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Buildings and energy: architectural history in the climate emergency

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As the current climate emergency deepens, it is no longer adequate to leave ideas of sustainability to engineers, practitioners, and studio-based educators. Ways of understanding and teaching architecture's history must also respond. This needs to go beyond highlighting exemplars and models from the past for what they may teach us practically in terms of passive environmental conditioning. The very terms and frames of reference we use to discuss buildings in the context of history require reconsideration. This article proposes that understanding architecture from a radical material perspective has the potential to foreground the entrenched relationship between architecture and energy consumption in the history of architecture. Energy consumption is the key factor in climate change. Making historians and students more aware of how this critical relationship shaped the built environment through time places an emphasis, and thus responsibility, on the very high energy consumption of architecture. We propose two essential questions: how has humanity's changing ability to harness useful energy interacted with the history of architecture? And how might we understand buildings through time not as objects fashioned solely by individual genius, patronage, stylistic movements and/or theoretical considerations, but as products that also result from the powerful nexus between assemblage and energy? This article attempts to demonstrate a possible approach, by sketching out three historical 'scenarios' that speak to different periods in time (pre-industrial, agrarian; industrial, coal- and steam-based; and late industrial, oil- and electricity-based). In these scenarios we trace regimes of energy consumption and their attendant networks of production, suggesting the centrality of such an approach to a full appreciation of building as a material process. We propose that this approach might form a new and complementary basis for research and teaching in the history of architecture.

Introduction

A proper understanding of the energy conditions of any period is crucial to interpreting its material history. More than this, energy has long been understood by scientists as promoting 'the fundamental unity of science', being 'the most powerful single tool in human understanding of experience'.[1] This article makes the case for bringing aspects of architectural history into this framework of scientific understanding. Engaging with the growing field of energy history is of course deeply illuminating to how we understand processes of

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construction. But it also contributes to the interpretation of a surprisingly diverse range of aspects of human culture, including architectural design.

Understanding the relationship between the historic built environment and the long history of human energy systems brings architectural history to bear on the most insistent and inspiring challenge of contemporary architectural scholarship and practice: today's urgent need to curtail our use of fossil fuels. With some impressive exceptions, architectural history's contribution to the development of today's emphasis on sustainable architecture has for the most part been tangential or non-existent, ceding the field to technical research.[2] But a new sense of urgency is now emerging among historians concerning the relationship between architecture and the environment.[3] As Daniel Barber has recently observed, architecture resides at the very heart of humanity's troubled relationship with energy, both as a material force for transition and as a cultural reflection of given energy systems.[4] For the authors of this piece, and in consideration of this emergent historiographic context, the nexus between architecture and energy use indeed provides the key.[5] The originality of our approach lies in examining not only the relationship between older buildings and climate, or twentieth-century buildings and servicing, but the entire interface between architecture and energy. It is something akin to what contemporary architectural science terms 'whole-life carbon assessment'.

What we propose in this article, therefore, is not so much a theory as a question: how has humanity's changing ability to harness useful energy interacted with the history of architecture? We suggest that this is a question that has immense analytical power in helping us understand the material context of architectural production. By extension, it sheds a surprising light on other aspects of architectural culture and its wider human and natural dimensions.

Naturally, any history of this kind is most perceptible at moments of rapid, large-scale energy change. The transition of ancient societies from foraging to agriculture brought about the conditions for the existence of cities. An equally radical transformative step-change in energy consumption occurred with the rising exploitation of fossil fuel energy in European/western-world economies, starting in London in the 1600s and rising rapidly through the late eighteenth and early nineteenth centuries: what is commonly referred to as 'industrialisation'. This resulted in nothing less than the fundamental shift from an organic, fungible economy – the type of economy that characterised (and limited) all human societies up to that point, whether comparatively complex or simple – to a mineral-based, consumptive one.[6]

Crucially, energy consumption, and thus productivity, was limited in organic economies, owing to the limited proportion of solar energy that could be harvested through photosynthesis: what economists call the 'production horizon'. Such economies were limited by their inability to translate this energy efficiently into mechanical force. Much of this energy dissipated or was 'wasted' through bodily maintenance, whether human or animal, before it could be utilised effectively. Photosynthesised energy stocks for producing heat, notably firewood, were also limited to the availability of, and access to, sustainably managed woodland.[7] This *flow* of (solar) energy and its effective use was highly constrained, forming an impediment to exponential economic growth. Organic economies effectively had a ceiling beyond which they could not progress.[8]

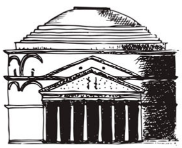
However, economies founded on fossil fuel consumption – firstly coal, and later oil and natural gas – faced no such limitations (other than fossil fuels being finite resources). This represented an energy revolution. Its first major phase came with the efficient harnessing of steam power in the second quarter of the nineteenth century. The massive carbonised stocks of accumulated photosynthesis that an abundant supply of coal (and oil) represented made available potentially billions of 'ghost acres' from what Rolf Peter Sieferle has termed the great 'subterranean forest'.[9] This crucial transition from organic to energy-rich consumptive economies in many parts of the world obviously had far-reaching consequences, both in terms of productivity and on the environment. As an economic activity, architecture – both as a logistical and cultural enterprise – was massively affected by these changes.

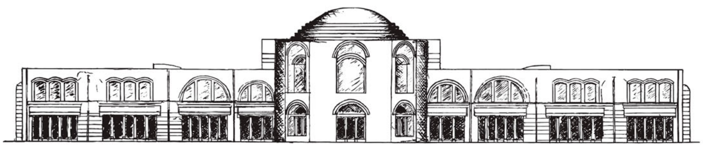
The investigation of the interfaces between energy history and cultural history is only in its infancy. Such investigation has been repeatedly called for by leading energy historians whose background tends to be in economic history or history of technology.[10] The worldview established by the research of energy historians is of manifest importance in periods of rapid energy change. But it is equally rich in contributing to the understanding of periods with less fast-changing energy economies.

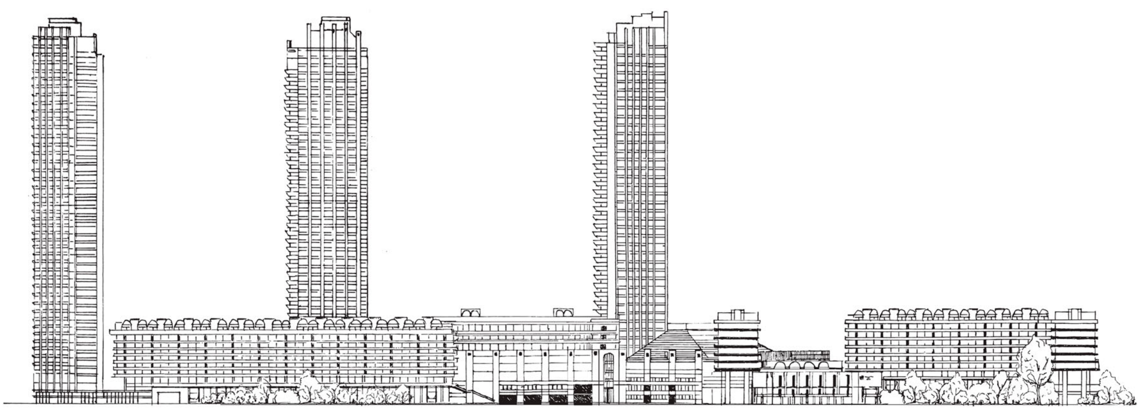
Energy availability (quantity, cost, and type) has formative implications for architecture in any period. Three of the obvious ways in which the energy context shapes all buildings are: the energy required to procure/produce, move, and work construction materials; control of climate within buildings, both passive and active; and the energy to light the building (natural and artificial).

A complete history of this relationship between architecture and energy is of course not possible within the limitations of a single journal article. What we offer instead are three historical glimpses of architectural production at three different points in time. Each of these represents a distinct economy relating to energy generation and use. These points may be understood as highlighting a set of fundamental conditions concerning the abundance of energy and its consequences, from overwhelmingly organic, preindustrial economies prior to the eighteenth century, through the nineteenth-century coal-fired age of steam, to twentieth-century petroleum- and nuclear-based forms of production and the new energy carrier, electricity.

Through these historical case studies, what we term 'scenarios', we aim to demonstrate how a different kind of architectural history emerges when architecture is understood as a material phenomenon shaped by the constraints of the energy economy. The creative achievements of architects, engineers, and craft workers, the cultural priorities that drove them and their clients, and the reception of the buildings that resulted can all be understood more completely within the framework of their energy context.







In this we agree with Esther de Costa Meyer that ontology, temporality, and scale are among the most important analytical registers for how architectural history can critically inflect issues concerning the climate emergency. As she observes, our fixity with buildings as finished objects tends to blind us to the reality of architecture as a trans-temporal and trans-scalar phenomenon that has both a presence and impact beyond itself.[11] Hence, throughout this article we seek to avoid simplistic, overly casual or deterministic observation by engaging with and applying modes of analysis drawn from history of technology studies and the anthropology of infrastructure. In so doing, our aim is to highlight the deep-seated structural conditions that underpinned, and to a certain extent shaped, economies of building design and construction through time and across space.

Our main intention is to reveal how the specific conditions pertaining to any given energy regime exerted a powerful influence on the possibilities available in the building design and construction industries.[12] In so doing, we also draw heavily on the literature of energy economics, thus positing architecture (a dynamic process enabled by evolving infrastructural networks) as an important subset in the history of energy consumption, understood spatially. In doing this, we are of course aware that our comparative schema and frames of reference are themselves conceptually entwined with the intellectual construct of 'energy' itself.[13] This article therefore represents a starting point rather than a conclusion, with a view to encouraging further discussion and debate. Seen in the context of the Anthropocene and the environmental crisis we now face, it is clear that there is an increasing demand to inflect the history of architecture in new and socially responsive ways.[14] As Barber observes, in light of the expansion of environmental histories of architecture in the last decade, the concern must be 'not simply to add more objects to the architectural-historical canon, but, rather, to offer new terms and context for analysis'.[15] In what follows, we attempt to address an aspect of this concern, presenting architecture and its relationship to energy in the long view as a means of demonstrating the possibilities inherent in these alternative approaches (Fig. 1).

Figure 1. (opposite)
Major buildings discussed in this article, illustrated to scale by GingerheadDesign for Barnabas Calder, *Architecture: From Prehistory to Climate Emergency* (London: Pelican, 2021): (top to bottom) the Pantheon in Rome (c. 112–121 CE), dome span 43.3 m; The Baths of Caracalla in Rome (c. 212–216 CE), one of the largest monuments of the agrarian millennia, reflecting the large labour force supported by an optimal farming climate and very substantial grain importation to Rome; St Pancras Station (1866–1868) and the Grand Midland Hotel (1868–1877), train shed span 73.2 m, owing to the lightness and strength of wrought iron; the Barbican Estate and Arts Centre (1963–1982), showing the scale and complexity of buildings made possible by affordable concrete and steel.

