Buildings and energy

Architectural history in the climate emergency

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Buildings and Energy: Architectural History in the Climate Emergency

Abstract

As the current climate emergency deepens, it is no longer adequate to leave ideas of sustainability to engineers and practitioners. Ways of talking about 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.

Keywords: architectural history; energy consumption; embodied energy; climate change; sustainability

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Buildings and Energy: Architectural History in the Climate Emergency[1]

At the time of writing, a blog appeared on the website of a major United Kingdom museum featuring a Mamluk mosque lamp of the fourteenth century. The account given of this object, despite being generally informative, contained the following rather curious sentence: ‘Although many lamps were hung together, they would not have provided a great deal of light; however, they had a symbolic function, alluding to Allah's guiding light’.[2] The suggestion seemed to be that the symbolic function of such lamps was primary. In fact, bright or dim, these lamps were the sole source of illumination for mosques and other important buildings in medieval Cairo and elsewhere: they may not have been bright, but they were all there was.

The museum’s account of this lamp exemplifies a widespread blindness found in writing about the material culture of previous ages: it is very hard to think away our current rich-world norms enough to imagine pre-industrial energy conditions. In a world without powerful electric lighting, a mosque lamp, although clearly having strong symbolic value, cannot usefully be compared to the flicker of a contemporary restaurant candle. In its own time and place it was a strikingly bright primary light-source.

As late as the early seventeenth century, European ambassadors wrote in obvious admiration about the brilliantly-lit Maydan square in Isfahan, where, one thrillingly exotic night, they had their first sip of coffee.[3] The darkness of the pre-industrial night is hard to imagine for most contemporary western historians; the brilliance of the Versailles *Galerie des Glaces*, when its mirrors, gilding, and silver furniture were

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[1] Some of the ideas in this article were aired and discussed at the symposium ‘Architecture of Energy’ (3 November 2017), organised by Mark Crinson and the Architecture, Space and Society Centre, Birkbeck College, University of London. Bremner is currently working on a new history of Victorian architecture for Oxford University Press that takes account of the impact of embodied energy; while Calder has written a book entitled *Architecture: Buildings and Energy from Prehistory to the Present*, to be published by Pelican in 2021.

[2] http://www.wallacecollection.org/whatson/treasure/38. Accessed 26 March 2018.

[3] Farshid Emami, ‘Coffeehouses, urban spaces, and the formation of a public sphere in Safavid Isfahan’, in *Muqarnas: An Annual on the Visual Cultures of the Islamic World*, ed. Gülru Necipoğlu, 33 (2016), pp. 177-220.

reflecting thousands of candles, must have given plausibility (in a way we can never experience ourselves) to Louis XIV's claim to be the Sun King.

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'.[4] 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 construction, but it also contributes to the interpretation of a surprisingly diverse range of aspects of human culture, including architectural design. Moreover, 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.[5] But a new sense of urgency is now emerging among historians concerning the relationship between architecture and the environment.[6]

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[4] R. B. Lindsay, 'The Concept of Energy and Its Early Historical Development,' *Foundations of Physics*, 1 (1971), 383-393.

[5] For example, Dean Hawkes, *The Environmental Tradition*: *Studies in the Architecture of Environment* (London: E & FN Spon, 1996); idem, *Architecture and Climate: An Environmental History of British Architecture 1600–2000* (London: Routledge, 2012); Daniel Barber, *A House in the Sun: Modern Architecture and Solar Energy in the Cold War* (Oxford: Oxford University Press, 2016); Jiat-Hwee Chang, *A Genealogy of Tropical Architecture: Colonial Networks, Nature and Technoscience* (New York: Routledge, 2016). See also *Climates: Architecture and the Planetary Imaginary*, ed. by James Graham (Baden: Lars Muller Publishers, 2016); R. Urbano Gutiérrez, 'Le pan de verre scientifique: Le Corbusier and the Saint-Gobain glass laboratory experiments (1931–32)', *Architectural Research Quarterly*, 17 (2013), 63-72.

