reality. They are themselves shaped by the limits and possibilities created by energy and information.

That is one reason this paper matters now. For all its historical range, it is really a paper about the present and the near future.

Our own view at Castleforge is that, after a long period in which information mastery was the more binding constraint on progress, contemporary AI progress may now drive a step-change in our ability to generate, refine and apply information.

If that is right, then energy will increasingly reassert itself as the constraining variable: not in theory, but in the very practical forms of power generation, transmission, grid capacity and physical infrastructure.

That shift will not stay neatly contained within the technology sector. It will create winners and losers across the economy, including in real estate. Sectors tied most directly to knowledge work, automation, power demand and digital infrastructure are unlikely to emerge unchanged. In that sense, this paper is not just an attempt to interpret the past. It is an attempt to build a framework for thinking about the next phase of economic change, and about where structural tailwinds may emerge as the balance between energy and information shifts again.

Whether one agrees with every line is, in a sense, secondary. The more important test is whether the framework helps illuminate something real. Good models do not eliminate disagreement. If anything, the history of economics should have cured us of that hope by now. What they can do is sharpen debate, organise complexity, and make the world slightly more legible. That is the spirit in which this paper is offered. It is an ambitious synthesis, necessarily imperfect, but written in the hope that it helps readers think more clearly about the deepest forces shaping human progress and, by extension, the built environment that sits downstream of it. If it provokes debate and criticism, that should be seen as a feature, not a bug.

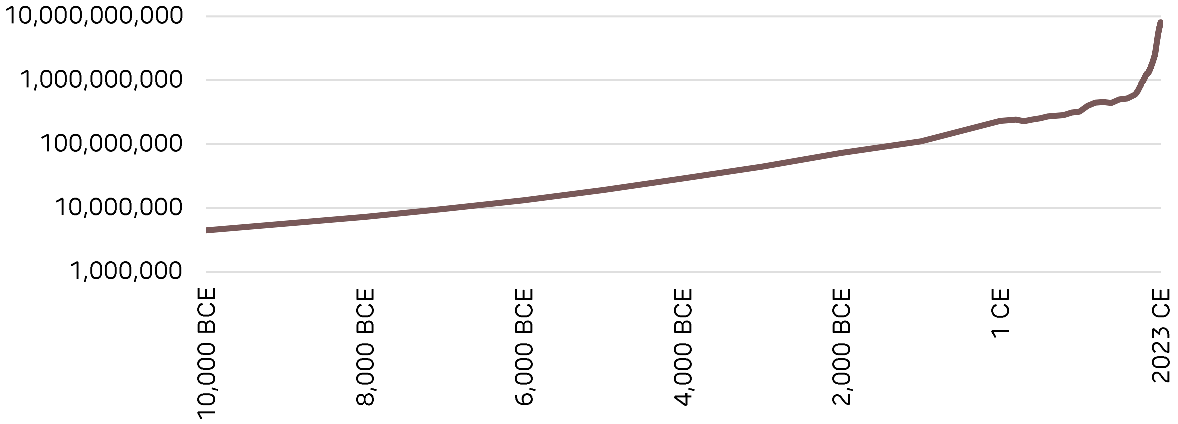
Michael Kovacs
March 2026

I. The Progress Problem

Over the past few centuries, the global economy has operated under a virtuous cycle of investment, growth, and reinvestment. Markets have consistently bet on economic expansion, be that in the form of rising GDPs, expanding market capitalisations, or higher living standards. In doing so, they have created new products and sought to sell solutions in order to eke out a return. On average, these investments have worked, leading to consistent progress that has uplifted the human condition from one generation to the next.

Although it may seem as if humanity has always advanced steadily, historical evidence suggests otherwise. For most of human existence, progress was minimal. Population figures are a useful measure because they reflect aggregate improvements in agriculture, health, and technology that enable societies to sustain more people. The following graph shows how the human population barely grew for much of recent history, with a glaring change in the slope of the line at the time of the Industrial Revolution. Indeed some scholars estimate that 25% of all human births occurred within the past 275 years. For reference, humans have existed on Earth for approximately 200,000 years.[1]

Figure 1: Human population growth from 10,000 BCE to 2023



Economic growth was close to immobile for most of recent human history, too. Between the years 1 and 1500 CE, global GDP is estimated to have grown by around 135%, representing a compounded annual growth rate (CAGR) of around 0.06%. Since then, GDP has had a CAGR of closer to 1%.[2] While this data represents only a small portion of human history, we can only assume that life in the 94% of human existence before 10,000 BCE was quite stagnant, with the humans of 50,000 years ago living largely similar lives to their ancestors 50,000 years before that.

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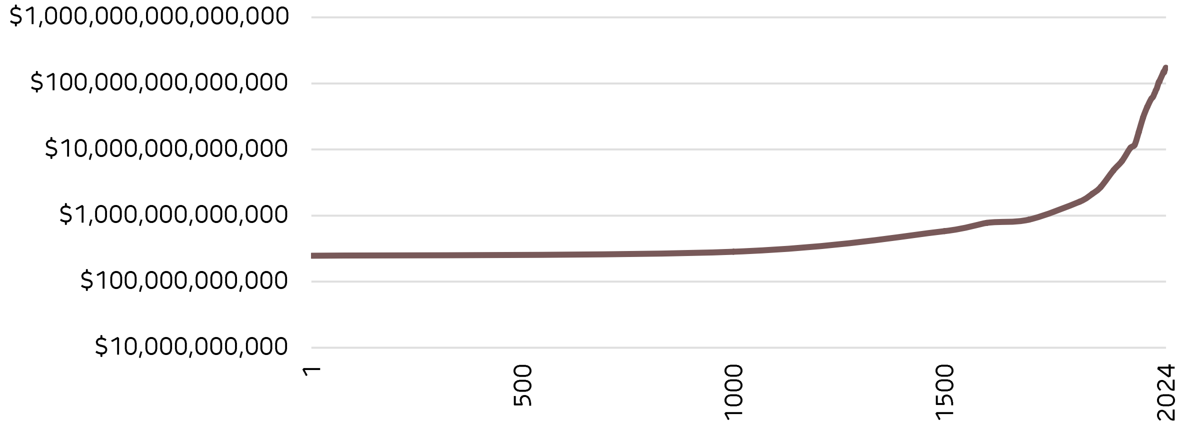
[1] "Data Page: Population", part of the following publication: Hannah Ritchie, Lucas Rodés-Guirao, Edouard Mathieu, Marcel Gerber, Esteban Ortiz-Ospina, Joe Hasell, and Max Roser (2023) - "Population Growth". Data adapted from PBL Netherlands Environmental Assessment Agency, Gapminder, United Nations. Retrieved from https://archive.ourworldindata.org/20260309-085120/grapher/population.html [online resource].

[2] Bolt, Jutta and Jan Luiten van Zanden (2024), "Maddison style estimates of the evolution of the world economy: A new 2023 update", Journal of Economic Surveys, 1–41. DOI: 10.1111/joes.12618.

Figure 2: *Global GDP since 1 CE (constant international $)*



The difficulty in thinking about how humanity has grown as a species is that most of the tools we use to measure progress are products of the very era we are trying to explain. Concepts like GDP or market capitalisation were developed within industrial societies and reflect industrial priorities, which makes them poorly suited to understanding the 99% of human history that preceded our current period. And yet the question is worth pursuing. If we want to understand whether the growth of the past 275 years is sustainable, or what conditions might produce another such period of rapid development, we need a framework that holds across the full span of human history. That means identifying factors that are universal to the human experience – ones that remain meaningful regardless of the economic or political context in which a society finds itself.

To get around the “progress problem,” we must find measurable factors that are universal to the human experience. During the Space Race, astronomers thought of ways in which humanity might understand an alien civilisation’s progress relative to our own. Soviet astronomer Nikolai Kardashev suggested that a society could be measured by its ability to harness energy available in the universe. Under the “Kardashev Scale,” a Type I civilisation could harness all of the energy available on its planet. A Type II civilisation would be able to exploit entire solar systems, and a Type III civilisation an entire galaxy. Later, American astronomer Carl Sagan offered a complement to the Kardashev Scale that emphasised information mastery as a measure of a civilisation’s advancement. Sagan proposed that a civilisation could be measured by how much information it had access to, measured in bits from 10^5 (Type A) and growing exponentially to 10^{31} bits of information (Type Z).[3]

Kardashev and Sagan intended to explain how humans should react to the possibility of intelligent extraterrestrial life – a possibility that we have yet to experience. But their frameworks turn out to be just as useful when pointed inward at our own civilisation. Between them, the two scales reduce the story of human progress to two variables: energy and information. Put another way, humanity values harnessing energy in the pursuit of understanding the universe.

Every human activity – from gathering food to performing surgery – requires both energy and information. Neither is sufficient on its own. A person who knows exactly what to do but lacks the physical means to do it is just as stuck as one who has the means but not the knowledge. The same logic holds at the level of civilisations: societies that have access to abundant energy but lack the knowledge to deploy it efficiently will plateau, as will those whose accumulated knowledge outstrips

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[3] *Sagan, C. (2000). Carl Sagan’s cosmic connection: An extraterrestrial perspective. Cambridge University Press.* Sagan also refined Kardashev’s energy scale by estimating more granular levels of energy access, positing that humanity was a Type 0.7 civilisation.

their energy supply. In this sense, energy and information are not just useful metrics – they are the two key inputs that mutually and exclusively constrain what any human society, at any point in history, can achieve.