Scenario 1: agrarian; ancient Rome

Augustus's famous boast 'marmoream se relinquere quam latericiam accepisset',[16] that he had found Rome a city of mud brick and left it a city of marble, reflects one of the great periods of pre-industrial energy harnessing in Europe. Rome's population, rising to perhaps as much as a million under Augustus, was only to be equalled by coal-fuelled London as late as 1801.[17] The number and mass of Rome's monuments dwarfed anything else in Europe before the nineteenth-century industrial city. Buildings on the scale of the Temple of Venus and Rome or the Colosseum each required the processing, transportation, and assembly of hundreds of thousands of tons of materials. Even the rickety *insulae* which housed the majority required enough mud brick and timber for perhaps 10% of them to rise above two storeys.[18]

Yet, Rome's achievements were within the bounds of what energy historians have dubbed 'the photosynthetic constraint'. Almost all the energy used to build, feed, and run Rome came from farmed crops and other new-grown plant matter, the burning of firewood, and water and wind power.[19] In the case of plant matter, this meant that the total amount of energy available from a given area of land was subject to inflexible upper limits. Less than 1% of the sunlight energy to hit a given hectare of crop was typically captured by the plants, and only 15% or 20% of food calories eaten by humans results in useful physical work.[20] Animals offer greater power but slightly worse efficiency (10–15%) in terms of muscular output relative to calories ingested.[21] The percentage of sunlight hitting a given area of farmland that ended up as useful energy for movement in an agrarian economy was capped by these physical limitations. It could also be considerably lower in cases like animal husbandry for food.

As we shall see in Scenario 2 below, the great cities of the nineteenth century were at last to equal and surpass the population of Rome by exploiting the additional energy wealth of fossil fuels. Whilst the Roman Empire made limited local use of coal where it occurred near the surface, the overwhelming bulk of the energy supplement which allowed Rome to grow so large was achieved by transporting energy stocks – predominantly grain – over distances often exceeding 2000 km from some of the world's most fertile farming areas.[22] As Suetonius recorded, the architectural impact of this immense agrarian energy boom was spectacular. His portrait of Republican Rome is certainly just: before Augustus's long reign, Rome was largely constructed from '*later*' (unfired or 'mud') brick.[23] Whilst potentially vulnerable to rain, and hospitable to vermin and parasites, unfired brick was a widespread choice of building material in agrarian economies for its very limited construction-energy requirements. By using locally available mud and straw, brick obviated the need to transport heavy, bulky materials over longer distances. Long-distance transportation, where needed, could become the biggest cost of some construction projects.[24]

Just as importantly, drying mud bricks in the sun saved firewood. In an agrarian economy, slow-growing firewood radically reduced the potential food output of the land on which it grew. Of course to an extent wood production could be a relatively efficient use of land that was less suitable for arable farming. But, at risk of a crude oversimplification, in a well-developed agrarian energy economy (one without extensive potentially productive unexploited land), the production of heat could come into more or less direct competition with the production of food for finite hectares of land.[25] In time, there was the added problem of timber scarcity owing to increased deforestation, or the lack of decent firewood (*lignum*) in certain locations, which required the transportation of wood around the empire.[26] Access to firewood was a particularly important limitation in colder climates: towns in premodern southern Italy required one tenth of the firewood of towns in northern Scandinavia, effectively restricting the upper limits of population growth for northern European cities.[27] Nevertheless, considering its exported production footprint (and thus energy needs), a city like Rome required immense amounts of firewood (and charcoal) for purposes such as the firing of bricks and the burning of lime in kilns for its vast building industry, which were located as far as 70 km away, along the river Tiber and its tributaries.[28] In the city itself, large amounts of firewood were also required for the heating of public baths (*thermae*).[29]

Amidst a Rome largely of low-energy mud brick, special buildings were built, from around the second century BCE, in *opus incertum*. This was a more durable composite of stone, bound together by a mortar of lime mixed with a volcanic ash, *pozzolana*. The facing of the wall (beneath any decorative treatment) was composed of naturally occurring irregular rocks, tessellated expertly by the labourers. This required more skill and more labour than mud brick, but again drew on fairly local materials that did not require extensive processing before use. Roman concrete (*opus caementicium*) was, in energy terms, in an entirely different category from modern concrete, which requires immense industrial heat. The lime that was cement's closest analogue until the nineteenth century was produced by the application of intense heat, which consumed very large quantities of plant-based fuels. Jean-Pierre Adam describes the process of lime kilning without fossil fuels. It took seven days to load a kiln with limestone, seven days of intense burning to calcine it, and seven more days to dismantle the kiln and retrieve the lime.[30] This does not include the prodigious effort involved in extracting and transporting the limestone, much of which came from mountain ranges within an 80 km radius, and the gathering of large surface-area-to-volume, high-energy fuels like nut husks to get the stone up to around 1000 degrees centigrade, at which temperature the limestone calcines (releasing CO_2).[31] To sustain such heat for a protracted period using only plant matter required considerable manpower to remove ash and shovel in more quick-burning fuel.

Despite Augustus's lofty dismissal of its architecture, Republican Rome was an impressive city in its size and busyness, with many substantial buildings. It had grown through a period of gently warming climate which increased crop fertility. Through a protracted programme of military expansion, the city–state had also come to control fertile farmland in Italy, then Sardinia, Sicily, and North Africa. The great change for which Augustus took credit was the addition of Egypt to the Roman Empire after the defeat of Cleopatra at Actium in 31 BCE. Now the fertile flood basin of the Nile, an area whose astonishing fertility had supported the vast monumental constructions of the pharaohs for millennia, was available to Rome as personal property of the emperor. The sudden boom in Rome's construction industry following the conquest of Egypt is characteristic here. Major buildings and infrastructural projects initiated by Augustus and his circle included aqueducts, temples, public baths, a forum, and Augustus's own astoundingly large mausoleum. The scale and quality of reconstruction initiated by Augustus and continued by his successors was unprecedented in the history of the world's cities in its sheer ambition over several centuries. The overwhelming majority of the large-scale ruins that still dominate contemporary Rome were built under Augustus or his successors, not under the Republic.

Yet, even with immense grain energy subsidies from around the Mediterranean, Augustus and his successors were not really rebuilding in marble, aside from thin cladding sheets and some important decorative elements. The structural walls of important buildings in Republican Rome were of stone-faced rubble and mass concrete. On top of that facing would be plaster or a revetment of marble or other prestigious stones.

The new scale of simultaneous construction as Rome grew may well have exerted a pressure to de-skill masonry construction and introduce greater division and specialisation of labour. Possibly in response to this need, *opus incertum* gave way to *opus reticulatum* during the tail end of the Republican period, and became the norm under Augustus. Square-fronted pyramid-shaped stones were then built into the concrete as the wall rose, like permanent shuttering.[32] It involved more work (cutting facing stones to standard dimensions), but shaping stones could be a separate skill from placing them. Both shaping and placing could separately be done more repetitively, and with less training time, allowing faster expansion of the workforce, faster construction, and more reliable final quality.

This kind of standardisation and division of labour is a recurrent pattern throughout the history of energy booms, recurring in diverse contexts worldwide. These range from Song Dynasty China's *Yingzao Fashi* (a manual that standardised and documented building technologies and techniques across the empire, breaking the monopoly of hereditary craft guilds) to the standardised prefabrication kits of England, Sweden, France, and the USSR during the fossil-fuel energy boom of the 1950s and 1960s, and further on into the present off-site factory production of almost all building components.[33]

Back in Rome, *opus reticulatum* was rapidly to be joined, and then largely supplanted, by *opus latericium*, where the same core wall structure of concrete and rubble was faced with triangular, kiln-fired bricks. These tile-like bricks were the easiest of all to lay, and their durability is attested by the amount of Roman ruins today, where red brick remains the dominant exposed surface. Both *opus reticulatum* and *opus latericium* have been shown by Janet DeLaine to have cost considerably less than *opus incertum* for a given quantity of wall.

As with earlier Roman projects, when Augustus and his successors used marble, or other prestigious decorative stones, it was either for especially important elements (most strikingly column shafts), or as a thin veneer to the robust *opus reticulatum* or *opus latericium* of chunky concrete walls.

Thanks to the outstanding research of DeLaine, it is possible to study the mix of materials, and their probable origins, in one of the largest public projects of the Empire, the Baths of Caracalla (built c. 212–216). The original appearance of the baths would have supported Augustus's sense of a Rome made of marble, but in its despoiled state. With the marble having been removed for use in dozens of later projects, the brick structural facings and the concrete cores are much more in evidence. When present, the stones with which the building was so lavishly finished came from a range of quarries dotted around the empire, including Greece, Asia Minor, Egypt, and Africa.[34] This ostentatious display of technical skill and energy wealth was characteristic of ımperial *magnificenza*.

Command over more basic bulk building materials also mattered. For example, for the amount of concrete alone deployed at the Baths of Caracalla, DeLaine has calculated that for the first four years of construction, one 1500 *librae* (roughly one half tonne) cart of *pozzolana* would have had to leave the quarry every minute, for twelve hours every day, for 300 days, just to keep pace with the speed of work.[35]

Even with the vast wealth of grain that Rome enjoyed in the centuries after Actium, and the immense labour forces it could support as a result, the scale of imperial construction projects could run up against the limits of what was achievable in an agrarian economy. Paul Davies, David Hemsoll and Mark Wilson Jones have convincingly suggested that the bizarre irregularities in the otherwise perfectionist design of the Pantheon may well have arisen from a late change in portico design from 50′ columns to 40′ columns, which weighed only just over half as much as a 50′ column.[36] They even referred to a contemporary Egyptian papyrus in which the leader of a 50′ column-transport team appeals for more grain to feed his draught animals.[37]

The amount of stone extracted and moved for these purposes represents an immense energy investment, since imperial use was only part of a much wider market in ornamental stone.[38] There is some tangential evidence that this conspicuous consumption of labour was made more ostentatious by the emperors. Vespasian is said to have rejected an engineer's proposals for reducing the labour required to raise column shafts, and the regulations prohibiting transport of goods through Rome during daylight (an attempt to mitigate extreme congestion) made an exception for the materials for imperial projects.[39] It seems probable that the emperors valued this demonstration of their power.