[6] On this, see Esther da Costa Meyer, 'Architectural history in the Anthropocene: towards methodology', *Journal of Architecture*, 21:8 (2016), 1203-1225. See also the most interesting Field Notes section entitled 'Architecture and the Environment' in *Architectural Histories*, 1 (2018): https://journal.eahn.org/articles/10.5334/ah.259/. Accessed 21 September 2020. See

Crucially important in this, however, is the idea and use of energy. 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.[7] 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.[8] 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: 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? It is a question, we suggest, that has immense analytical power in helping us understand the material context of architectural production, and, by extension, sheds surprisingly 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

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also the 2017-18 'Architecture and/for the Environment' research programme at the Canadian Center for Architecture: https://www.cca.qc.ca/en/events/55861/multidisciplinary-research-program-architecture-andfor-the-environment. Accessed 21 September 2020.

[7] Daniel A. Barber, 'Heating the Bauhaus: Understanding the History of Architecture in the Context of Energy Policy and Energy Transition' (Philadelphia: Kleinman Center for Energy Policy, University of Pennsylvania, 2019).

[8] Barber, 'Heating the Bauhaus', 4. Barber's piece is to date the single most trenchant contribution to the debate concerning energy use, the environment, and architectural history.

limited) all human societies up to that point, whether comparatively complex or simple – to a mineral-based, consumptive one.[9]

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 in particular 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.[10] This *flow* of energy (solar) 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.[11]

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 coming 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'.[12] This crucial transition

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[9] E. A. Wrigley, *Energy and the English Industrial Revolution* (Cambridge: Cambridge University Press, 2010), p. 22.

[10] A compounding factor was that plant photosynthesis itself was only capable of capturing a tiny fraction of the energy contained in incident sunlight – something in the order of less than 1% of the annual total of the solar radiation reaching each square metre of soil, or around 4,000 kilocalories in every 400,000 kilocalories on an annual basis. See E. A. Wrigley, *The Path to Sustained Growth: England's Transition from an Organic Economy to an Industrial Revolution* (Cambridge: Cambridge University Press, 2016), p. 7.

[11] This is often referred to as "the photosynthetic constraint". See Astrid Kander, Paolo Malanima and Paul Warde, *Power to the People: Energy in Europe over the Last Five Centuries* (Princeton: Princeton University Press, 2013), pp. 39-41.

[12] Rolf Peter Sieferle, *The Subterranean Forest: Energy Systems and the Industrial Revolution* (Knapwell: White Horse Press, 2001). To give a key statistic: by 1850 the amount of coal being

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, who tend to be economic historians or historians of technology by background.[13] The world view established by the research of energy historians is of manifest importance in periods of rapid energy change, but 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 most obvious ways in which the energy context shapes all buildings are: 1) the energy required to procure/produce, move, and work construction materials; 2) control of climate within buildings, both passive and active; and, 3) 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 which 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 coal-fired

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consumed within England and Wales was the equivalent of 48.1 million acres of land area that would have been required to meet the same energy needs through the harvesting and burning of wood – 150% of the total land mass of England and Wales. Wrigley, *Energy*, p. 99.

[13] For instance, see Vaclav Smil, *Energy and Civilization: A History* (Cambridge, MA: The MIT Press, 2019), pp. 1-4; Andreas Malm, 'Who lit this Fire? Approaching the History of the Fossil Economy', *Critical History Studies*, 3:2 (2016), 215-48 (esp. 215-23). See also opening sentence of the Preface in Crosbie Smith, *The Science of Energy: A Cultural History of Energy Physics in Victorian Britain* (Chicago: Chicago University Press, 1998), p. ix. For an excellent recent response to this call, see Cara New Daggett, *The Birth of Energy: Fossil Fuels, Thermodynamics, and the Politics of Work* (Durham and London: Duke University Press, 2019).

age of steam during the nineteenth, to petroleum- and nuclear-based forms of production, and the new energy carrier electricity, during the twentieth.

The purpose of these historical case studies – what we term 'scenarios' – is 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.[14] Therefore, throughout this piece 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.[15]

The basic intention is to reveal how the particular conditions pertaining to any given energy regime exerted a powerful influence on the possibilities available in the building design and construction industries.[16] 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

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[14] Costa Meyer, 'Architectural history in the Anthropocene', 1205-09.

[15] Here we turn to the work of Thomas P. Hughes, Andrew Barry, Timothy Mitchell, and Brian Larkin, among others.