Yet energy and information are not, on their own, sufficient to explain the pace of progress. What matters is how societies interact with them. Generating a resource, refining it into useful forms, moving it to where it is needed, and applying it to productive work are distinct challenges, and history suggests that mastering all of these tasks is rarely achieved at once.

Set against the progress problem, the links between the uneven pace of human advancement, the different modes through which mechanisms interact, and Kardashev and Sagan's view that energy and information form the two universal variables lead to a central claim: progress accelerates when a binding constraint on either variable is eased, and it accelerates most when the final bottleneck on the constrained side is removed. The sections that follow develop this into a framework and examine it against the historical record.

II. The Framework

We use the insight that progress in the long term is a function of energy and information as a starting point for the framework that will guide the rest of the paper. Our purpose for creating this framework and writing this paper is to better understand the factors that enable humanity to benefit from periods of accelerated change. At the simplest level, these periods occur when a limiting factor (either energy or information), is temporarily lifted through technological innovation.

Before exploring how constraints are lifted, we must first define energy and information for the purposes of this discussion. Energy represents the capacity to do work by manipulating matter. Humans interact with energy in many different forms, including the chemical energy stored within our cells, electrical energy transported through powerlines, and the kinetic energy of rushing water. We also apply energy to tools to enable us to do new tasks or increase our efficiency.

Information is the synthesis of data and context. It emerges when raw data is combined with meaningful patterns, relationships, or frameworks that allow us to answer questions and make decisions. Information differs from mere data – which consists of isolated facts or measurements – in that information requires interpretation and understanding. For instance, temperature data can become climatic information when analysed within the context of atmospheric patterns, seasonal variations, and historical records. Humans use information to predict outcomes, minimise risks, and make plans.

Human progress, at its core, is about expanding the reach and duration of human life – more people, living longer, across a greater span of the world (and perhaps one day beyond it). Productivity is better understood as a means to this end than as a goal in itself. Within that framing, energy and information emerge as the two variables that have most consistently set the ceiling on what human societies can achieve. The concept of mastery, rather than mere access, captures more precisely how our relationship with these resources has changed over time – not just whether energy or information was available in some quantity, but how deeply and flexibly we could work with it.

In this paper, we consider humanity's interactions with energy and information through four mechanisms, each representing a distinct pathway to increasing mastery:

- **Generation** refers to gathering raw inputs from their sources. For energy, this might involve farming crops for calories, capturing the motion of air molecules with a windmill, or operating a power plant to produce electricity. For information, generation is better understood as data capture – the recording of observations, measurements, and events in a form that can be stored and retrieved. At this stage, the raw material exists but has not yet been made useful.
- **Refinement/Organisation** transforms those raw inputs into forms better suited for human needs. Energy is refined when crude oil is turned into kerosene or gasoline – the underlying resource is the same, but its utility is transformed. Information undergoes an analogous process when raw data is combined with context, patterns, and relationships to produce something that can actually inform a decision. Just as a barrel of crude oil and a tank of aviation fuel represent very different degrees of usefulness, so too do a temperature reading and a weather forecast.
- **Distribution** means moving resources from sites of production to consumption. Distribution has both geographic and temporal aspects. Someone might distribute energy geographically by moving food from one place to another. Similarly, they may distribute energy temporally by preserving food so that it may be eaten long after the time of production. Information distribution can be accomplished by methods such as sharing cuneiform tablets, speaking, or sending digital signals through fibre optic cables.
- **Application** represents the ultimate purpose – using energy and information resources to accomplish productive work. We apply energy when we use our bodies or tools to move and manipulate matter. Information application involves using knowledge to make decisions that allow us to reach our goals.

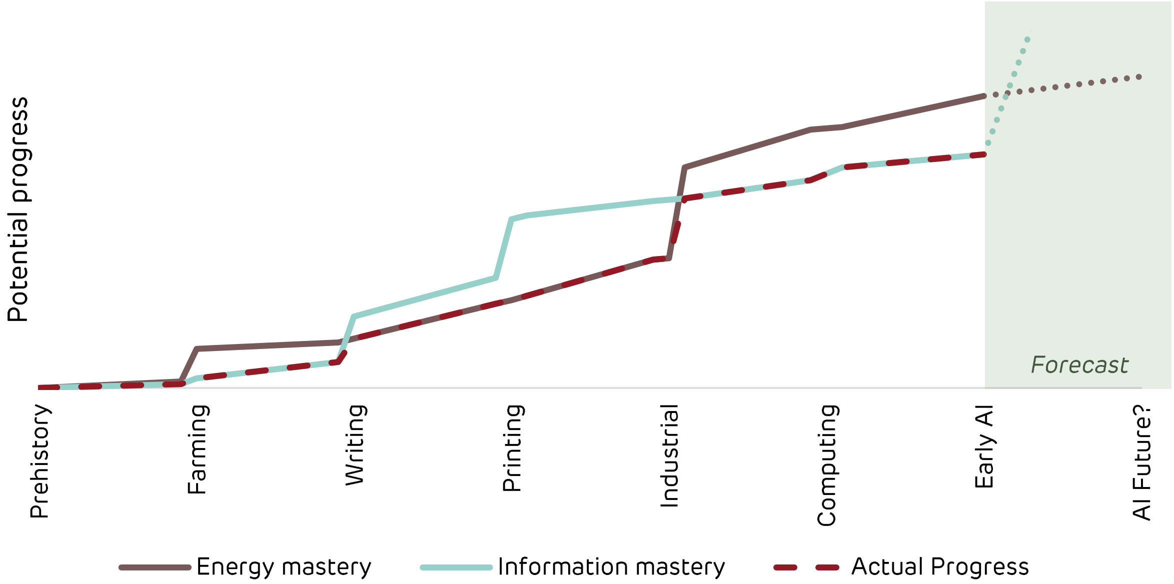
Developing any one of these pathways creates interconnected feedback loops that often catalyse periods of productivity growth and social change. Improvements in one area create surpluses that enable investment in others. For instance, better energy generation methods create surpluses that enable demand for distribution infrastructure, which in turn makes energy more widely available for diverse applications. Similarly, advances in information organisation improve our ability to generate new knowledge by building upon previous discoveries.

This framework is complicated by the fact that humanity is constantly working on all mechanisms of mastery, making neat periodisation difficult. The framework's value lies not in providing an airtight taxonomy, but in offering a lens through which to recognise when constraints are being lifted and feedback loops are beginning to accelerate. Observers will naturally differ in how to interpret different events.

What is rarer – and historically more disruptive – is when the final remaining constraint on a limiting factor is lifted. The central argument of this paper is that human progress accelerates when a binding constraint on either energy or information is relaxed, and accelerates most when the last missing mechanism of mastery on the constrained side is unlocked. Most eras involve advances in one or two mechanisms while others remain bottlenecks. But occasionally all four are operating without a binding constraint simultaneously, and when that happens the feedback loops that ordinarily operate in sequence begin to reinforce each other at once, producing a step change in productive capacity that is difficult to anticipate from the vantage point of the preceding era. There are only a handful of moments in the historical record where this appears to have occurred, which makes it worth asking whether we might be in one today. The following section explores how that pattern has played out across history.

While not meant to show actual data, we can close with a potentially helpful way to visualise this dynamic. One might start by imagining two lines tracking humanity's mastery over energy and information across time. For most of history, both lines advance slowly and in rough parallel. Occasionally, one jumps – a technological breakthrough opens up a gap and sparks a period of intense change. This represents the breaking of a key bottleneck. Over time, however, actual progress is essentially a function of whichever line is lower, demonstrating the effect of bottlenecks.

Figure 3: Imagining the growth of progress over key revolutionary moments[4]



III. Historical Overview: Understanding the Past Through Energy and Information

To understand how humanity's relationship with energy and information has shaped civilization, we must examine key inflection points where revolutionary changes in our ability to generate, refine, distribute, or apply these fundamental resources triggered cascading societal transformations. We examine four pivotal moments: the Agricultural Revolution, the invention of writing, the printing revolution, and the Industrial Revolution – when all four masteries seem to have reached an apex altogether. Each represents a fundamental restructuring of how humans interact with either energy or information, and collectively they demonstrate the relationship between these two pillars of progress.

Farming as a Source of Energy from the First Agricultural Revolution (c. 10,000–8,000 BCE)

The First Agricultural Revolution, also known as the Neolithic Revolution, was a transformative period in human history when some groups of people began adopting sedentary agriculture as the primary means of securing the calories needed for their survival. This transition began around 10,000 BCE in the Fertile Crescent of the Middle East, but also independently at other times in places like China, Mesoamerica, and the Andes. Before this revolution, anthropologists believe that human communities were primarily nomadic, moving frequently to exploit local food availability whenever resources were available.