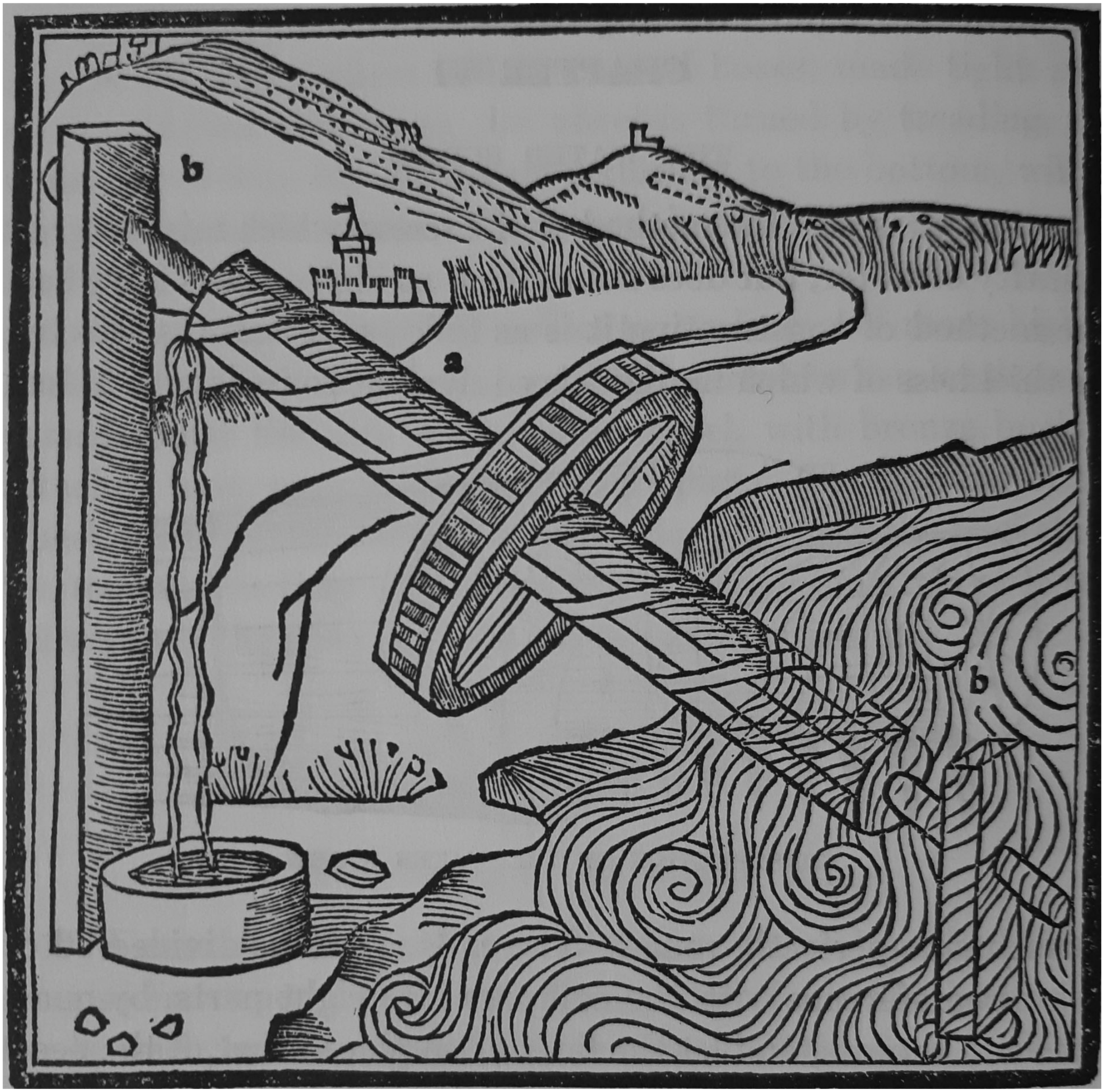
This is suggestive of a certain energy mentality, or 'regime', in a hierarchical agrarian society such as that of Imperial Rome. Through their immense wealth and power, the Roman emperors, much like the Egyptian pharaohs before them, knowingly commissioned high-energy-cost projects, simply because they could. Leading figures in Roman society, such as Caesar and Pompey, also competed with one another in their displays of command over resources. Such projects conferred high prestige, and were exploited mercilessly for propaganda purposes. Here one need only mention the ancient Roman craze for rare and expensive marbles, which instigated its own empire-wide industry, making up a significant proportion of Mediterranean trade by the first century CE. This included the enormous logistical difficulty in extracting certain prestigious stones, such as black porphyry (*knekites*), from the Eastern Desert of Egypt, or that of procuring and transporting great monoliths around different parts of the empire. For these purposes, coloured marbles were coming from all over the Roman world, from modern-day Spain and Turkey to Germany and Tunisia. Some of these quarries required over 1000 personnel to operate effectively. The presence of these materials in Rome was as much an affective emblem of the might and reach of centralised imperial organisation as they were about personal aggrandisement.[40] Such a regime, and the organisational capacity it represented, is what ecologists refer to as a 'high-gain' energy system. This is realised via the appropriation of accumulated surpluses of conquered lands and peoples resulting from imperial expansion, including increased logistical and building capabilities.[41]

The sources of the Baths of Caracalla's metals are much harder to trace than those of its stones. Lead (crucial for waterproofing) may have been from Spain, where it was often a welcome by-product of silver production, or from British open-cast lead mines. Iron was produced in numerous places around the empire, and the prestigious bronze too may have come from a number of sources.[42] As far as iron is concerned, this also raises the question of the resources required for the production of tempered iron tools that were used in the procurement, transportation, and construction of buildings, which has been noted by J. Clayton Fant.[43]

Whilst these stones and other energy-hungry materials were crucially important for display, they were nevertheless subject to discreet energy savings where available. For instance, as testified by Vitruvius, among others, the Romans knew of and exploited water-, wind-, and animal-driven machinery to gain efficiencies in procurement and haulage processes associated with building (Fig. 2).[44] This included the thinly cut, imported stone veneer mentioned above. From at least by the later third century CE, evidence exists that such slabs were cut by water-wheel-powered saws, sparing the extensive human labour that would have been the alternative.[45] At the other end of the supply chain, and especially where the sustenance of labour was concerned, there is evidence to suggest that the Romans had also developed an array of water-powered grain-processing pestle and bread-kneading machines, thus industrialising the process of food production. Even the outflow of dirty water from the Baths of Caracalla was channelled through a small water mill.[46] In terms of the recycling of building waste, DeLaine also suggests that the tesserae for the stone mosaics of the Baths are likely to have been made from chippings generated by the shaping of the main luxury-stone elements, another quietly economical form of ostentation.

Above all, however, luxury stone represented only a small proportion of a building's actual bulk. Again, in the case of the Baths of Caracalla, DeLaine has demonstrated that prestigious stonework represented only a tiny proportion of the total volume of the main building. Almost all the rest, the structural bulk, was built using materials and techniques that carefully minimised transport costs whilst still ensuring structural strength. According to DeLaine's meticulous calculations, 76% of the volume of the Baths was composed of materials quarried within 20 km of the site (in particular, strong, heavy *selce* stone for robust foundations, *tufa* for aggregate in the walls, and *pozzolana* as binding). Crucial for the strength of the construction, though expensive in labour and heat energy, were lime (3.2% of the building's volume) and brick (just 2.7% of the volume). Marble, despite its visual prominence in the building when new, formed less than 0.5% of the volume of the building, reflecting its high cost in extraction and transportation.[47]

The picture is clear: the spectacular conspicuous energy consumption of the great imperial projects of ancient Rome was partly smoke and mirrors. The visible surfaces and most memorable theatrical moments in construction were centred around beautiful, rare stones and bronze, brought thousands of kilometres across the seas to Rome, and serving as reminders of the extent of the empire. Yet, these materials made up a minute proportion of the whole building; almost all of it was built of materials sourced as locally as possible. Even the heat-hungry brick which seems so prominent today when



visiting Rome's ruins turns out to be used in the smallest possible quantities. For all its vast food supply, Rome's firewood was finite and in great demand by so much industrial and cooking activity in the city's very large population. It has even been suggested that the aforementioned depletion of timber stocks may have contributed to Rome's vulnerability and ultimate conquest.

What was not stinted on, as a glance at the ruins of the Baths of Caracalla makes clear, is the level of manpower involved. DeLaine's calculations

Figure 2.
Woodcut print of water screw from Fra Giovanni Giacondo's 1511 edition of Vitruvius's *De architectura*

suggest an average daily workforce of 7200 men involved in material production and construction, with a further 1800 men plus oxen involved in transport of materials in and around Rome. Indeed, the shipping and haulage of stone alone, including the relatively small amounts of marble, accounted for more than 50% of the project's total construction cost.[48] At peak times the number of labourers perhaps rose as high as 13,100 men involved in building the central block of the Baths, with more constructing the surrounding buildings in the complex.[49] An extraordinary amount of animals (and therefore feed) were also sometimes required for bulk material haulage on grandiose building campaigns of this nature. Adam has estimated that, in the case of the trilithon at Augustus's Temple of Jupiter at Baalbek (Heliopolis) in modern-day Lebanon (completed in the second century CE), between 800 and 825 oxen were required to move each 800-tonne stone block.[50]

The emphasis on economising long-distance transport and heat, and making use of very extensive labour, was economically rational in an agrarian context. Walter Scheidel has demonstrated that unskilled labourers were paid fairly comparable amounts (when converted into the number of litres of grain this money could buy) across societies from 1800 BCE to the medieval period. Typically the level of pay was only sufficient to support a family to a level of 'bare bones subsistence' if the family's adult women and children generated supporting income.[51] Despite Rome's vast grain imports, the pay for unskilled labourers seems not to have been at the upper end of the normal range; it may have been towards the lower end.[52] The abundance of labour is indicated by the fairly modest differential between skilled and unskilled labourers: skilled labourers were only paid twice the day-rate of unskilled labourers, and even those whose artistic prowess was crucial for the quality of the work (mosaicists, for example) were paid only 20% more than normal skilled labourers.[53]

The great projects built in Rome during the long peak of its grain imports were exceptional in the history of agrarian Europe. The level of difference that Rome's very substantial energy imports made is clear from the fate of the city and its architecture after the fall of the Western Roman Empire and the loss of grain imports from south of the Mediterranean. Rome's population collapsed, and those wishing to build exploited as convenient prefabricated elements the stone, brick, tile, and metal of buildings put up during the period of high-energy imports. The familiar pitting of monumental Roman stone walls like those of the Colosseum record where medieval Romans chiselled deep into the masonry to retrieve the modest amounts of iron and lead used by the original builders to pin the blocks together. Even where the ores occurred locally, mining these metals from buildings consumed less of the scarce local energy supply than smelting them afresh.