[16] This idea of course borrows something from the arguments in Sigfried Giedion's famous study *Mechanisation Takes Command: A Contribution to Anonymous History* (1948).

construct of ‘energy’ itself.[17] 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.[18] As Daniel Barber has recently observed, in light of the expansion of environmental histories of architecture in the last decade or so, 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’.[19] 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 (**Figure 1**).

Scenario 1

Agrarian: Ancient Rome

> *marmoream se relinquere quam latericiam accepisset*
>
> – Suetonius, *Divus Augustus*, 28

Augustus’s famous boast 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

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[17] This is what Cara New Daggett has termed ‘the dominant logic of energy’. See Daggett, *The Birth of Energy*, pp. 15-103.

[18] We use the term ‘Anthropocene’ here fully aware of its limitations, but appreciate its general communicative power. Some have contemplated using more specific terms, such as ‘Econocene’, ‘Technocene’, or ‘Capitalocene’. See Andreas Malm and Alf Hornborg, ‘The geology of mankind? A critique of the Anthropocene narrative’, *The Anthropocene Review*, vol. 1:1 (2014), 62-9.

[19] Daniel A. Barber, ‘Architectural History in the Anthropocene’, *Journal of Architecture*, 21:8 (2016), 1165-70.

be equalled by coal-fuelled London as late as 1801.[20] 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, and even the rickety *insulae* which housed the majority required enough mud brick and timber for perhaps 10% of them to rise above two storeys.[21]

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.[22] 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 15-20% of food calories eaten by humans results in useful physical work.[23] Animals offer greater power but slightly worse efficiency (10-15%) in terms of muscular output relative to calories ingested.[24] 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, and could be considerably lower again in cases like animal husbandry for food.

As we shall see in Scenario 2, 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

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[20] Dominic Rathbone, 'Mediterranean Grain Prices c. 300 to 31 BC: the Impact of Rome', in *Documentary Sources in Ancient Near Eastern and Greco-Roman Economic History: Methodology and Practice*, ed. by Heather D. Baker and Michael Jursa, (Barnsley: Oxbow Books, 2014), pp. 289-312 (p. 307).

[21] Glen Storey, 'Regionaries-Type Insulae 2: Architectural/Residential Units at Rome', *American Journal of Archaeology*, 106:3 (2002), 411-434 (p. 429, n.73).

[22] Kander, Malanima and Warde, *Power to the People*, pp. 39-41; Andrew Wilson, 'Raw Materials and Energy', in *The Cambridge Companion to the Roman Economy*, ed. Walter Scheidel (Cambridge: Cambridge University Press, 2012), pp. 133-55.

[23] Kander, Malanima and Warde, *Power to the People*, pp. 39, 42.

[24] Kander, Malanima and Warde, *Power to the People*, p. 65. This, of course, does not take account of the enormous energy cost of cooking human food.

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 2,000 km., from some of the world's most fertile farming areas.[25] As Suetonius recorded, the architectural impact of this immense agrarian energy boom was spectacular. Suetonius's portrait of Republican Rome is certainly just: before Augustus's long reign Rome was largely constructed from '*later*' (unfired or 'mud') brick.[26] 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.[27]

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

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[25] For Roman use of coal see, for example, John Hatcher, *The History of the British Coal Industry: Volume 1: Before 1700: Towards the Age of Coal* (Oxford: Oxford University Press, 1993), p. 17. There is extensive literature on Roman grain importation, see e.g. Rathbone, or Paul Erdkamp, *The Grain Market in the Roman Empire: A Social, Political and Economic Study* (Cambridge: Cambridge University Press, 2005), or G. E. Rickman, 'The Seaborne Commerce of Ancient Rome: Studies in Archaeology and History', *Memoirs of the American Academy in Rome*, 36 (1980), 261-275.

[26] Henrik Gerding, '*Later*, *laterculus* and *testa*: new perspectives on Latin brick terminology', *Opuscula: Annual of the Swedish Institutes at Athens and Rome*, 9 (2016), 7-31 (p. 11).