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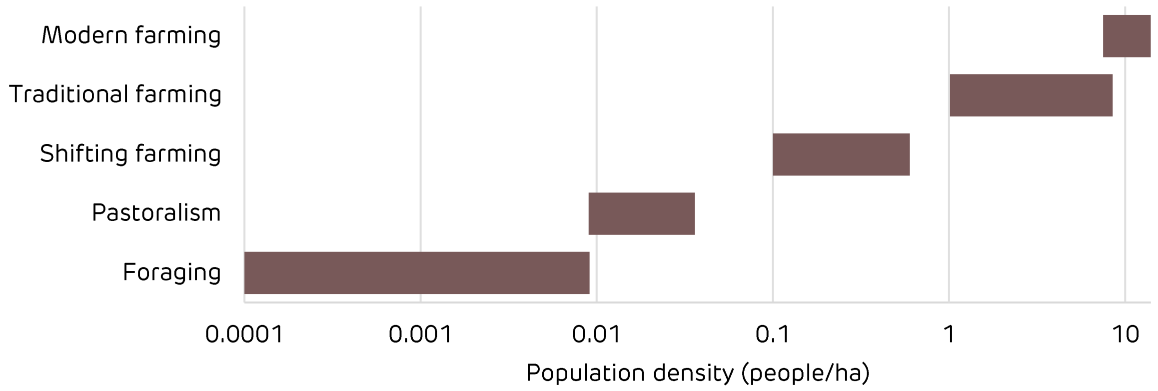
[4] This "graph" is meant to be more an artistic interpretation than a statement of fact. The axes and amplitude of growth, for example, are largely meant to be illustrative of general patterns of growth, rather than descriptive numerical explanations of what actually happened.

The adoption of agriculture as the primary means of meeting energy requirements enabled (or perhaps forced) groups of people to settle in one place, leading to the development of permanent villages and, eventually, civilisation.[5] From an energy perspective, agriculture represented a new form of generation – though it may not have necessarily resulted in a greater supply of calories at first. Early forms of agricultural production may not have generated meaningful energy returns relative to foraging and hunting strategies due to the labour required to plough, seed, weed, and harvest crops.[6] Over time, however, farming processes became more efficient due to innovations such as animal domestication, irrigation, fertilisation, and multi-cropping, which eventually led to agriculture delivering positive energy returns and supporting denser populations.[7]

In the terms of this framework, generation was the mechanism that had been missing. Refinement of food had existed for millennia, as had the distribution of calories through seasonal migration and the application of human and animal muscle to productive work. What foraging societies lacked was not the ability to process or use energy, but the ability to produce it reliably and at sufficient scale in one place. Agriculture resolved that, and in doing so allowed the other three mechanisms to compound against each other for the first time.

Figure 4: Population densities supported by different agricultural strategies and foraging[8]



The refinement and application of energy saw a more modest change. In terms of refinement, the key development was in food processing – the transformation of raw agricultural output into more stable and digestible forms. Grain could be dried, milled, and stored at scale in ways that hunted game or foraged plants could not, extending the useful life of the energy surplus that farming created. Application, however, remained much as it had always been. Tasks were completed through the movement of human and animal bodies – what the energy scholar Vaclav Smil calls prime movers:

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[5] While there is a correlation between the discovery of farming in the Middle East and sedentary civilisation, the historical record is much more complicated than this paper can reasonably discuss. There is evidence that some societies may have adopted sedentary strategies and perhaps even engaged in lighter forms of agriculture before the First Agricultural Revolution, perhaps on a seasonal basis. Moreover, the adoption of agriculture by certain members of a society did not preclude other members of that same society from continuing to engage in hunting and foraging strategies to diversify the food supply.

[6] Vaclav Smil. *Energy and Civilization: A History*. Cambridge, 2017.

Scott, James C. *Against the Grain: A Deep History of the Earliest States*. Yale University Press, 2017. Yale Agrarian Studies Series.

Smil and Scott note that early Mesopotamian agriculturalists may have exploited seasonal river flooding to prepare fields for sowing, thereby reducing the energy inputs needed when farming.

[7] Smil.

[8] Vaclav Smil. (2004). “World History and Energy”. In C. J. Cleveland (Ed.), *Encyclopedia of Energy* (Vol. 6, pp. 549–561). Elsevier. https://doi.org/10.1016/B0-12-176480-X/00025-5

entities that convert energy into motion. In early agricultural societies, these prime movers were almost exclusively muscle, whether human or animal, and the fundamental process by which the body extracted energy from food was unchanged. However, greater access to calories from farming naturally raised the ceiling on how much energy could be applied to do work.

Distribution may have seen modest improvements. Grains offered superior storage capabilities compared to hunted game or gathered plants, enabling societies to buffer against seasonal variations and create food surpluses. Yet this advantage came with risks: dependence on a few staple crops meant that disease, natural disasters, or parasitism could destroy a community's entire caloric base for a year.[9] Moreover, the storage of grains could invite hostile competition from other groups of people.

The most important impact of the Neolithic Revolution was that agricultural strategies supported higher population densities than hunting and gathering could. Before 10,000 BCE, global population densities were estimated to be between <1 and several hundred people per 100 km^2, with an average of around 25.[10] By contrast, cultivated land could support between 10 and 100x more people in the same amount of space.[11]

Populations began aggregating in permanent settlements, with some becoming much larger than most pre-revolution tribes had been. This energy dividend enabled the first labour specialisation, with individuals dedicating themselves to crafts, trade, governance, and military roles rather than subsistence activities.[12] Yet the breakthrough in energy generation through agriculture created mismatches elsewhere in the system. While communities could now produce surplus calories, they initially lacked sophisticated methods for refining those surpluses into more useful forms or distributing them efficiently across time and geography. The energy was there, but the infrastructure to fully exploit it lagged in comparison.

What followed was a prolonged period of adaptation as societies worked to improve their mastery through the other paths. Better storage techniques emerged to preserve grains through lean seasons. Trade networks developed to move surpluses between regions. New tools and techniques refined raw agricultural output into diverse food products. Each innovation created feedback loops: as storage improved, communities could support larger populations, which generated more labour for building better storage facilities and developing new agricultural techniques. Yet there were limits to how far these adaptations could go without a corresponding advance in information mastery. Managing surpluses across growing populations required more than memory and word of mouth – it required the ability to record debts, track quantities, and coordinate labour at a scale that oral communication could not sustain. The concepts of property ownership, inheritance, and territorial control that emerged alongside permanent settlements created an urgent demand for more sophisticated information tools. It is no coincidence that writing and early mathematics appear to have developed precisely in response to these administrative pressures, as the next section explores. The energy breakthrough of the Agricultural Revolution had, in time, made information the binding constraint.

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[9] Scott.

[10] Smil.

[11] Smil and Diamond, Jared M. *Guns, Germs and Steel: The Fates of Human Societies.* Norton, 1997.

[12] Smil.

The Invention of Writing and Managing Information in Complex Society (*c. 3200–3000 BCE*)

As the intensity of farming improved over the thousands of years following the Agricultural Revolution, early societies often needed to organise labour for projects such as irrigation or the clearing of new areas for farmland. As agricultural societies evolved into more complex civilizations with thousands of inhabitants, the cognitive limitations of human memory and face-to-face interactions became a critical bottleneck to progress. Early cities faced administrative challenges that exceeded what oral communication could manage. Tracking agricultural surpluses, organizing labour for massive construction projects, managing trade relationships, and codifying laws for diverse populations cannot run on hearsay.

James C. Scott argues that any human polity with more than a few thousand inhabitants would need some form of recordkeeping to maintain order.[13] The solution for the issue of urban populations was the invention of writing, which refines the ephemeral information stored within our thoughts and memories to a more permanent medium. Over time, however, the earliest examples of writing emerged in Mesopotamia around 3000 BCE and with the practice being found in other civilisations later.[14]

As societies produced more materials, retrieval became challenging. An early form of bureaucracy emerged as the solution: centralising records and standardising reporting created institutional knowledge, with small numbers of priests and civil servants serving as scribes and becoming integral to early states.[15] Written records created powerful feedback mechanisms – sophisticated administrative systems managed larger populations, generating more data that required documentation, which drove innovations in writing and bureaucratic organisation. This self-reinforcing cycle explains why writing and state formation appear so closely linked, with Scott noting that the decline of early states coincides with the decline of writing in the historical record.[16]

Writing represented an advance across all four dimensions of information mastery. It improved generation by providing a means of capturing observations and transactions that would otherwise be lost to memory. It enabled refinement, as information could now be organised, cross-referenced, and built upon in ways that oral tradition could not support. Distribution improved too, albeit modestly – a clay tablet could carry information further and more reliably than any messenger's recollection. And application advanced as administrators, merchants, and rulers could make decisions on the basis of recorded knowledge rather than hearsay alone.