Even as late as the seventeenth century, the papacy was stripping ancient buildings of their materials for the new priorities of their day. Thus, the remaining original bronze from Hadrian's portico at the Pantheon was melted down under Pope Urban VIII to be turned into cannons. These cannons were intended for the defence of the same Hadrian's mausoleum, itself repurposed as a castle by Rome's low-energy rulers, living like Stig of the Dump on the leftovers of a much higher-energy society.[54]

But even at its ancient height, Rome's access to energy-intense materials was a costly luxury. Despite Suetonius's catchy formulation, Augustus found Rome a city of mud brick, and left it a city whose leading monuments consisted of around 0.5% marble by volume. Truly energy-rich architecture was to be brought about, as our second and third scenarios show, by the exploitation of coal.

Scenario 2: coal and steam; Victorian Britain

From the early eighteenth century onwards, coal became increasingly important as a source of energy, especially in Britain. Initially used as a substitute for wood, it quickly proved its effectiveness at intense heat transfer. Coal's high energy-density per unit mass meant that, once conditions for its controlled and efficient combustion had been established, it would become the principal energy source for industrialisation. Such had coal's dominance become by the mid-nineteenth century that in 1865, at the height of Victorian industrial transformation, the noted English economist Stanley Jevons declared it 'all-powerful'; it stood 'not beside but entirely above all other commodities', being the 'motive power' that underpinned the British economy. Coal had become *the* factor (not *a* factor) 'in everything we do'.[55] Given the available evidence regarding energy consumption during the Victorian period, Jevons's observation that 'the Coal we happily possess in excellent quality and abundance is the Mainspring of Modern Material Civilisation' is no exaggeration.[56]

Despite this economic reality, it is easy for those concerned with the history of architecture to forget how important coal had become to the British building industry by this time, and the contingent effects it had on building design and production. Indeed, a key characteristic (or defining feature) of the Victorian building world was its direct and exponential reliance upon a ready and abundant supply of coal-fired energy. Without this supply of coal, architecture in the Victorian age would have looked very different; and whatever it did look like, it is safe to say that it would have been on a much reduced scale. This suggests that the story of Victorian architecture may, in part at least, be understood as the story of the relatively new and especially intense relationship between architecture and energy in the form of the industrial-scale combustion of coal.

To make sense of this relationship, we must first address the key input itself: coal. Essentially, coal is but the carbonisation (under heat and pressure) of dead plant matter. As an economist would define it, coal is therefore a *stock* (as opposed to a *flow*) of energy resulting from the capture of solar radiation through the process of plant photosynthesis.[57] Its chemical composition, particularly anthracite (its purest form) is in the order of 92% to 98% carbon (C). Thus, when one speaks of an 'age of coal', as Jevons does, one is effectively announcing the rise to dominance of what today would be referred to as the 'carbon economy', or what some have termed 'fossil capitalism'.[58]

To illustrate this point, one need only chart the rise of coal consumption in Britain during the modern era. By the 1850s, coal represented an incredible 92% of all annual energy use per capita in England and Wales, compared to just 10% in the 1560s, or 40% in the first decade of the eighteenth century. More striking still is the jump from 61% in the 1750s, the very beginning of that technological transformation referred to as the Industrial Revolution (Fig. 3).[59] This reliance on coal as a key energy input during the Victorian age had significant consequences not only for architectural production, but also, and more importantly, for how we understand buildings as material objects. This material dimension is important. It does not concern the notion of 'materials' in their straightforward or conventional sense, as components of assembly, but the idea of substance instead: what might otherwise be termed architecture's ontology. When considering the relationship between architecture and energy with respect to materiality, we must therefore concern ourselves with process.

Take, for example, a building material as simple as the humble brick. The fact that a building be made of brick is, in one sense, neither here nor there. It is more pertinent to inquire into the nature of that brick: although the bricks in two different buildings (architectures) may look superficially similar or the same, they may differ radically in terms of the way they were procured. In other words, how do such bricks differ as a matter of substance (handmade unfired/wood-fired versus machine-made coal-fired)? It is this basic difference in nature that fundamentally distinguishes much 'Victorian' architecture (after the 1830s) from that which preceded it, despite whatever stylistic continuities may be evident. This fundamental distinction marks out the true difference between these phenomena: a difference in which energy inputs were crucial (Fig. 4).

Experiments in machine-powered brick manufacturing had not only increased output substantially by the 1850s; they had also created the conditions for an improved supply of better-quality bricks, made to reliable standards of form, colour, density, hardness, and non-porosity (compared to the patchy quality of hand-made equivalents). Consequently, a substantive and measurable difference began to open up between hand-made and machine-produced bricks in Victorian Britain. Developments in coal-fired kiln technology also made for greater scales of efficiency in terms of evenness and thoroughness of burn, producing less wastage in the process. These transformations led in turn to an equal divergence between hand- and machine-made products with respect to their aesthetic attributes, as bricks became smoother, more consistent, and 'truer' (critics of mechanised brick production highlighted this aesthetic distinction). The location of brickworks along railway lines likewise facilitated transportation of both energy inputs (coal) and finished products, putting such works across the country in reasonable economic striking distance of major markets in the southeast and elsewhere.[60] Although, in many cases, transporting bricks further added to the cost at point of delivery, it was generally considered a price worth paying. This applies especially to the growing taste

	(1)	(2)	(3)	(4)	(5)
	1560s	*1700-9*	*1750-9*	*1800-9*	*1850-9*
	Coal production ('000 tons)				
England	177	2,200	4,295	11,195	51,650
Wales	20	140	220	1,850	13,400
Scotland	30	300	715	2,000	9,000
Total	**227**	**2,640**	**5,230**	**15,045**	**74,050**
	Energy consumption, England and Wales (petajoules)				
Draught animals	21.1	32.8	33.6	34.3	50.1
Population	14.9	27.3	29.7	41.8	67.8
Firewood	21.5	22.5	22.6	18.5	2.2
Wind	0.2	1.4	2.8	12.7	24.4
Water	0.6	1.0	1.3	1.1	1.7
Coal	6.9	84.0	140.8	408.7	1,689.1
Total	**65.1**	**168.9**	**230.9**	**517.1**	**1,835.3**
Total less coal	**58.2**	**84.9**	**90.1**	**108.4**	**146.2**
	Other related energy estimates, England and Wales				
Coal as a percentage of total energy consumption	10.6	49.7	61.0	79.0	92.0
Per caput energy consumption (gigajoules)	20.5	29.6	35.1	52.3	96.5

Figure 3.
Coal production in England, Wales, and Scotland (in 1000s tons) and related statistics, table based on E. A. Wrigley, *Energy and the English Industrial Revolution* (Cambridge: Cambridge University Press, 2010), p. 37, tab. 2.1

among Victorian architects (and their clients) for polychromatic effect, requiring a variety of different coloured bricks from a number of locations. Take, for instance, William Butterfield's insistence on using quality black bricks from Cowbridge in Wales on All Saints', Margaret Street in London for an astonishing £4 per 1000 (compared to around £1 for ordinary hand-made stocks, or £2 for ordinary manufactured). To be sure, a demand for locally produced hand-made bricks never ceased, and disagreements over the best

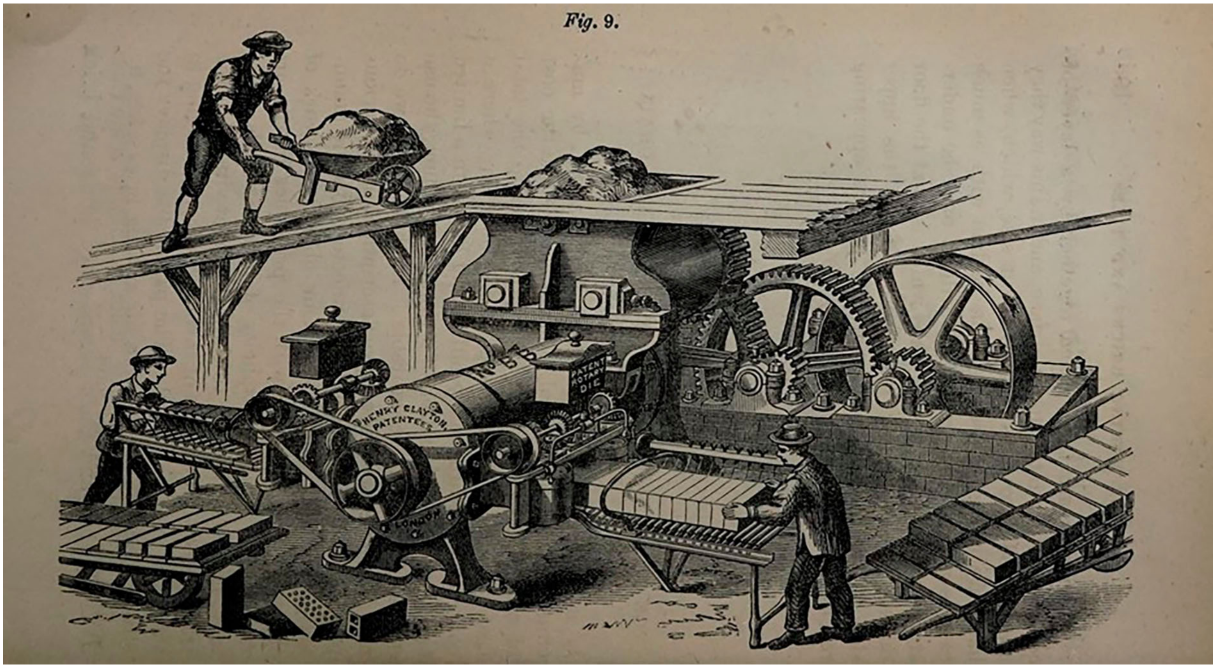


Figure 4.
Henry Clayton & Co. steam-powered brick making machine, Britain c. 1870s, in Edward Dobson, *A Rudimentary Treatise on the Manufacture of Bricks and Tiles* (London: Crosby Lockwood & Co., 1877), p. 220. Similar Clayton machines were used in the production of stock bricks for the construction of St Pancras Station in London.

methods of machine production continued. But by the close of the nineteenth century, mechanisation of the industry was all but complete.[61]

Therefore, in considering the relationship between architecture and energy, we must contend with buildings first as objects, before addressing what they might mean or represent. After all, many of the peculiarities we observe in the phenomenon of Victorian architecture (or at least what made them possible) – the vastly increased scale, precision, material complexity, and frequency of buildings of all kinds – pertain more to architecture's ontology than its meaning.