[27] For instance, Janet DeLaine has calculated, extrapolating from the work of others, that the production of bulk building materials on any given project in ancient Rome between the 1st century BCE and the 2nd century CE typically accounted for one third to one half of labour expenditure. See Janet DeLaine, 'The Supply of Building Materials to the City of Rome', in *Settlement and Economy in Italy 1500 BC – AD 1500*, ed. Neil Christie (Oxford: Oxbow Books, 1995), p. 555.

into more or less direct competition with the production of food for finite hectares of land.[28] In time, there was the added problem of timber scarcity owing to increased deforestation, or the lack of decent firewood (*lignum*) in certain locations, requiring the transportation of wood around the empire.[29] Access to firewood was a particularly important limitation in colder climates – towns in pre-modern 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.[30] Nevertheless, considering its exported production footprint (and thus energy needs), a city such as 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.[31] In the city itself, large amounts of firewood were also required for the heating of public baths (*thermae*).[32]

Amidst a Rome largely of low-energy mud brick, special buildings were built, from around the 2nd 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

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[28] An example of how such a problem was overcome in the Roman world, in its grain-producing heartlands, see Lynne C. Lancaster, 'Ash Mortar and Vaulting Tubes: Agricultural Production and the Building Industry in North Africa', in *Archeología de la Construcción III: Los Procesos Constructivos en El Mundo Romano: La Economía de Las Obras*, ed. by Stefano Camporeale, Helene Dessales, and Antonio Pizzo (Siena: Università di Siena 2012), pp. 145-60.

[29] Wilson, 'Raw Materials', pp. 149-50; Örjan Wikander, 'Sources of Energy and Exploitation of Power', in *The Oxford Handbook of Engineering and Technology in the Classical World*, ed. John P. Oleson (New York: Oxford University Press, 2010), p. 139. For deforestation in the ancient Mediterranean owing to energy consumption, see Russell Meiggs, *Trees and Timber in the Ancient Mediterranean World* (Oxford: Clarendon Press, 1982), pp. 371-403 (esp. 379-82).

[30] Kander, Malanima and Warde, *Power to the People*, pp. 56-58.

[31] Lynne C. Lancaster, *Concrete Vaulted Construction in Imperial Rome* (Cambridge: Cambridge University Press, 2005), pp. 16-17.

[32] Wilson, 'Raw Materials', pp. 149-50.

require extensive processing before use. Roman concrete (*opus caementicium*) was, in energy terms, in an entirely different category from modern concrete, with the latter's immense requirements for 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: seven days to load a kiln with limestone, seven days of intense burning to calcine it, and seven more days dismantling the kiln and retrieving the lime.[33] 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 it calcines (releases CO_2).[34] To sustain such heat for a protracted period using only plant matter required a lot of 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, and through a protracted programme of military expansion in which the city state had 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 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.[35] The sudden boom in Rome's construction industry following the conquest of Egypt is

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[33] Jean-Pierre Adam, *Roman Building: Materials and Techniques*, trans. Anthony Mathews (London: Routledge, 1999 [first published in French in 1989]), p. 69.

[34] Lancaster, *Concrete Vaulted Construction*, p. 16.

[35] Both Roman authors and modern economic historians (Erdkamp, Rathbone, Rickman, etc.) have discussed extensively the extent of increase to Rome's grain supply brought about by the conquest of Egypt, but the evidence remains contested. Roman taxation figures were assessed in units of grain (itself an indication of the prime importance of grain to the empire), but taxpayers were permitted to pay in kind or in cash, meaning that the actual tonnage of grain is unknowable.

unmistakeable. 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 stone.

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 built into the concrete as the wall rose, like permanent shuttering.[36] It involved more work (cutting facing stones to standard dimensions), but shaping stones could be a separate skill from placing them, and 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, 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

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[36] A. Wilson, 'The economic impact of technological advances in the Roman construction industry', in *Innovazione tecnica e progresso economico nel mondo romano*, ed. Elio Lo Cascio (Bari: Edipuglia, 2006), pp. 225–236, p. 227.

USSR during the fossil-fuel energy boom of the 1950s-60s, and on into the present off-site factory production of almost all building components.[37]

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.[38]

As with earlier Roman projects, when Augustus and his successors used marble, or other prestigious decorative stones, it was either for specially 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 Janet 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 ca. 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, 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.[39] This ostentatious display of technical skill and energy wealth was characteristic of Imperial *magnificenza*.