Yet significant barriers remained, and their nature reveals something important about this period. Distribution was vastly improved (with writing, a single person's thoughts could be in many places at once), but it was still a stubborn bottleneck – replicating written information required painstaking manual labour by skilled scribes whose training demanded years of education that could otherwise be devoted to other productive activities. This constraint meant that the benefits of information mastery were largely confined to priestly and administrative elites, and that the feedback loops which writing enabled operated within a narrow slice of society rather than across it. In the terms of this framework, refinement was the mechanism that had been missing. Information was already being generated through observation and oral record, distributed through speech and messenger, and applied to decisions in trade, governance, and agriculture. What those societies lacked was any means of making

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[13] Scott.

[14] Diamond.

[15] Harari, Yuval Noah. *Nexus: A Brief History of Information Networks from the Stone Age to AI.* Fern Press, 2024.

[16] Scott.

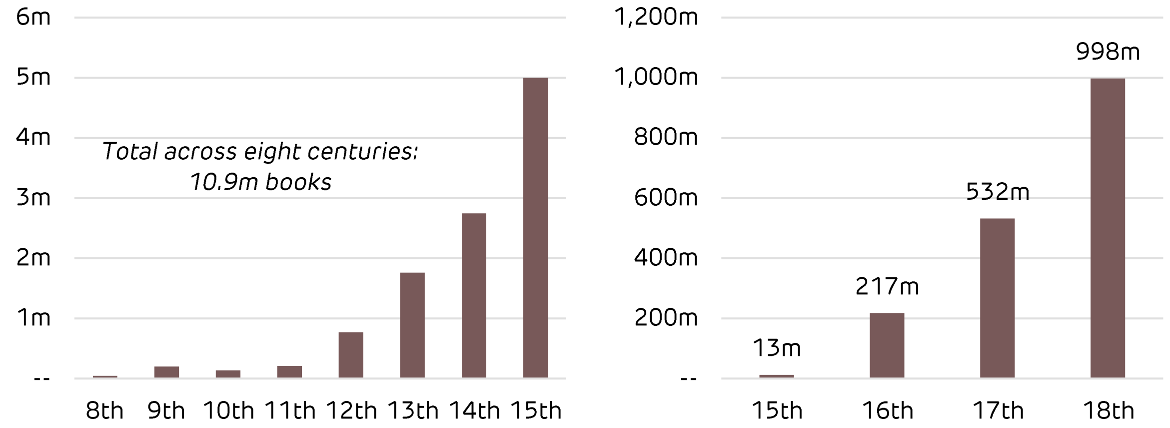
information durable and organised enough to accumulate over time. Writing resolved that – and immediately exposed distribution as the next constraint, one that would persist for another four millennia.

The Gutenberg Printing Revolution and the Commoditisation of Written Language (c. 1440 CE)

Before Johannes Gutenberg's innovations in the mid-15th century, the distribution of written information depended on small classes of scribes. In 15th century Europe, monks were significant producers of books, with a single item often requiring weeks or months of labour. This time-intensive process made books expensive, accessible only to wealthy individuals and influential institutions. The scarcity meant only texts deemed most valuable – primarily religious works and classical philosophy – warranted reproduction. In Europe, the Catholic clergy served as a principal gatekeeper of information as one of the most powerful institutions on the continent.

By around 1440, Gutenberg began developing prototypes for a new form of writing production. His principal innovations involved combining moveable metal type, oil-based inks, and a printing mechanism inspired by wine presses to dramatically reduce the marginal cost of information replication. Gutenberg's presses could produce around 240 impressions per hour – a remarkable improvement over hand copying, though still modest compared to what would later be with the introduction of steam power.

Figure 5: Manuscripts (left) and printed books (right) produced per century in Europe



The transformation in production capacity was extraordinary. In the half-century between 1454 and 1500, European presses produced more books than scribes had in the 1,000 years prior.[17]

The societal impacts of Gutenberg's innovations were even more transformative. The democratisation of information access upended existing power dynamics across Europe. One way this occurred was via the Protestant Reformation, where nonconformist opinions by reformers such as Martin Luther were able to spread rapidly through the dissemination of printed materials.

The printing press initiated multiple reinforcing feedback loops. As books became cheaper, literacy rates rose. In Germany, for example, literacy grew from 9% in 1475 to 31% in 1650.[18] This represented

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[17] Harari and Buringh and Van Zanden (2009) – processed by Our World in Data. "Production of printed books per half century" [dataset]. Buringh and Van Zanden (2009) [original data].

[18] "Data Page: Literacy rate", part of the following publication: Hannah Ritchie, Veronika Samborska, Esteban Ortiz-Ospina, and Max Roser (2023) - "Global Education". Data adapted from UNESCO, Buringh and van Zanden, van Zanden, J. et al., UNESCO Institute for Statistics. Retrieved from

a larger market for printed materials, which justified further investment in printing technology and distribution networks. Simultaneously, the rapid circulation of ideas accelerated scientific and technical progress, generating new content to print while also spurring innovations in the printing process itself – from better inks to more efficient presses. These interlocking cycles transformed information from a scarce resource controlled by elites into an increasingly abundant one that could drive further innovation.

In the terms of this framework, distribution was the mechanism that had been missing. Since the invention of writing, information generation had been advancing through the accumulation of texts and observations; refinement had grown more sophisticated through bureaucratic organisation, scholarship, and the codification of law; and application had progressed as literate administrators and merchants put recorded knowledge to productive use. The constraint that prevented those gains from spreading beyond a narrow elite was distribution – the inability to replicate written information at anything approaching the scale of demand. Gutenberg resolved that, and the feedback loops that writing had initiated but could not propagate were suddenly free to operate across society as a whole.

Yet the printing revolution also revealed important limitations in both energy systems and human information processing. The presses themselves remained constrained by the somatic energy of their operators until steam power became available. The information in books could only be transported by humans and animals, too. This points to the intricate relationship between energy mastery and information distribution that would become increasingly important in later technological revolutions.

The Industrial Revolution and the Development of New Prime Movers (c. 1760–1840)

The Industrial Revolution is challenging to describe because of its breadth. It at once involves revolutions in transportation, mineral extraction, metallurgy, production technologies, organisational management, and countless other fields. As it relates to the framework of this paper, however, the most important change of this era was in the application of energy – specifically, the development of the steam engine as a new class of prime mover. What the steam engine made possible was not merely the burning of coal for heat and light, which had been done for centuries, but the conversion of that stored energy into mechanical work that could be directed at almost any productive task. It was this – the ability to apply fossil fuel energy through an inanimate machine, rather than through a human or animal body – that represented a qualitative transformation in humanity's relationship with energy itself.

In the 16th century, a timber shortage caused Britain to transition "almost completely" to meeting its energy needs with coal by 1700.[19] This transition did more than replace wood; it transformed coal into a key driver of industrial change. As mining expanded, demand for deeper extraction created a cycle of innovation. While coal was originally burned for heat and light, humans began using its energy to power machinery, such as pumps to drain mineshafts. The replacement of human efforts with machines to complete work represented the discovery of a new prime mover. With time, the other energy sources such as oil, natural gas, and nuclear power (used to generate electricity) would be further applied to machines to continue supplying these new prime movers.

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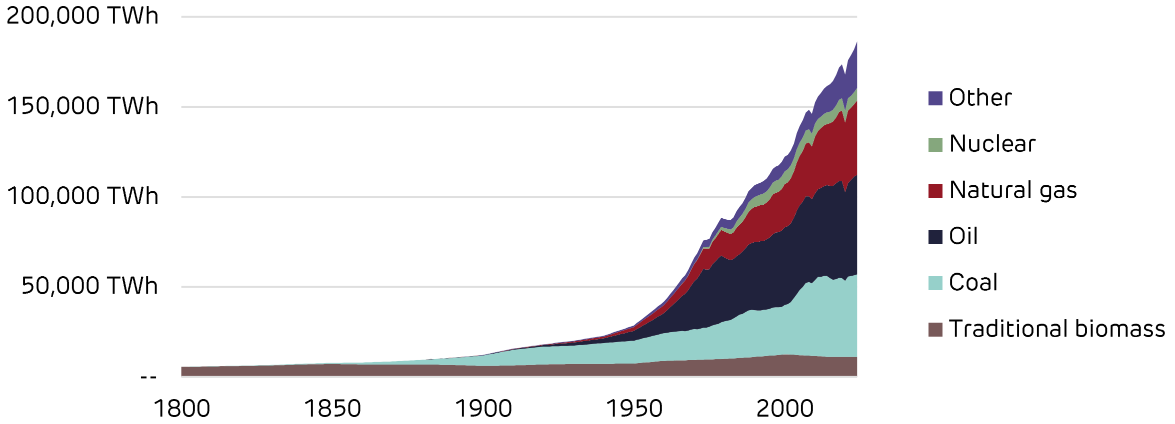
https://archive.ourworldindata.org/20260304-094028/grapher/cross-country-literacy-rates.html [online resource].

[19] MES. "From the Editor: When Britain Ran Out of Wood." *Challenge* 22, no. 5 (1979): 3–4. http://www.jstor.org/stable/40719808.