The implications that coal-fired mechanisation had for the building industry in nineteenth-century Britain were evident across the sector, not just in brick production. There would have been no 'iron problem' in 1850s British architectural discourse, for instance, without iron; and there would have been no iron (in any significant quantity, at least) without efficient production processes driven by industrial-scale, coal-fired furnace technology.[62] Nor would there have been any concern over the social and psychological malaise caused by mass production in architecture without the advances in mechanisation that resulted from the efficient harnessing of steam power, itself only made possible (again, on any significant scale) by the effective transferral of heat energy through the controlled combustion of coal.[63] Nor would there have been any talk of making use of richer and harder-wearing materials such as marble and granite, to any extent in Victorian architecture, without vast improvements in speedy and efficient steam-powered transportation technology and steam-driven cutting and polishing machinery. Indeed, one might go so far as to say that the very idea of the 'High Victorian' would not have arisen without easy and relatively cheap access to modern transport infrastructure. As the architect G. E. Street so aptly observed, new transport infrastructure gave the middle-class professional no excuse not to familiarise himself with Continental art.[64] Moreover, once the inspiration of Continental art had been realised, its effective and widespread dissemination within the British architectural community through high-volume book and periodical production would likewise not have been possible without the steam-powered printing press, and the coming of the so-called second print revolution.[65]

What is evident in all of this is the advent of a new and quite peculiar kind of (material and intellectual) architectural ecology, in which virtually every constituent element, process, and connection is not only disparate but also dependent upon a ready and abundant supply of energy in the form of coal. This constituted a production environment founded on increasing demands for speed and quantity. In this regard alone, Victorian architecture by the 1850s and 1860s was in many ways as different (or more so) from early 1800s Georgian architecture as Georgian architecture was from the pyramids of ancient Egypt or the temples of Abyssinia.

Another way to understand what is meant by ecology in this sense is to think of it as akin to how geographers and anthropologists of infrastructure use the term 'technological zone'. A technological zone is both a physical and intellectual space in which technological practices, procedures, or forms of knowledge not only coalesce through cumulative degrees of productive co-dependency (say, between coal mine, railway, steam engine, and industrial furnace), but also where the differences between these have been reduced and common standards established.[66] Zoning of this kind is typical of industrial regimes, where fields of qualification necessarily emerge that connect producers and consumers, knitting them into a steadily increasing regulatory framework in which industrial products and processes may be assessed and compared, and through which certain economic and political strategies can be reliably planned for and realised.[67] The abovementioned increasing standards, quality, and scale observable in Victorian architecture were a result of the performance of 'zones' of this kind. These zones required both technologies and infrastructures to operate effectively. The infrastructure pulled the various (instrumental and intellectual) technologies together to form a series of interlocking systems that created a wider 'ecology'.

This architectural ecology was emergent in the sense that it was pegged to, and thus the outcome of, compounded technology feedback loops. Ultimately, once Watt's engine had proven its utility in the efficient rotary propulsion of machinery, an ideology (if not fetishisation) of steam prevailed. This ushered in inescapable regimes of time and scale against which all economy was measured (positively or negatively), including in architecture. Why this initially occurred in Britain rather than elsewhere involved some luck. There was a readily accessible abundance of coal in the British Isles, but this was also coincident with a high-wage economy, in comparison to other parts of Europe and

Asia during the eighteenth and early nineteenth centuries. The cheap supply of energy in Britain thus incentivised British business to invent technology that effectively substituted energy for labour. As Britain's success in the wider global economy increased over time, including imperial expansion, wages and living standards also climbed relative to competing nations. As such, they exerted sustained demand within the local economy for technological solutions that utilised these cheap and apparently inexhaustible supplies of energy.[68] Indeed, as the architect G. E. Street reckoned at the time: '[s]urely all our facilities of locomotion, of friendly intercourse and acquaintance with foreign lands, and the like, are so many points in which we have a great advantage'.[69] Thus, steam power reordered nature, rather than responding to the world as given; from then on, advanced economies began to shape themselves around the opportunities and demands of steam power.[70]

Rather crucially, however, the switch to steam-powered production in the British economy was a conscious choice, so to speak. It was in no way natural or inevitable; it was primarily concerned with the control of labour and efficiency gains in the modern capitalist economy. As Andreas Malm has argued, it was precisely this choice that caused fossil-fuel consumption (and thereby its massive and disastrous CO_2 emissions) to become irrevocably attached to the 'engine of self-sustaining economic growth', and thus to the myth of limitless progress, which haunts us to this day.[71] But industrial expansion on the scale that occurred in Britain during the nineteenth century still required a huge workforce, despite the new efficiencies brought by steam-powered machinery. Much of this workforce was sucked into industrial centres from the surrounding rural hinterland, or from places further afield such as Ireland.[72] This had wider embodied-energy implications with regard to the supply of labour. In this respect, labour supply contributed various and significant indirect energy inputs with regard to mining, product manufacture, and transportation. Feeding beasts of burden was one thing, but feeding, clothing, and warming the growing human workforce was another. It was this new, 'dominant logic of energy', as Cara New Daggett has argued, that enabled the comparative evaluation (and thus sublimation) of labour/work as an 'energetic' activity in the first place.[73]

This had effects for what Jane Hutton has called 'reciprocal landscapes', both in Britain and abroad, which were responsible for the supply of food and materials – what might otherwise be described here as Britain's production footprint, local and exported.[74] For instance, by the close of the nineteenth century, much of Britain's wheat supply was coming from North America (produced and ferried across the Atlantic by steam-powered engines); while by 1890 over two million frozen sheep carcases were arriving annually from as far away as New Zealand.[75] Moreover, the growth of the wider imperial economy necessitated the sourcing of coal supplies throughout the British Empire for its strategically located steamer coaling stations, servicing both merchant and naval shipping.[76] Merchant steamers brought building materials, especially exotic timbers, from across the British imperial world, based as they were in extractive economies that often relied upon indentured labour, if not slavery.

The effective moment of this key transformation in the British economy was c. 1830, with the reliable application of steam-powered locomotion. Owing to the proliferation of industrial processes and networks of transportation that ensued, mainstream architectural practice became a vastly different phenomenon. Over a relatively short period of time, architectural offices became noticeably larger, more organised, and technologically orientated. As Street observed, no 'architecture […] [can] be the best which is content to forego the use of the greatest mechanical advantages and inventions'.[77] Those architects that would succeed in this brave new world fully appreciated this transformation. Some well-known architects, such as William Butterfield, were of course still concerned to employ local materials when they could (more so in rural than in urban commissions, in Butterfield's case); but others, like Alfred Waterhouse, fully embraced the new industrial regime and the opportunities for architectural innovation it afforded.[78] Waterhouse's extensive use of machine-manufactured products such as terracotta and encaustic tiling are evident in most of his major commissions, including the Manchester Town Hall (1868–1877), the Natural History Museum (1865–1880) and the Prudential Assurance Building (1885–1901) in London.

Based on some of the outline observations above, it is useful perhaps to think of these transformations, initially at least, with respect to economics. The advent of what we call Victorian architecture stands at the tipping point of the most dramatic and disruptive transformation in human history, the consequences of the full and effective harnessing of steam power.[79] This transformation in Britain resulted from the aforementioned fundamental shifts in energy consumption. But the conceptual leap in terms of industrial science and technological innovation was equally significant. As the economic historian Joel Mokyr has remarked, the equivalence between heat (thermal energy) and work (kinetic energy) was not suspected by people in the eighteenth century. The notion that a horse working a treadmill, and a coal fire heating a lime kiln, were in some sense doing the same thing would have appeared absurd to them.[80]

Alongside factors of resource abundance, accessibility, and processes of exploitation were the large-scale efficiencies to be gained from the economical transportation of huge quantities of energy. These provided strong incentives to invest in canal and railway construction. Thus, with the heavy investment in railway lines in the 1830s and 1840s in Britain, by the time of the Great Exhibition of 1851, an embryonic national rail network of over 6000 miles had been constructed.[81] As the economic historian E. A. Wrigley concludes: 'The building of a rail network in England symbolised the fact that mechanical energy no less than heat energy could be secured as required from coal'.[82] In many ways, the Victorian building world was a by-product of the advent of this system and its ecology of energy extraction, transportation, and consumption.

A useful way to consider what this might mean architecturally, and thus allow us to comprehend better the radical distinction between Victorian architecture and its preceding manifestations, is to think about building assemblage via what sustainability experts call the 'embodied energy' of building production and life-cycle analytics; or, in laymen's terms, what is referred to as a building's 'carbon footprint'.

Embodied energy may be taken as specifically 'the sum of the energy requirements associated, directly or indirectly, with the delivery of a good or service'.[83] This includes the energy embodied in individual building components, such as the energy required to extract the raw materials (say, to quarry stone), process them, assemble them into usable products, and then transport them to site, as well as the energy required to assemble those same components once on site, including labour. When thinking about the materiality of Victorian architecture, we tend to forget just how crucially the development of the Victorian stone industry, for instance, relied on these technologies and networks, and thus just how much embodied energy its products contained. A hitherto near unobtainable array of decorative and common building stones, not just from within Britain, but from across Europe and the Mediterranean basin, appeared rather suddenly in quantities and of a quality and at a cost that made them available for general use for the first time. But this was entirely dependent upon a particular input of energy, whether in terms of new steam-driven cutting and polishing technology, or reliable steamship transportation, or indeed, the laying out of higher-speed and higher-capacity rail networks.[84] This applied as much to marble and granite as to other common building stones, and was recognised at the time.[85] For instance, A. J. B. Beresford Hope, a leading ecclesiologist and theorist of the High Victorian movement, observed how '[t]he application of coloured material – marble, brick, and so on – both to the main features and the decorative details of buildings, is every day coming into vogue with a fulness which never could have been compassed while the steam-engine was still unknown'.[86] This, too, has implications for how we factor the 'reciprocal landscapes' of product supply and demand, with many of these materials having been extracted and transported across long distances.

What this points to is a fundamentally new dynamic in which disparate events and processes and even technologies, which, seen in isolation, may have seemed unimportant, or perhaps not even connected, suddenly coalesced, as Sigfried Giedion noted, with explosive force (i.e. the 'zoning' effect).[87] This is the tipping point that opened up a new world of possibilities in architecture, not just for the buildings themselves but through involvement in the process at every step along the chain of production. The increased speed and frequency of movement that resulted from this effect was one of the key features of the energy revolution resulting from the industrial-scale combustion of coal during the Victorian age.[88]

Therefore, what really distinguishes Victorian architecture vis-à-vis the new carbon economy is that it is fundamentally, and at base, an architecture of energy and movement – if not the first architecture of energy and movement, then at least the most vigorous and disruptive that had yet been experienced. Architectural production during this period may, on the whole, be considered so much the by-product of steam power and, in particular, of movement on a previously unimagined scale: materials coming from far away, procured under increasingly mechanised conditions, entailing the consumption of fossil-fuel energy in huge quantities. When we consider further what we call 'Victorian architecture' in this context, we must understand it as a peculiar outcome of this technological shift.