Command over more basic bulk building materials mattered, too. 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

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[37] For *Yingzao Fashi*, see Qinghua Guo, 'Yingzao Fashi: Twelfth-Century Chinese Building Manual', *Architectural History*, 41 (1998), 1-13.

[38] Delaine, summarised in Wilson (2007), p. 227.

[39] Janet DeLaine, *The Baths of Caracalla: A Study in the Design, Construction, and Economics of Large-scale Building Projects in Imperial Rome*, supplementary series to *Journal of Roman Archaeology* (1997), pp. 21, 33.

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.[40]

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. Davies, Hemsoll and 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.[41] They even refer to a contemporary Egyptian papyrus in which the leader of a 50' column-transport team appeal for more grain to feed his draught animals.[42]

The amount of stone extracted and moved for these purposes represents an immense energy investment – imperial use was only part of a much wider market in ornamental stone.[43] 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.[44] It seems probable that the emperors valued this demonstration of their power.

This suggests to us the presence 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,

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[40] Janet DeLaine, 'The Supply of Building Materials to the City of Rome', in *Settlement and Economy in Italy 1500 BC – AD 1500*, ed. Neil Christie (Oxford: Oxbow Books, 1995), p. 558.

[41] Paul Davies, David Hemsoll and Mark Wilson Jones, 'The Pantheon: Triumph of Rome or Triumph of Compromise?', *Art History*, 10:2 (1987), 133-156.

[42] Davies, Hemsoll and Wilson Jones, 151 (n. 51).

[43] Ben Russell, *The Economics of the Roman Stone Trade* (Oxford, 2013), p. 355.

[44] Vespasian's role and the and column shafts are described by Dr Barbara Levick in 'The Roman Way', Episode 3, first broadcast on Radio 4, February 2003: https://www.bbc.co.uk/sounds/play/p00cbxzh, accessed 21 September 2020; DeLaine, *The Baths of Caracalla*, p. 99.

commissioned high-energy cost projects, knowingly, 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 in this regard. 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 1st 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, as mentioned, in 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 one thousand personnel to operate effectively. The presence of these materials in Rome were as much an affective emblem of the might and reach of centralised imperial organisation as they were about personal aggrandisement (both of which naturally went hand-in-hand).[45] Such a regime, and the organisational capacity it represented, is what ecologists refer to as a 'high-gain' energy system realised via the appropriation of accumulated surpluses of conquered lands and peoples resulting from imperial expansion, including increased logistical and building capabilities.[46]

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

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[45] For this trade in marbles in the Roman empire, including its political implications, see J. Clayton Fant, 'Quarrying and Stoneworking', in Oleson, *Oxford Handbook of Engineering and Technology*, pp. 121-35. The most comprehensive and authoritative account, which covers many of the points made here in detail, can be found in Ben Russell, *The Economics of the Roman Stone Trade* (Oxford: Oxford University Press, 2013).

[46] For this in relation to ancient Rome, see Joseph A. Tainter, T. F. H. Allen, Amanda Little and Thomas W. Hoekstra, 'Resource Transitions and Energy Gain Contexts of Organization', *Conservation Ecology*, 7:3 (2003), http://www.consecol.org/vol7/iss3/art4. Accessed 21 September 2020.

may have come from a number of sources.[47] 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.[48]

Whilst these stones and other energy-hungry materials were fantastically important for display, they were nevertheless subject to discreet energy savings where available. For instance, as testified by Vitruvius (*De architectura* 10.1.1-7), 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 (**Figure 2**).[49] This included the thinly cut, imported stone veneer mentioned above, where, from at least by the later 3rd 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.[50] 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).[51] In terms of the recycling 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, though, 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

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[47] DeLaine, *The Baths of Caracalla*, pp. 97-98.

[48] Fant, 'Quarrying and Stoneworking', p. 125.

[49] Fant, 'Quarrying and Stoneworking', p. 132; Wikander, 'Sources of Energy', pp. 141-52.

[50] Tullia Ritti, Klaus Grewe, and Paul Kessener, 'A Relief of a Water-Powered Stone Saw Mill on a Sarcophagus at Hierapolis and Its Implications', *Journal of Roman Archaeology*, 20 (2007), 139–63.