Figure 6: Global primary energy consumption by source[20]



This new mode of applying energy represents the most important part of the Industrial Revolution. For millennia, humanity had relied exclusively on biological prime movers, supplemented occasionally by the intermittent natural forces of wind and flowing water. An adult human male performing sustained manual labour could generate approximately 75 watts of mechanical power, while a horse might produce around 750 watts. Steam engines, as mentioned before, could output thousands of watts of power – and they could do for as long as there was fuel and new parts. This transition from biological to mechanical prime movers liberated production from constraints that had defined human civilisation since its inception. In our framework, this is fundamentally a matter of achieving mastery through application.

The Industrial Revolution exemplifies the idea of energy and information switching places as limiting factors to productivity growth. In the wake of Gutenberg's innovations, scientific discoveries flourished in Europe, but they often lacked the energy resources to be applied by engineers. For example, Christiaan Huygens designed an early prototype of a piston driven engine, but his designs were impractical as they ran on gunpowder. Only when coal, which releases its energy more gently, could be applied through the intermediary of steam did the technology achieve viability. A similar pattern appears in Leonardo da Vinci's famous designs from the late fifteenth and early sixteenth centuries. His sketches of ornithopters and aerial screws demonstrate remarkable mechanical intuition, yet they remained theoretical for centuries. The ideas of da Vinci, coupled with those of Enlightenment thinkers like Bernoulli, could not be realised until more energy-dense fuel sources became available.

Each of the four historical episodes represents a moment when the last remaining constraint on a limiting factor was resolved – and the Industrial Revolution is the clearest illustration of what follows when that happens. Energy generation via coal had been expanding for over a century; refinement of fuel into more useful forms was already underway; and distribution via roads, rivers, and canals was functional. The missing mechanism was application – the ability to direct stored energy through an inanimate machine at almost any productive task. Once the steam engine provided that, all four mechanisms were operating without a binding constraint simultaneously, and the speed of what followed reflected that completeness in a way that no previous energy advance had.

The four episodes examined in this section were chosen to test whether the framework holds across the full span of recorded history – not just the industrial and post-industrial periods for which we

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[20] Energy Institute - Statistical Review of World Energy (2025) – with major processing by Our World in Data. "Wind consumption" [dataset]. Energy Institute, "Statistical Review of World Energy" [original data].

have reliable economic data, but the deeper past where conventional measures of progress like GDP or market capitalisation are simply unavailable. The argument of the previous section was that energy and information are universal constraints on human progress, meaningful regardless of the economic or political context in which a society finds itself. The historical record bears that out. Agriculture, writing, the printing press, and the steam engine are separated by millennia and involve entirely different technologies, social structures, and geographies, yet each can be understood as a moment when mastery over one of the two variables was substantially advanced – and when doing so exposed the other as the new bottleneck. That the same framework can illuminate a Mesopotamian city-state's administrative challenges and a nineteenth-century British coalfield suggests it is capturing something genuinely fundamental about how human societies develop, rather than something specific to the era that produced the analytical tools we typically reach for.

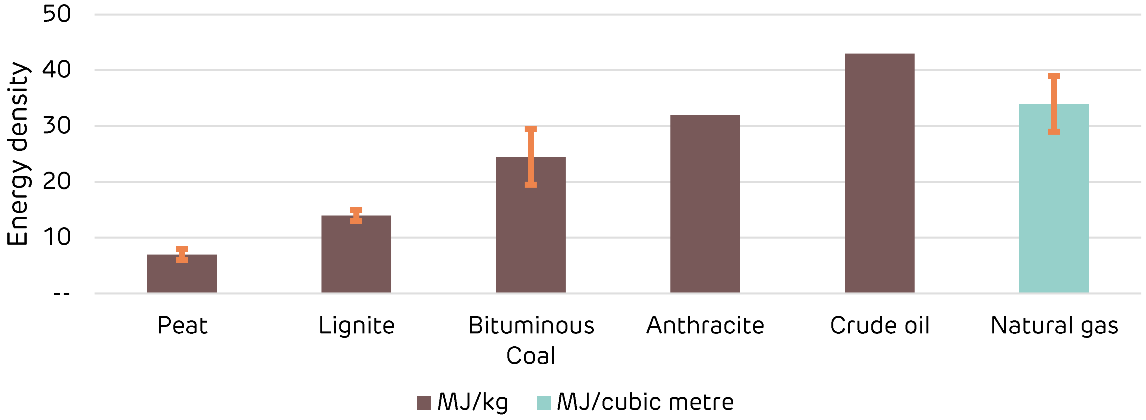
IV. The World Since the Industrial Revolution

Energy as a Solved Problem

The human population reached approximately 1 billion in the 1840s and has grown more than eightfold since then. Despite the massive growth of the population, predictions of humanity falling into a Malthusian Trap or a "Population Bomb" have failed to materialise.[21] This is largely because the supply of available energy was greater than the aggregate level of demand, made possible by continued innovations in energy mastery.

There were multiple ways in this happened. For one, humans continued to discover and use new forms of energy. After turning coal into fuel for machines, people moved onto other hydrocarbons such as oil and natural gas. Refining processes (such as turning crude oil into gasoline or kerosene) further increased the energy density of raw materials. Moreover, the energy stored in natural materials could be transformed into electricity, which offers benefits in that it can be generated centrally and distributed to points of demand. Later, non-hydrocarbon sources such as nuclear and solar photovoltaic power would be added to the energy mix.

Figure 7: Energy density of different fossil fuels[22]



Of course, humans cannot subsist on coal or uranium. The rising population in the centuries after 1750 was also supported by increasing agricultural efficiency, made possible through mechanised agriculture, chemical fertilisers, and genetic modification of crops. The Green Revolution of the 1960s

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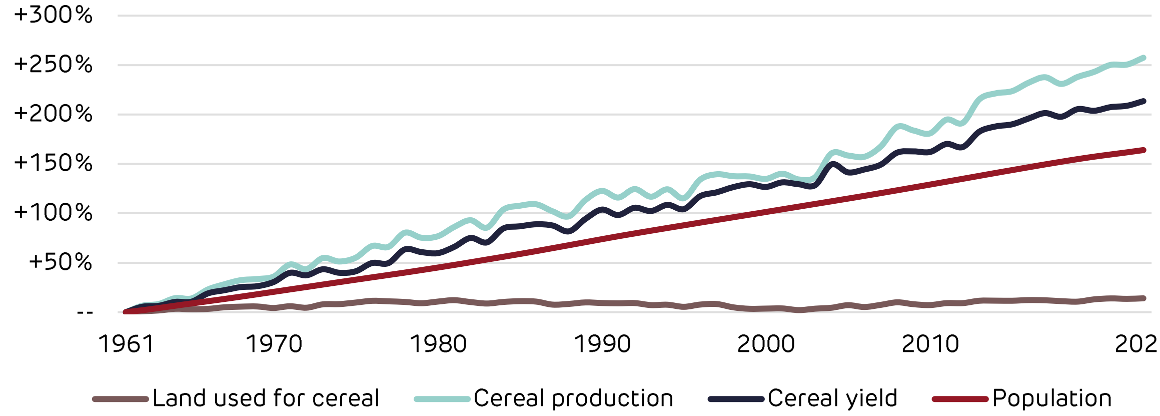
[21] See Ehrlich, Paul R. *The Population Bomb*, 1971.

[22] Smil.

was an especially important moment in human history, as it allowed the global food supply to absorb rapid population growth as a new wave of regions in Asia and Sub-Saharan Africa began to industrialise in the mid-20th century. Despite the global population growing 165% between the 1960s and 2022, available calories per person did not decline – in fact, they increased by 35%, from around 2,184 kilocalories per day to 2,957.[23]

Figure 8: Change in cereal production, yield, land use and population



On the demand side, continued innovations in engine technology reduced the energy demands of the growing industrial economy, providing much-needed headroom between global energy capacity and aggregate need. Thomas Savery's first practical steam engine of 1698 was notoriously inefficient, wasting vast amounts of fuel. Thomas Newcomen's atmospheric engine of 1712 represented a substantial improvement, achieving roughly 5,500 watts of mechanical power. James Watt's innovations, patented beginning in 1769, achieved similar outputs with approximately 75% less fuel consumption.[24] Yet the relationship between efficiency and consumption proved more paradoxical than these engineering triumphs might suggest. William Stanley Jevons observed in 1865 that Watt's improvements, rather than reducing Britain's coal consumption, had actually accelerated it. As engines became more efficient, they became economically useful for more applications, driving demand upward for fuel. What became known as the Jevons paradox has recurred throughout the modern era, leading to ever-higher demands for energy and fuel.

By the mid-20th century, energy had largely become a solved problem for industrialised societies. The combination of abundant fossil fuels, efficient conversion technologies, and agricultural innovations meant that humanity possessed both the capacity and the technical mastery to support a growing population and expanding economy. Energy was no longer the binding constraint it had been for most of human history. The question shifted from whether there would be enough power to sustain civilisation to how that power might be deployed.

With this abundance came new possibilities. Energy could now be directed toward purposes beyond the immediate demands of survival, production, and transport. One such purpose was the management of information. As societies grew more complex and geographically dispersed, the ability to communicate and process information became increasingly valuable. Electricity, already flowing

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[23] Food and Agriculture Organization of the United Nations (2025) – with major processing by Our World in Data. "Land used for cereal production – UN FAO" [dataset]. Food and Agriculture Organization of the United Nations, "Production: Crops and livestock products" [original data].