While this phenomenon is observable in a multitude of so-called anonymous or 'non-pedigreed' examples of building practice throughout Britain and its empire, a representative instance, by the leading Victorian architect G. G. Scott, is St Pancras Station in London (1866–1877).[89] As the London terminus of the Midland Railway company, the materials for both the main hotel building and the adjoining train shed (by W. H. Barlow) came from across Britain, but largely from the Midlands. The facing portion of the sixty million bricks used in the station's construction were produced at major industrial brickworks in Nottingham and Leicestershire, while the stone used included Red Mansfield (Notts.), Ketton and Ancaster, with Shap and Peterhead varieties of granite. The ironwork came from the Butterley Company in Ripley (Derbys.), while slate roofing was brought from Wales and Charnwood (Leics.). Coal-fired industrial machinery and processes were employed throughout, even for the common bricks used in the building's substructure, which were produced at a rate of 60,000 per day, using extrusion machines and a Hoffmann kiln (Fig. 5).[90] In this respect, the St Pancras Station complex – both in its material variety and consequent aesthetic quality – was the veritable embodiment of industrial 'zoning' and its networked connectivity.

None of this is necessarily to suggest that the connection between architecture and energy was merely taken for granted, or viewed uncritically, in the Victorian age. The associations between fossil-fuel consumption, industrial production, and architecture were, as mentioned, well understood. An awareness of the potential long-term dangers of carbon-dioxide pollution was also beginning to emerge.[91] Some were extremely wary of these connections and their effects. For John Ruskin, the mining and combustion of coal had manifold moral consequences with respect to idleness (vital force versus mechanical force), rampant consumerism, and the disciplining of desire.[92] Pollution, too, was a key concern. Later, misgivings over industrial manufacturing and its effects on craftsmanship would become the *cause célèbre* of William Morris and friends, as the Arts and Crafts movement sought to strike a pose against the regrettable consequences of the new energy-rich, carbon-based economy. But none of this changed the facts, and the doubting of Ruskin and others was largely a pushing against the insuperable tide of technological progress.

Ultimately, the transformation of Britain from an organic economy to an industrialised, fossil-fuel-based one established the conditions for the emergence of an infrastructural system that worked to create a technological zone for the production and supply of building materials. This was itself part of a larger zone of manufacturing and transportation infrastructure relating to the Victorian building world as a whole, but one that obviously required a certain quantum of energy input in order to be both economic and sustainable.

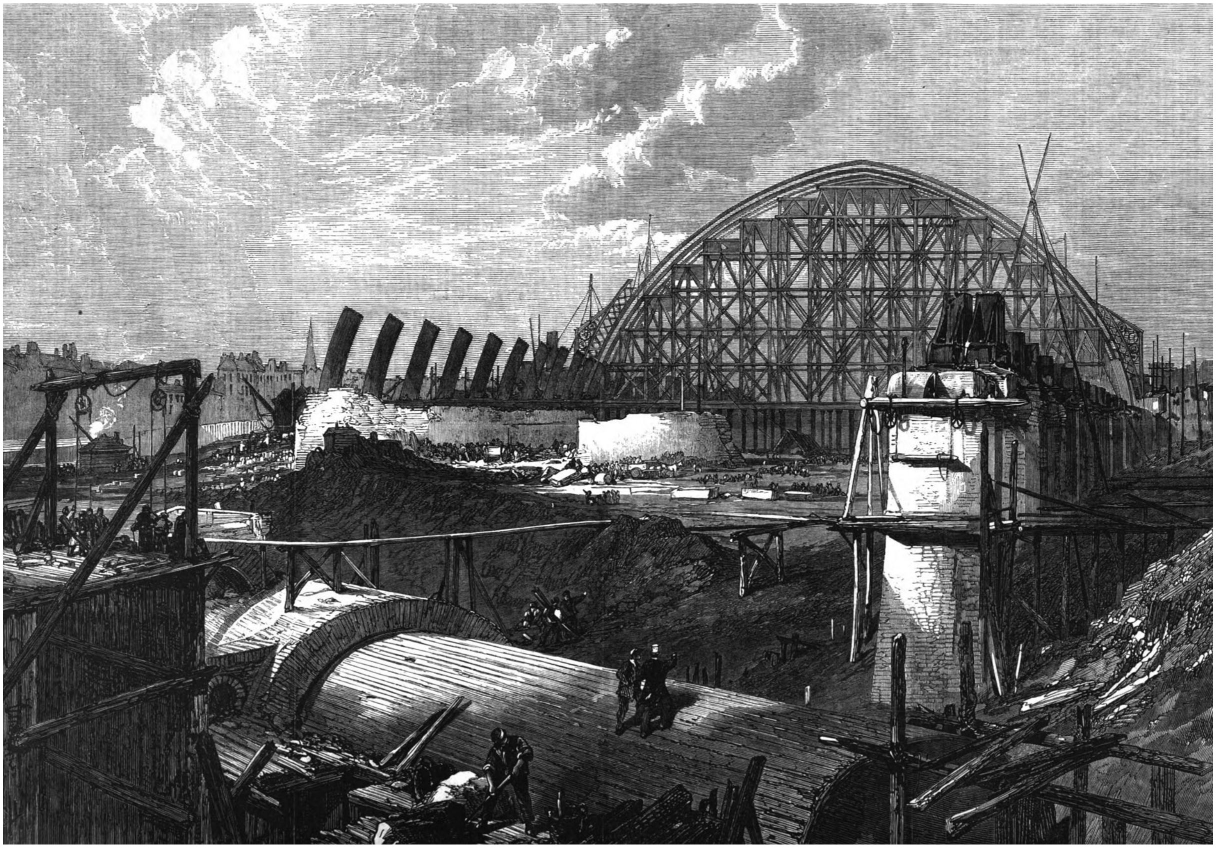


Figure 5.
Print of St Pancras Station trainshed under construction, London, 1868, in *Illustrated London News*, 16 February 1868. The massive, incomplete solid brick substructure and walls of the trainshed are visible here.

As a result, a new architectural reality evolved. Increasingly fast, linear, punctiform, and thus efficient systems of modern production characterised this new carbon-rich economy, as large amounts of machine-processed material were procured and transported from point to point via rail and steamer, increasing not only quality and quantity, but also reducing time and cost. Therefore, in understanding the relationship between architecture and energy in the Victorian period, we would do well to consider architecture from this ontological perspective.

Scenario 3: oil and electricity; the twentieth century

Filippo Tommaso Marinetti's exciting, overheated, and violent 'Futurist Manifesto' of 1909 exalted the 'beauty of speed'. The text is shot through with his outpouring of enthusiasm for the new energy technologies maturing in the fast-changing early years of the twentieth century. A racing car wreathed in shuddering pipes was, he famously declared, more beautiful than the Winged Victory of Samothrace. All of the major energy revolutions of the turn of the century are present in Marinetti's text: electric lighting, right in the first sentence, allowing him and his group of wealthy young friends to stay up all night stirring to ever greater heights their hysterical technophilia; two-storey trams with artificial lighting rumbling past, in Marinetti's bleak simile, like a village being washed away mid-festival by a flooding river; coal-fuelled engine rooms of great ships; railway locomotives; even aeroplanes, only a few years after the first one took off. Marinetti foresees himself in a decade as an ancient and washed-up relic of over forty, sheltering under his aeroplane wing from his young followers who will tear him apart out of love, hatred, and jealously.

Marinetti's Futurist mentality, a love of industrial power so great that he found the polluted mud in a factory ditch fortifying and maternal, came in the context of Italy's new and sudden Industrial Revolution: a sustained period of radical, rapid, accelerating energy change.[93]

In more sober terms than Marinetti's, Walter Gropius, working in another country that had begun industrialising later than Britain and was industrialising fast in the decades leading up to the Great War, was to celebrate indirectly the revolutionary impact of cheaply intense energy on architecture.[94] He wrote of the 'new synthetic substances' that had contributed to the genesis of Modernism, singling out 'steel, concrete, glass'.[95] These three 'new' materials had come into use respectively around 4000, 2000, and 5000 years earlier, and had all been put to architectural uses at times over the intervening millennia.[96] Yet, Gropius's suggestion that they were 'new' does reflect a reality: the hugely increased scale of their use in architecture by the early twentieth century was both novel and important, and was bringing about rapid technical progress in understanding and using them. Even in the USA, for example, where most houses were of machine-cut wood, and steel had a dominant role in larger structures, concrete consumption rose from a little over three million tons in 1900 to nearly fifteen million by 1914, and over thirty million in 1928.[97]

The factor limiting the use of these materials in earlier periods seems less likely to have been technical competence, which tends to grow with rising demand, than the limited availability of intense heat set out here in Scenario 1: the more firewood one uses, the more expensive it gets, whereas the coal supply is elastic in response to demand, and has a tendency to become cheaper with higher sustained demand, as this supports ever greater investment in improved extraction and transportation methods.[98]

It is well documented that the all-changing potential of 'new' materials thrilled Le Corbusier: 'reinforced concrete has brought about a revolution in the aesthetics of construction'.[99] Along with this, however, he was seduced by the potential of the revolutionary new energy carriers that were to shape the architecture of the twentieth century: refined oil and electricity. Because he and his generation tended to refer to the changes under the name 'mechanisation', focusing on the mechanical novelties rather than the energy that drove them, the centrality of energy supply to the technological developments of the Modernist period tends to have been downplayed. Yet, Le Corbusier placed himself within the circle of Gabriel Voisin, whose company was to sponsor not only the Paris plan that bears his name, but also to contribute

25,000Fr to the Pavillon de l'Esprit Nouveau, in which the Plan Voisin was exhibited.[100] Voisin's manufacturing interests in aircraft up to the First World War, and cars thereafter, put him at the cutting edge of the European exploration of the remarkable new energy source, refined petroleum oil.[101] The unprecedented energy-density of fuels like kerosene, petrol, and diesel, and their convenient liquid form, was a crucial precondition for heavier-than-air flight, and a major stimulus to the development of automobiles.