[24] Smil.

through homes and factories, could be harnessed to send messages across vast distances and, eventually, to perform calculations at speeds no human mind could match.

The Early Information Revolution and the Internet

While our relationship with energy changed rapidly in the wake of the Industrial Revolution, mastery over information expanded, too. Early on, some innovations in information seem to be enhancements or complements to energy revolutions. For example, applying steam engines to the printing press allowed for even faster production of printed materials. By the 1860s, steam-powered presses could produce as many as 25,000 impressions per hour.[25]

A turning point for the development of more robust information systems emerged with the development of general purpose computing near the end of the Second World War. Early mainframe computers such as ENIAC could be programmed to solve a wide array of problems by encoding data in electrical signals. These networks remained largely the domain of the military and academia at first, as equipment was expensive and rarely interoperable. The case of Stanford University in 1982 provides an illustrative example. In 1982, the University had 5,000 computers, most of which struggled to communicate with each other.[26]

The first problem – cost – was addressed through the development of silicon-based transistors and continuous improvements in how densely they could be packed onto microchips. Moore's Law, which posits that the number of transistors on a microchip doubles every two years, represents a rapid improvement in humanity's ability to refine information through the use of tools. The declining cost of memory and storage made computing increasingly accessible, with prices per terabyte falling dramatically over subsequent decades.

The second problem – interoperability – required processes of standardisation and rules for organisation. Early on, file transfer protocols and encoding rules had to be established so that different systems could understand one another. Perhaps the most significant breakthrough in information organisation came with Tim Berners-Lee's development of the World Wide Web in 1989-1991. The Web introduced standards and rules for building and organising pages that made the internet far more accessible to ordinary users. The impact was immediate: between 1991 and 1997, the number of websites grew from just one to over 1 million.[27]

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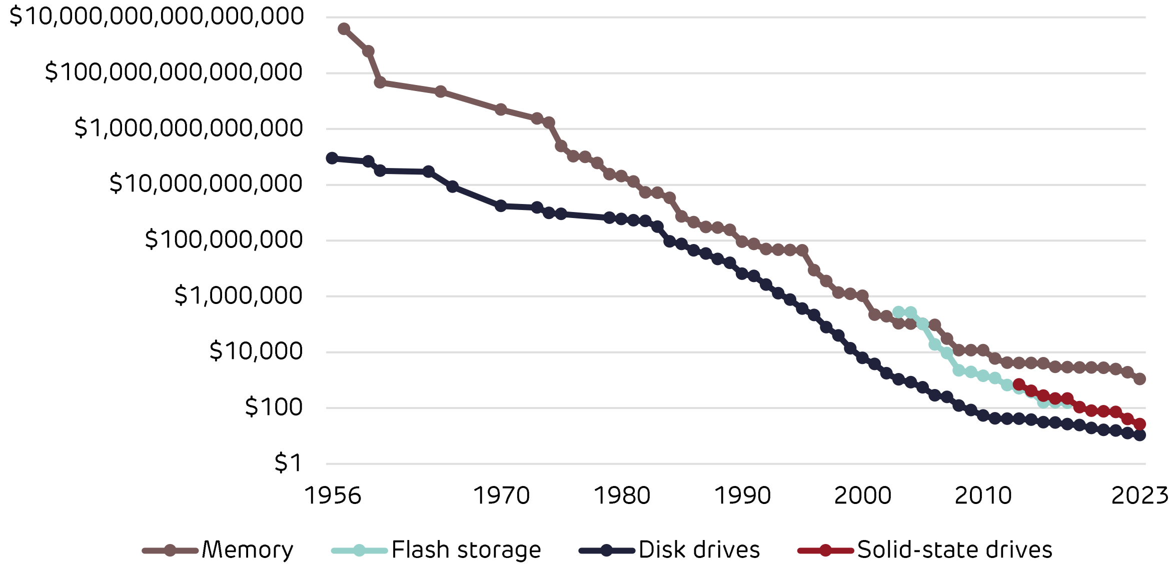
[25] Smil.

[26] Nairn, Alasdair. *Engines That Move Markets: Technology Investing from Railroads to the Internet and Beyond.* Wiley, 2002.

[27] *Total Number of Websites - Internet Live Stats.* https://www.internetlivestats.com/total-number-of-websites/.

Figure 9: Historical price per terabyte of computer memory and storage (constant 2020 US$)[28]



The internet as we know it began to emerge from these developments, radically transforming how we distribute information around the world. What had been a network connecting researchers and institutions became a global infrastructure for near-instantaneous information exchange. Geographic distance ceased to be a meaningful constraint on information distribution in ways that would have been unimaginable even to those who witnessed the telegraph's arrival.

As costs continued to fall and standards took hold, the internet became a mass market commodity with powerful network effects. Large businesses emerged to service both corporate needs and consumer desires, storing content and connecting buyers with advertisers. Social media providers grew rapidly, fundamentally changing who could contribute to the global repository of information. It was no longer just businesses, academics, and governments adding content, but billions of individuals sharing their content, too. The speed at which new platforms reached 100 million users accelerated dramatically: the World Wide Web took seven years, the iPhone three years and seven months, Facebook four years and six months, Instagram two years and six months, TikTok nine months, and ChatGPT just two months.[29]

Between 2017 and 2023, global useable data grew from under 30 to around 120 zettabytes (1 zettabyte = 10^{21} bytes, or 1 trillion gigabytes). This explosion in data creation drove increased demand for new ways to store, manage, and process information. While most people might be familiar with services like Google as a curator and indexer of the web, on a physical level, this transformation has manifested in the growth of the data centre industry. Data centres are facilities designed to house and operate large numbers of servers and networking equipment. Specifically, they provide the electricity needed for all of the computer hardware, along with cooling systems to prevent overheating and network connectivity to move data. The relationship between information processing and energy

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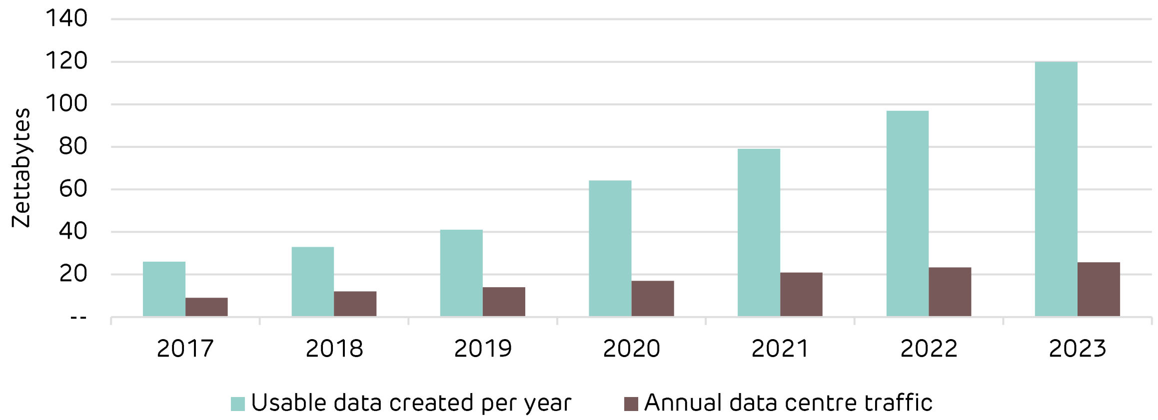
[28] John C. McCallum (2023); U.S. Bureau of Labor Statistics (2025) – with minor processing by Our World in Data. "Memory" [dataset]. John C. McCallum, "Price and Performance Changes of Computer Technology with Time"; U.S. Bureau of Labor Statistics, "US consumer prices" [original data].

[29] PwC. "Resetting Expectations, Refocusing Inward and Recharging Growth." 2023, https://www.pwc.com/hu/hu/kiadvanyok/assets/pdf/pwc_gemo_2023.pdf.

consumption, which had been relatively modest in the early days of computing, became increasingly direct and substantial.

Figure 10: Global Datasphere vs data centre traffic[30]



While the data centre market has grown rapidly, the gap between the size of the Datasphere (measured by the International Data Corporation), which estimates the total amount of data created, captured, and replicated in any given year, and total data centre traffic (which we use as a heuristic for supply) has been widening. This divergence points to a tension in our information systems: we are generating data far faster than we are building the infrastructure to refine it into useable information and apply it effectively. The strain manifests in single-digit vacancy rates across major markets, with available capacity struggling to keep pace with demand.

Today, the growth of artificial intelligence threatens to split this gap even wider. The scale of this challenge is striking. Global electricity consumption by data centres reached about 415 TWh in 2024, representing 1.5% of total electricity use, and has grown at an annual rate of 12% since 2017. This growth is set to accelerate: demand is projected to more than double to 945 TWh by 2030 and could reach 1,200 TWh by 2035, with high-growth scenarios projecting up to 1,700 TWh. Supply, meanwhile, has struggled to keep pace. Grid connection queues stretch up to 10 years in some regions, and about 20% of planned global capacity faces risk of delay by 2030.[31]

In the terms of this framework, the computing revolution advanced three of the four information mechanisms in close succession. Generation improved dramatically as sensors, transactions, and interactions of every kind began producing data automatically and continuously. Refinement followed, as Moore's Law drove down the cost of processing and storing that data, and the Web provided the organisational standards needed to make it navigable. Distribution, once the binding constraint that had kept information confined to scribal elites and then to institutional gatekeepers, was effectively resolved – a person with a smartphone now has access to more recorded knowledge than any library in human history. What computing did not resolve was application. The infrastructure for turning data into information existed; what remained missing was the capacity to

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[30] PwC. "Edge Data Centers: Riding the 5G and IoT Wave." 2019, https://www.pwc.com/us/en/industries/capital-projects-infrastructure/library/assets/pwc-edge-data-centers.pdf.
International Data Corporation. "Volume of Data or Information Created, Captured, Copied, and Consumed Worldwide from 2010 to 2029." Statista, 2026, https://www.statista.com/statistics/871513/worldwide-data-created/?srsltid=AfmBOopIAOcU5fJo7kOwoZ542-j4dqwl6uJ_hPWDRO5TZiJqR1tijc9Z. Web.

[31] IEA (2025), Energy and AI, IEA, Paris https://www.iea.org/reports/energy-and-ai, Licence: CC BY 4.0

act on that information at scale, autonomously, and across the full range of tasks that human societies need performed. That constraint is what AI now confronts.

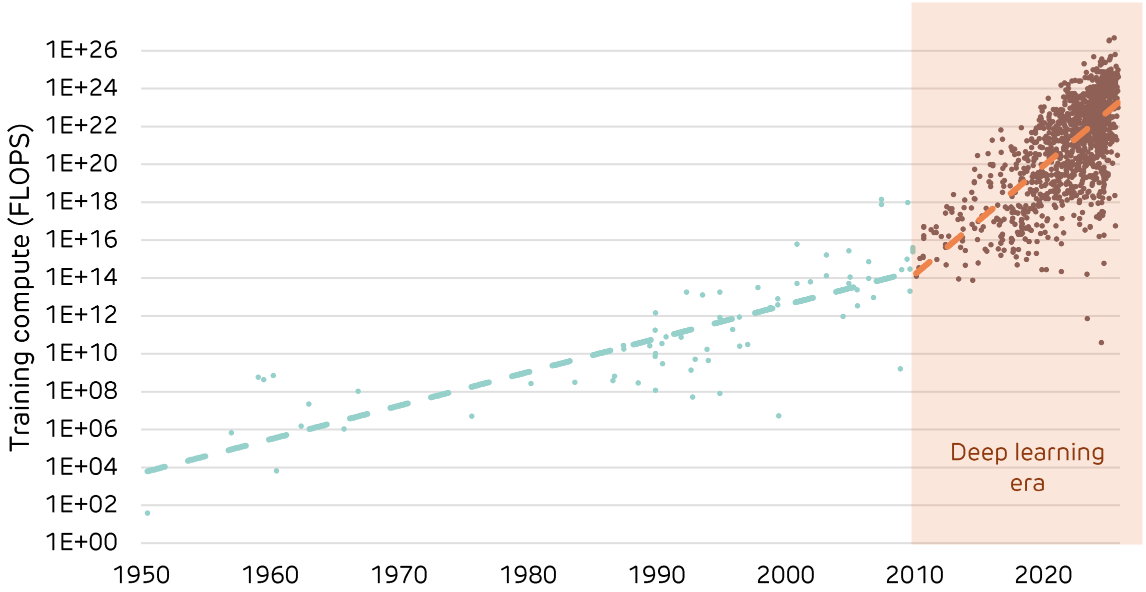
AI and the Computing Revolution Today

Ever since the first mass-market generative artificial intelligence (AI) products were released in 2022, the field has seen immense growth. AI models like Claude and DeepSeek have shown promise in augmenting and potentially even replacing human labour through their ability to analyse massive amounts of existing data, find patterns, and create inferences for potential solutions for entirely novel queries. Despite their massive potential, however, the mass adoption of AI is also a potential source of strain for the current energy-information nexus that has governed the modern economy.

Large language models are artificial intelligence systems trained to understand and generate human-like text. They work by analysing vast quantities of written material to discern statistical patterns about how words and concepts relate to each other. During this process, which is called "training", the model ingests billions of text examples, gradually adjusting internal parameters to predict what word should come next in a sequence. Once trained, these models can apply their learned patterns to generate coherent responses to new prompts, translate between languages, answer questions and perform various text-based tasks in a process called "inference".

The computational requirements for training and running these models have grown exponentially, placing enormous demands on data centre infrastructure. Training a state-of-the-art language model requires large amounts of computing hardware to operate continuously, consuming megawatts of electricity in the process. As companies have sought to build better AI models, they have turned to increasing parameter counts and, in turn, raised training requirements. The inference phase also demands significant resources, particularly as these systems handle millions of user requests daily. Each interaction requires substantial memory to load the model's parameters and processing power to generate responses, leading companies to build vast server farms dedicated solely to AI workloads.

Figure 11: Training compute for AI models has grown exponentially[32]



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[32] Epoch AI, "Data on AI Models". Published online at epoch.ai. Retrieved from 'https://epoch.ai/data/ai-models/' [online resource].

Data centres have become critical to the development of AI due to their ability to provide large amounts of concentrated power (which is then used to run computing equipment). The growth of AI and data centres has had a noticeable impact on global energy consumption, data centres consuming 1.5% of total global energy consumption in 2024. As the sector grows, so too will its energy demands. The IEA estimates that data centres could account for 4.5% of total energy demand by 2035, consuming as much electricity as Russia did in 2023.[33]

Given the evolving nature of the field, there is naturally some concern that improved AI model efficiency – delivered either through algorithmic or hardware improvements – could interrupt the projected growth of the data centre industry. While it is impossible to rule out such a situation, it is also possible that improved efficiency may also raise aggregate demand for computing energy, in a manner similar to Jevons Paradox of coal in the 19th century.

Despite its massive demand for energy, information, and capital, the potential upside of artificial intelligence is immense. If the technology evolves, an AI model with comparable intelligence to a human (often called artificial general intelligence or AGI) could represent a fundamental shift to humanity's mastery over information. Similarly to how mechanical engines began to replace human physical labour during the industrial revolution, AI models could begin to supplant humans to manage the massive tasks of converting data to information today. It is unclear when this might happen. Despite the rapid improvement of current AI models, it seems unlikely that AGI will arrive and compete with human cognition in the next few years. However we must at least be open to the possibility of such an event happening within the next 20-30 years. Indeed many AI experts are doing just that, with a survey of 2,278 top AI experts estimating the probability of "unaided machines outperforming humans in every possible task" at 50% by 2047.[34]

Through the lens of this framework, AI represents something more precise than a general-purpose technology – it is a potential resolution of the one information mechanism that computing left untouched. Generation, refinement, and distribution of information are no longer meaningfully constrained in the way they were even two decades ago. Application is. The conversion of data into decisions – the final step that turns accumulated information into productive work – has, for all of recorded history, required a human mind to perform it. AI holds the possibility of removing that constraint, and in doing so completing the same pattern that farming completed for energy generation, that writing completed for information refinement, and that the printing press completed for information distribution. Whether current AI systems are capable of that, or whether something more powerful is needed, remains genuinely unclear. But the structure of the opportunity is legible: three mechanisms are already operating without a binding constraint, and one is not. If that last constraint is resolved, the feedback loops across all four would be free to compound simultaneously – and the historical record suggests that when that has happened, the consequences have been difficult to anticipate in advance.

The catch, as the next section explores, is that resolving the application constraint on information may itself depend on resolving a constraint that had been largely forgotten: energy.

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[33] "Yearly Electricity Data." *Ember*, https://ember-energy.org/data/yearly-electricity-data.

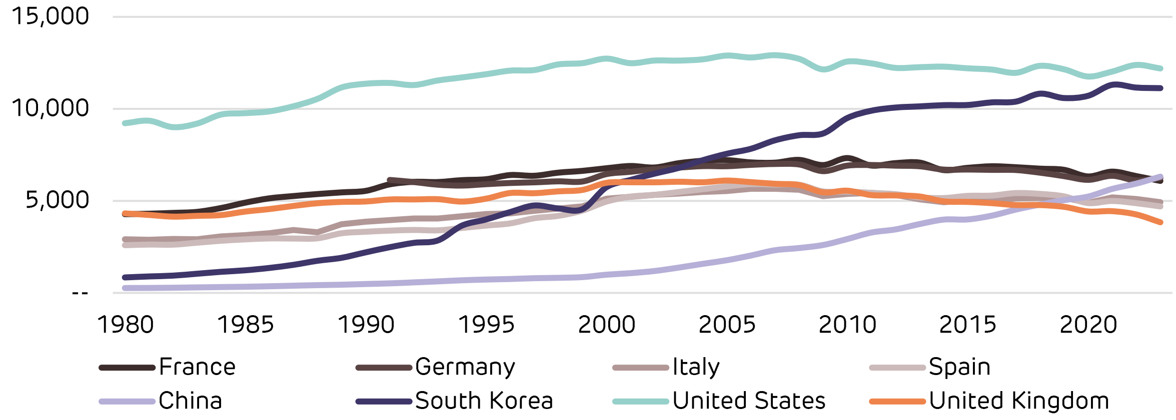
[34] Grace, Katja, et al. "Thousands of AI Authors on the Future of AI." arXiv:2401.02843, arXiv, 8 Oct. 2025. *arXiv.org*, https://doi.org/10.48550/arXiv.2401.02843.