Le Corbusier's mentality was famously inflected by a powerful belief in the importance of cars and aeroplanes, as shown in his 1920s urban schemes. Cars are equally prominent in both the planning and photography of the villas that Le Corbusier's proudly car-owning clients commissioned at pleasant driving distances from Paris. An original photograph taken beneath the Villa Stein de Monzie, puzzlingly unglamorous to today's eyes, revels in the petrol supply for the car and the oil tank for the house – thrilling demonstrations of Modernist energy capabilities to the eyes of the 1920s.[102]

Le Corbusier was just as stimulated by electricity, the other revolutionary new energy carrier that was taking off in France in the 1920s. The frontispiece of the final chapter of *Towards an Architecture*, 'Architecture or Revolution', depicts a 40 MW electrical turbine.[103]

Oil could replace coal-driven steam engines, manual labour or draft animals piecemeal, as it was initially distributed on a modest scale through existing shops. Electricity was different, requiring a substantial scale of adoption to become a viable economic proposition. Le Corbusier's celebration of electricity in his suburban villas came hard on the heels of improvements in French electrification. Efficient, low-maintenance steam turbines replacing steam engines hugely increased supply in the early twentieth century. More importantly for the suburban and rural reach of the new energy carrier, the development of high-voltage alternating current transmission systems made it economically viable to transfer power over longer distances by wire. Low-voltage, high-current transmission had made the resistance of longer cables into a major problem, wasting power as unwanted heat in the wire. The new high-voltage lines could carry electricity initially into the suburbs. By the 1920s and 1930s, it could link up separate electricity generators and users into networks spanning many hundreds of miles.[104]

Even with the improved and fast-improving electricity network, Le Corbusier was at the edge of what his clients would pay for in the way of beta-testing of new technologies. His wish to electrically heat the Villa Savoye through the floor plates was rejected, because the cost of the transformer station that would have been needed to supply the required currents would have been considerably greater than the cost of the heating system itself.[105]

Electricity and other new energy sources were a bone of contention in other schemes, too. At the Villa La Roche, as Tim Benton has shown, the stoically supportive client, who spent on average 10,000Fr per annum (almost the salary of a new schoolteacher) from 1929 to 1938 on repairs and replacements, was driven to gentle complaint by Le Corbusier's experimental approach to electric lighting.

> I understand perfectly your hesitancy over the way to light my house. But until you find something really good, it is essential at least that I should be able to see clearly in my home. It's six months since I moved in. […] It is becoming clear that your various pieces of equipment, however ingenious they might be, do show certain drawbacks and, since they are also very dear, I hesitate to proceed any further with them.[106]

Le Corbusier was equally bleeding-edge in his thinking about air supply and temperature. It was by no means unusual to look for new architectural solutions to the real risks of industrially polluted and coal-choked city air. Two of the nineteenth-century pioneers of mechanical ventilation compared dependence on windows for ventilation to opening a hole in the roof so that rain could supply the house's water requirements.

Le Corbusier's contributions to the development of artificial ventilation were a characteristic blend of impressively innovative ideas and ill-founded pseudoscience. He proposed with his usual absoluteness that 18 degrees centigrade was the healthy temperature for human lungs, and that filtered, temperature-controlled air with added ozone ('*air exact*') was necessary for health.[107] The USA-based company who checked his proposed 1930 implementation at the Tsentrosoyuz Building of the 'exact air' idea pointed out that ozone was significantly harmful to health. They added that his system, whilst providing only a third of the air flow they considered necessary, would also cost four times as much in steam and twice as much in mechanical power.[108]

Le Corbusier's 1920s and 1930s urban architecture often included glazing systems that would have no opening parts. This was to be picked up by Pietro Belluschi at the Commonwealth Building in Portland in the 1940s, and was indeed for decades important to effective control of mechanical ventilation.[109] Le Corbusier's preferred glazed façade would have had a double skin, with heated or cooled air circulated through the cavity to maintain a steady 18°C indoors. Rosa Urbano Gutiérrez has shown that Le Corbusier made real efforts to turn this fantasy into a reality, collaborating with a major French glazing company to test his ideas.[110] The most famous of Le Corbusier's reverses with this idea was at the Paris Cité de Refuge. Even after the mechanical ventilation had been dropped as too expensive, Le Corbusier retained a largely sealed glazing system, resulting in intolerable conditions for the homeless people who depended on the facility.[111]

Despite these unattractive live experiments in the architectural potential of new energy systems, Le Corbusier's architecture formed a contribution to the aesthetic and intellectual appeal of oil and electricity – an important part of the developing systems culture.[112] The reality of their implementation in many of Le Corbusier's interwar buildings was disappointing, but the image he gave to the new energy blocks was potent: visions of car-permitted spaciousness and speed outside, and in the home the simplicity of detail and healthy cleanliness made possible by electric lighting and sealed ventilation systems. All this was powerfully coupled with explorations of the aesthetic potential of concrete and steel, and factory-produced windows that he hoped would soon be widespread realities in domestic architecture.

Perhaps even Le Corbusier's ability to remain influential and find new work, despite overspending and encountering technical problems on almost every project, was dependent on the industrial energy revolution. The rapid mass printing and worldwide dissemination of illustrated books and journals that had helped shape Victorian architecture were even more speedy and international by the mid-twentieth century. Publications allowed Le Corbusier to attract new admirers and clients with a voice far more wide-reaching and charismatic than those of his disgruntled former clients. Versions of the ideas Le Corbusier had played with in the 1920s matured into widespread norms in the postwar decades.

Even Britain, the most industrialised country in the world for most of the nineteenth century, was to see a further huge expansion in its energy consumption in the postwar period: 34% between 1959 and 1973 alone (Fig. 6). This raw figure of energy per head underrepresents the amount of extra useful work the country's energy could do by the early 1970s. Alongside the general tendency for efficiency to rise over time within any given technology, the maturation of national and international electricity networks in industrialised countries in this period brought further huge improvements. The total British electricity system of the 1890s, disjointed as it was, saw only around 10% of the generated capacity being used. By 1929, the more networked system was managing to channel around 16% to productive end uses. By 1939, when Britain became the first country to unify its entire national grid, 84% of all the country's electricity was used productively.[113]

In cities around the world in the postwar decades, a new architecture and new city planning really did emerge from the changed energy conditions of the mature oil and electricity energy block. The scale of projects undertaken was vast, with whole new cities of concrete and steel rising in just years, and hectares of older urban fabric being demolished and excavated for vast new commercial and residential schemes. The Barbican Estate in London, a housing complex of around 2000 flats, two schools, and a large arts centre, designed by Chamberlin Powell and Bon from 1959, and built between 1962 and 1982, was one such scheme. It is typical in being built to meet the needs and exploit the benefits of a society enjoying cheap, high-quality energy. Its immense consumption of concrete and steel for construction was the most obvious choice in England by this date, with very substantial fossil-fuelled production of cement and steel keeping prices competitive and quality high. Steel-reinforced concrete freed the architects to dispose accommodation wherever they chose: burying a railway and a road discreetly beneath the buildings; poising hundreds of flats on high slim columns over an artificial lake and above broad walkways which gave a generous new ground level several storeys above the original ground level below, whilst a mix of housing and large underground carparks could fill out the lower levels. Fast lifts could exploit reliable, cheap electricity supplies to whisk residents tens of storeys into the air. Thanks to the strength of concrete and steel the wide-spanning roof of the 1943-seat concert hall could be used as a public square and outdoor sculpture gallery.

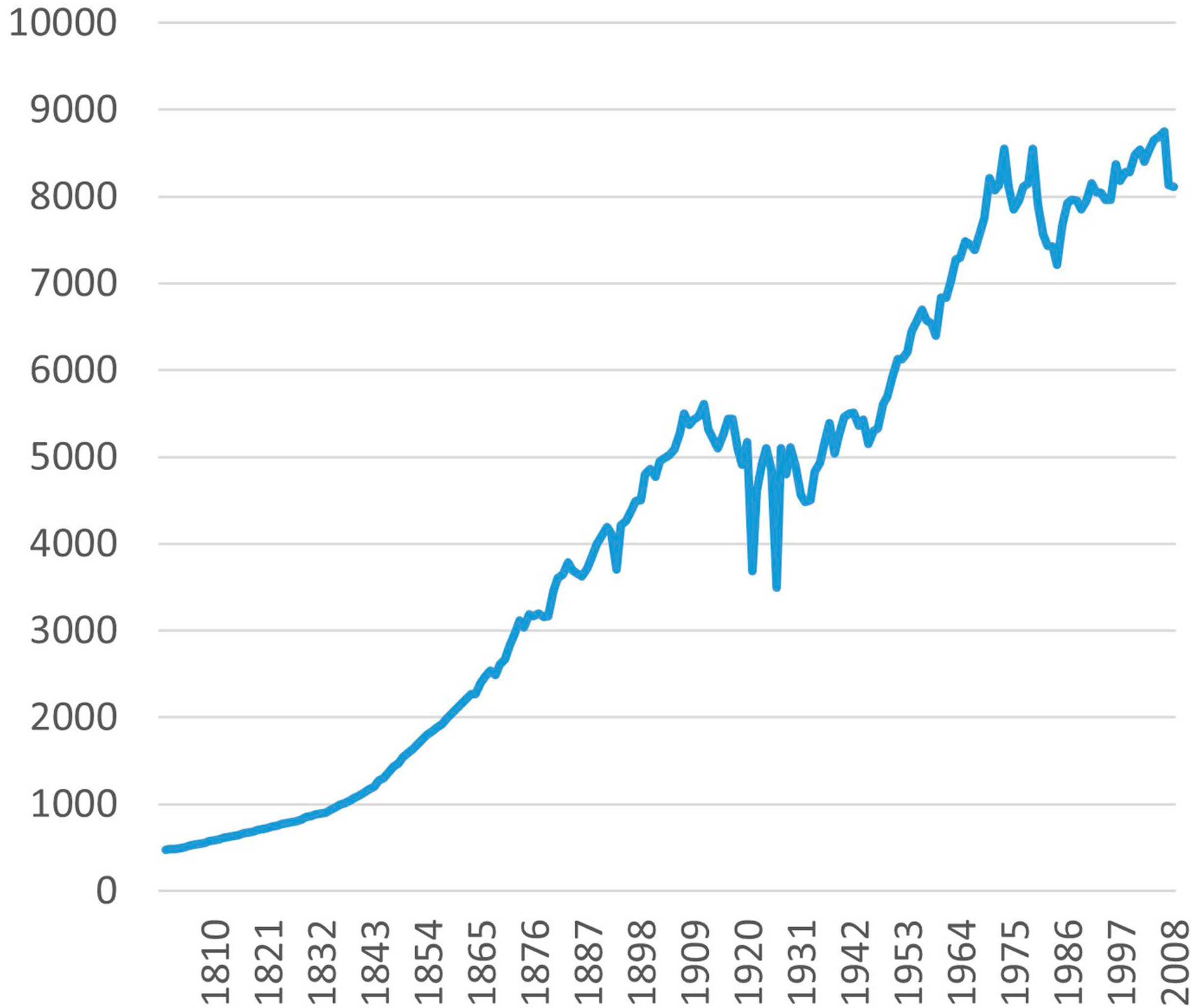


Figure 6.
Total energy consumption in England and Wales, 1800–2008 (Petajoules), www.energyhistory.org, graph based on updates to Paul Warde, *Energy Consumption in England & Wales, 1560–2004* (Naples: CNR, 2007), https://histecon.fas.harvard.edu/energyhistory/graphs/Total_Energy_Consumption_England.pdf [accessed 7 February 2021]