A Return to Energy Scarcity?

For the past few decades, access to energy was largely treated as a solved problem in advanced economies. Between fossil fuels, nuclear power, and a growing renewable energy industry, nations were relatively unhindered from meeting demand in spite of population growth. Moreover, energy demand in these countries actually began to fall over time due to a variety of factors. Increasing energy efficiency of appliances was one such example. Electric ovens and fridges in the US, for example, became 73% and 15% more efficient between 1980 and 2023.[35]

In an abundant environment, societies were allowed to invest heavily in mastering information, leading to significant transformation of economies from industrial manufacturing to knowledge-based work. Offshoring and deindustrialisation may have been an even more impactful driver of falling energy demands in the US than efficiency improvements were. There, industrial energy consumption fell by 60% in the years after 1970, around the same time China began its own industrial ascent. The data therefore shows a stark difference between early- and late-industrialising economies, with the former seeing stagnant or even falling energy demands over the past few decades while the latter has seen consistent growth – even after accounting for population changes.

Figure 12: Per capita electricity consumption since 1980[36]



In the years to come, we expect that the trend of industrialised economies not having to worry about energy access may come to an abrupt end, and decades of relative underinvestment will have to be rectified. The comfortable energy headroom that cushioned countries like the US and UK will likely be eroded by multiple factors. AI data centres represent one source, as mentioned earlier. As imposing as the goal of building out the global data centre industry is, there are even greater demands on global energy. Current base-case forecasts expect even greater impacts from sources such as reindustrialisation and electric transportation. In all, the IEA projects that global electricity demand will grow at an average of 3.6% annually between 2025 and 2030 – roughly 50% faster than the average rate recorded over the previous decade.

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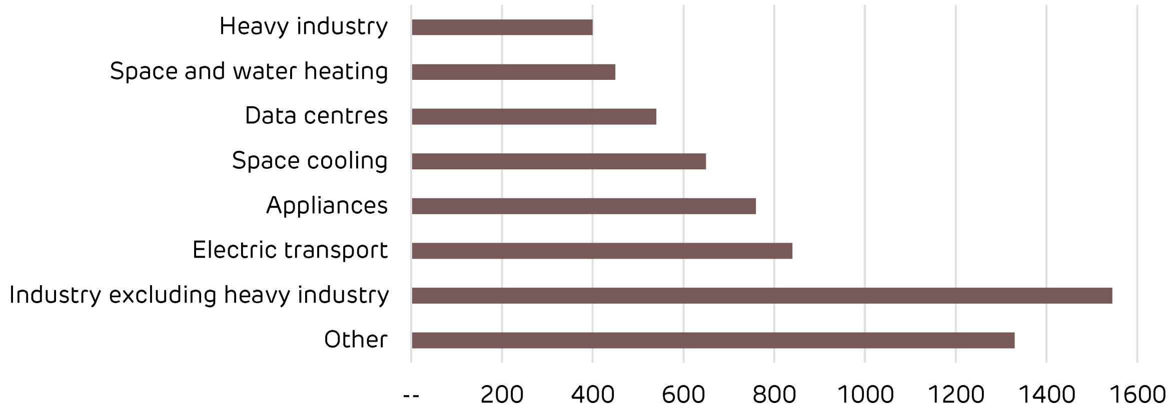
[35] Department for Energy Security and Net Zero.

[36] World Bank, US Energy Information Administration.

Figure 13: Base case electricity demand forecast 2025-2030, by sector[37]



Aside from the challenge of merely generating thousands of terawatt-hours of energy, another key issue is in building out the transmission infrastructure required to deliver that power to where it is needed. Grid connection queues have become severely congested across developed markets, with wait times stretching from 5 to 10 years in many jurisdictions.[38] In the United States, projects that reached commercial operation in 2023 spent an average of five years in the interconnection queue – more than double the wait time seen just fifteen years earlier. The UK has seen a similar deterioration, with over 326 GW of generation and storage capacity waiting for grid connections, whilst Ofgem reports that projects now face delays exceeding five years. The IEA estimates that roughly a fifth of planned global data centre capacity through 2030 faces risk of connection delay due to these grid constraints.

The transmission bottleneck stems from decades of underinvestment in grid infrastructure, much of which is operating well beyond its intended lifespan. In the United States, approximately 70% of transmission lines and transformers are more than 25 years old, with many approaching or exceeding their 50- to 80-year design life. The situation is particularly acute for large power transformers, where around 55% of distribution transformers in service are at least 33 years old and nearing the end of their operational capacity. The UK faces similar challenges, where many transformers have exceeded their intended operational lifespans by decades, whilst only approximately 25 pence of every pound spent on energy is directed toward grid maintenance and improvement.[39] The confluence of ageing assets, surging demand, and protracted planning processes suggests that transmission constraints may become the binding limitation on energy supply in the years ahead, regardless of improvements in generation capacity.

V. Conclusion

The story of human progress, as this paper has tried to show, is not one of steady accumulation but of moments when a constraint on either energy or information is lifted, setting off the feedback loops that reshape how societies work, organise, and grow. The Agricultural Revolution, the invention of writing, Gutenberg's press, and the harnessing of fossil fuels each represent such a moment. Each

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[37] IEA.

[38] IEA.

[39] Ambrose, Jillian. "UK 'Needs to Play Catch-up' in Global Race to Rewire Electricity Grids." *The Guardian*, 9 Dec. 2024. Business. *The Guardian*, https://www.theguardian.com/business/2024/dec/09/uk-renewable-energy-grid-connection-infrastructure.

time, the lifting of one constraint eventually exposed the other as a new bottleneck, and the cycle of mastery continued.

We appear to be living through a similar inflection point now, though its outcome is far from certain. On the information side, the emergence of large language models and generative AI represents what could be a genuinely transformative shift in humanity's capacity to process data. For all recorded history, the conversion of raw data into usable information has been constrained by the number of human minds available to perform that work – a biological prime mover no different from the muscle power that drove early agricultural societies. As humanity produces mountains of data every moment, AI holds the possibility of decoupling that process from human cognitive limits, just like the steam engine decoupled mechanical work from human and animal bodies. Whether the technology will fulfil that promise remains unclear.

We are not qualified to claim with certainty that AI is necessarily the information breakthrough that defines the next era of human progress. The framework does not require that any particular technological innovation fulfils that role, only that when a genuine breakthrough in information mastery does arrive – whether through AI, something that supersedes it, or a combination of developments we cannot yet anticipate – our mastery over energy will determine how much of its potential is actually realised.

The goal of this paper is not to make any specific recommendations for asset allocations or sectors to invest in. Rather, our goal has been to articulate the underlying logic that energy and information are not merely sectors or themes, but the two variables through which human productive capacity has always been either constrained or unlocked. That worldview shapes how we read technological change, how we think about where bottlenecks are forming, and how we assess which kinds of investment are likely to remain relevant. It gives us clues as to the pace of information- or data-driven progress and speed of change to the modality of the economy, for knowledge is not the only consideration when contemplating how much new discoveries in AI will change our investing landscape. Our access and mastery over power, too, plays a crucial role, and it appears to be an increasingly limiting variable for the near future. Thus the framework is less a map than a compass: it does not tell us exactly where to go, but it does tell us which direction we are facing.

What makes the current moment particularly difficult to read is that the two variables in our framework are pulling in different directions simultaneously. Previous periods of rapid progress were characterised by one factor becoming abundant enough to enable investment in the other. Today, the information side is expanding rapidly while the energy side is tightening in ways that were largely unfamiliar to the industrialised world for the better part of a century. The comfortable surplus of generation capacity that allowed advanced economies to redirect their attention and capital toward knowledge work is eroding. Ageing grid infrastructure, congested connection queues, and the structural challenge of integrating low-carbon generation at scale are all converging at precisely the moment when demand – driven not just by AI, but by electrification of heating, transport, and industry – is set to grow substantially.

The historical pattern does offer some grounds for cautious optimism. Constraints, once clearly identified, tend to attract investment and ingenuity. The transmission bottlenecks and generation shortfalls visible today are already prompting responses: new grid investment programmes, a reconsideration of nuclear power in several countries, and more speculative proposals – orbital data centres drawing on near-limitless solar energy among them – that suggest the market has already begun pricing in the tipping point. Whether these responses will be adequate, and fast enough, remains the central question. What the framework developed in this paper makes clear is that the answer will determine not just how to think about our current moment, but the pace of human progress more broadly.