The Barbican Estate and its Arts Centre were so big and complicated that they took two decades to construct even with the immense benefits of diesel-powered construction and transportation equipment. The tools made available by fossil fuels had reduced very sharply the amount of labour required and increased the amount of construction that could be achieved. A bulldozer today can replace around 10,000 preindustrial labourers. Builders on the Barbican's site themselves recalled the difference between the best equipment and the worst, with workers on one of the three tall towers having to wait long times for the slow hoist to bring up their next large precast component. As they waited, they watched the fast-moving hoist on the neighbouring tower, roughly doubling the speed of their rival contractors there.[114] Still, even the slow hoist would have been an immense improvement on the muscle-power that took much longer to lift far smaller elements in pre-industrial construction sites. As early as the 1870s, steam-powered chain-ladder elevators were saving up to 80% of the cost of construction of high buildings in New York, and early steam derricks were twenty times more productive than muscle-powered raising of components.[115]

Not only affordable steel, concrete, and site machinery, but also cheap electricity was crucial for the design of the Barbican. Habitable spaces deep beneath buildings depended on reliable, affordable lighting and pumped air, especially when the breath of almost two thousand concertgoers, or the exhaust fumes of numerous cars, needed to be evacuated safely. This is so normal now that it can be hard to distance oneself from it sufficiently to understand how much it revolutionised the city. The difference between Victorian city blocks and something like the Barbican illustrates the contrast well. The Victorian dependence on natural air and light meant that, even in dense city centres with high land values, office blocks required substantial lightwells, making a kind of honeycomb pattern when viewed from the air. By the 1960s, cheap electric motors of all sizes, fed by an inexpensive and reliable supply, had made it possible to get air and light into any depth of block. This contributed substantially to the profitability of redeveloping much lower-density Victorian buildings and replacing them with the deep plans and abundant open floorplates of the postwar office; the economic pressure to redevelop was immense in any area with moderate or high land values.[116]

At the Barbican, the ventilation and lighting were so reliable and potent that they allowed even the smelly, wet functions of the flats to be moved into the heart of the plan. Edwardian and earlier kitchens and lavatories needed windows to vent smells and moisture to the outdoors, as well as to furnish light. The Barbican, and many other housing projects of its period, relied on mechanical extraction of vitiated air – and on electrical lighting without which many spaces would be literally uninhabitable – to place bathrooms, lavatories, and kitchens in the middle of the flat away from windows. They thus preserved the precious light and views of the outside walls for enjoyable living spaces.

The Barbican is also typical in its ambivalent attitude to the increasingly universal car (from 1970 a majority of British households had one) brought about by cheap and abundant oil supplies in the postwar decades. The Barbican's planning aims to allow the fastest and smoothest traffic flow in the road that runs through it and those around its perimeter, keeping pedestrians out of the way of cars to the benefit of both. Determining as early as 1959 to furnish enough covered car parking for each flat to have a space, the design allowed every resident to get from their car to their flat without braving bad weather.

But whilst the Barbican was designed to serve the car, it also responded to their noisiness and pollution. The main road through the site is buried under car parking and pedestrian decks so that its noises and smells do not intrude on open space or housing. The perimeter of the site is ringed with a high defensive wall, much of it blind. Keeping out the road's ill effects, it has attracted criticisms that it is an unfriendly presence at street level.

Even as architects like Chamberlin Powell and Bon were pushing through vast schemes that were changing the face of the industrial city, other voices were arguing that architecture was not radical enough. Looking back at the High Tech movement of the 1950s and 1960s from our present anxieties about energy use, many of their ideas seem loopy or even pernicious fantasies. We shudder at the profligacy of using servicing rather than insulation to maintain warmth or cool in thin fabric or plastic enclosures.[117] Most now also reject early High Tech's enthusiasm for planned rapid obsolescence, which would have seen major building components scrapped and replaced every few years like rusty cars. Yet if one looks at the trajectory of change over the previous two centuries in Britain, America or Japan, the tendency was clear: exponential growth in energy availability, spurred on to great leaps by the periodic appearance of radically new energy technologies which dwarfed their predecessors in power and quality, and ever-increasing technological expertise in manipulating the material world. High Tech took off at a period when nuclear power was scaling up fast, and the nuclear disasters of Three Mile Island and Chernobyl, the oil crises of the 1970s, and an understanding of the environmental impacts of fossil fuels were still far in the future. There were hopes that fusion power and other new technologies might make energy, the great limiting force on all earlier architecture, 'too cheap to meter' – effectively unlimited.[118]

In this context of helter-skelter change, it was not absurd for architects to be considering not only how to adapt to their immediate energy context, but to start to extrapolate this energy curve and consider how to respond not merely to the next set of changes, but to the concept of ever-hastening change itself. Archigram's walking cities may have been still rather fantastical, but the reality of postwar university expansion in terms of student numbers and government financial support were so substantial that Cedric Price's Thinkbelt was only a proposal to change how the money and students were disposed, rather than a total fantasy. Within the lifetime of middle-aged architects in 1970, cars had gone from almost the equivalent of private aircraft today to being accessible to a (narrow) majority of Britain's households, and flight itself was rapidly becoming available to ordinary people in rich countries.

Conclusion

Framing the history of architecture in terms of energy use makes clear that our contemporary notion of what is 'normal' in architecture are deeply anomalous in a longer historical context. Alarmingly, despite extensive discussion of sustainability in architecture and other fields, and considerable research on how to reduce energy consumption in the built environment, our current energy systems worldwide are overwhelmingly a continuation of the 1960s rich-world pattern of dependency on very high levels of energy use, a substantial majority of it furnished by fossil fuels. The exciting and welcome economic development of hitherto predominantly agrarian regions worldwide is accompanied by a worrying scaling up of western industrial patterns of fossil-fuel use. For instance, China used more cement between 2011 and 2013 than the global economic superpower, the USA, had used in the entire course of the twentieth century.[119]

Foregrounding energy use in the long history of architecture is not an attempt to invalidate or sideline existing models of architectural history, but to enrich them. The role of energy inputs and energy context in shaping buildings of all periods determines limits and pressures on the processes of design and construction, but does not determine their outcomes. The range of responses to new energy technologies of the nineteenth and twentieth centuries, for example, guided the production of pairs of architects as different as William Butterfield and Alfred Waterhouse, or Le Corbusier and Edwin Lutyens. Each selected which aspects of the new forms of material processing and transport to engage with, which new services and construction techniques to embrace and emphasise, which to use but downplay in aesthetic and theoretical output, and which to shun. Yet, each produced buildings which, in their use and handling of materials, in their technologies, and even in their functions and meanings, could only be found in the energy context in which they were working.

In studying the historical relationship between architecture and energy, historians must be prepared to find varying levels of explicit reflection on the topic by contemporaries, and to read between the lines on occasion. Coal in Victorian England, industrial fabrication in New York from the 1870s to the 1930s, and 'mechanisation' in interwar Modernism, were all much discussed, and celebrated in architectural writing and practice, although none of them framed it in terms of 'energy'. Indeed, our contemporary concept of the unity of different forms of energy is relatively recent, and energy is so fundamental a human concern that it frequently goes as unnoticed as the air around us. Yet, it is always possible to find forms of energy as crucial determining factors in architectural decision making, whether this is expressed in terms of cost of materials or labour, as a problem of lighting or heating, or as a question of technological change and innovation. Energy is rather like gravity, in that it acts on the human world whether or not it has been successfully theorised.

If proper understanding of the energy dimensions of architecture is vital to the writing of architectural history, it also has a contemporary application. A considerable proportion of architectural historians teach in schools of architecture, and architectural practitioners and students make up much of the audience for our books. Framing architectural history in an energy context can make an immense contribution to students' and architects' understanding of the challenge of 'zero-carbon' architecture, setting out the material poverty that accompanied the last period of truly sustainable architecture, and the extent to which our contemporary architectural assumptions evolved in a period of vast energy wealth and total fossil-fuel dependency.

The history of architecture and energy encourages students and practitioners to hold up the many false prophets of sustainability to a rigorous examination, based on a robust understanding of the level of coal- and oil-dependency that our buildings have developed over the past three centuries. Implicit in an 'energy history' of architecture is a daunting and thrilling challenge to architects, theorists, and technologists to rethink architecture root and branch in the light of the climate emergency.

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88. For the issues and consequences of speed and time in this context, see Malm, *Fossil Capital*, pp. 165–222. Parallel to economists, Giedion's and Lewis Mumford's work on 'anonymous history' and so-called paleotechnic culture concluded that by the time we had reached the 1830s and 1840s, the production horizon had transformed fundamentally and irrevocably. See Lewis Mumford, *Technics and Civilization* (New York, NY: Harcourt, Brace and Co., 1934), p. 196.
89. For relations between the steamer economy and warehouse construction in the China Trade, see Bremner, 'Tides that Bind', pp. 39–40.
90. Ronald Firman and others, 'Brick, Stone and Iron: Building Materials at St Pancras', *British Brick Society Information*, 96 (April 2005), 5–20.
91. See the reference to Charles Babbage in Malm, 'The Origins of Fossil Capital', pp. 15–16. Babbage referred to carbon dioxide as 'carbonic acid'.

92. See Vicky Albritton and Fredrik Albritton Jonsson, *Green Victorians: The Simple Life in John Ruskin's Lake District* (Chicago, IL: University of Chicago Press, 2016), pp. 32–33; John Ruskin, *The Queen of the Air* (London, 1869).
93. Italy's imports of coal rose rapidly from the 1870s to the start of World War I. See Paolo Malanima, *Energy Consumption in Italy, 1861–2000* (Rome: Consiglio Nazionale delle Ricerche, 2006), <https://sites.fas.harvard.edu/~histecon/energyhistory/graphs/Energy_mix_Italy_lightversion.pdf> [accessed 7 February 2021].
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100. Richard Difford, 'Infinite Horizons: Le Corbusier, the Pavillon de l'Esprit Nouveau Dioramas and the Science of Visual Distance', *The Journal of Architecture*, 14 (2009), 295–323 (p. 318, n5).
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112. For the concept of 'systems cultures', see Hughes, *Networks of Power*, p. 15.

113. Kander, Malanima and Warde, *Power to the People*, p. 307.
114. See *Building the Barbican 1962 – 1982: Taking the Industry Out of the Dark Ages*, ed. by Christine Wall and others (London: University of Westminster, 2014), p. 17.
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