[51] Fant, 'Quarrying and Stoneworking', pp. 150-2; Jan Theo Bakker (ed.), *The Mills-Bakeries of Ostia: Description and Interpretation* (Amsterdam: J. C. Gieben, 1999), p. 10.

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.[52]

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 – reminders of the extent of the Empire. Yet these materials made up a minute proportion of the whole building, with almost all of it 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 depletion of timber stocks mentioned above 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 inescapably clear, is the level of manpower involved. DeLaine's calculations suggest an average daily workforce of 7,200 men involved in material production and construction, with a further 1,800 men plus oxen involved in transport of materials in and around Rome. Indeed, the shipping and haulage of stone alone – even the relatively small amounts of marble – accounted for more than 50% of the project's total construction cost.[53] At peak times the number of labourers perhaps rose as high as 13,100 men

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[52] DeLaine, *The Baths of Caracalla*, pp. 129-130.

[53] DeLaine has also calculated, extrapolating from the work of others, that the production of bulk building materials on any given project typically accounted for one third to one half of labour expenditure. See DeLaine, 'The Supply', p. 555.

involved in building the central block of the Baths, with more constructing the surrounding buildings in the complex.[54] An idea of the extraordinary amount of animals (and therefore feed) that were 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 2nd century CE), some 800-825 oxen were required to move each 800-tonne stone block.[55]

The emphasis on economising long-distance transport and heat, and making use of very extensive labour, was economically rational in an agrarian context. Scheidel has demonstrated that unskilled labourers were paid fairly comparable amounts (when converted into the number of litres of grain it could buy) across societies from 1800BCE 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.[56] Despite Rome's vast grain imports, the pay for unskilled labourers seems not to have been at the upper end of the normal range, and may have been towards the lower end.[57] 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.[58]

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

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[54] DeLaine, 'The Supply', p. 193.

[55] Adam cited in Russell, *The Economics of the Roman Stone Trade*, pp. 98-100. DeLaine has also commented on the large traffic of building materials on Rome's major highway network. See DeLaine, 'The Supply', p. 558.

[56] Walter Scheidel, 'Real Wages in Early Economies: Evidence for Living Standards from 1800 BCE to 1300 CE', *Journal of the Economic and Social History of the Orient*, 53:3 (2010), 425-462.

[57] Scheidel, 'Real Wages in Early Economies', table 4.

[58] DeLaine, *The Baths of Caracalla*, p. 209.

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, it was that 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.[59]

Yet even at its ancient height, Rome's access to energy-intense materials was a costly luxury. Although Suetonius's formulation is more catchy, 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

> Day by day it becomes more obvious that the Coal we happily possess in excellent quality and abundance is the Mainspring of Modern Material Civilisation.
>
> – W. Stanley Jevons, *The Coal Question* (1865)

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[59] Tod A. Marder, 'The Pantheon in the seventeenth century', in *The Pantheon: From Antiquity to the Present*, ed. by Tod A. Marder and Mark Wilson Jones (Cambridge: Cambridge University Press, 2014), pp. 296-329.

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 middle of the nineteenth century that in 1865, at the height of Victorian industrial transformation, the noted English economist Stanley Jevons declared it 'all-powerful'; that 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'.[60] Given the available evidence regarding energy consumption during the Victorian period, Jevons' observation is no exaggeration.

Despite this economic reality, it is easy for those concerned with the history of architecture to forget just 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.

In order 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.[61] Its chemical composition, particularly anthracite (its purest form) is in the order of 92% - 98% carbon (C). Thus, when one speaks of an 'age of coal', as

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[60] W. Stanley Jevons, *The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines* (London: Macmillan & Co., 1865), pp. vii-viii.

[61] For more on this, see Wrigley, *The Path to Sustained Growth*, pp. 31-44.

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'.[62]
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 (**Table 1**).[63]

This reliance on coal as a key energy input during the Victorian age not only had significant consequences 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'

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[62] Andreas Malm, *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming* (London: Verso, 2016).

[63] E. A. Wrigley, *Energy and the English Industrial Revolution* (Cambridge: Cambridge University Press, 2010), p. 37. For comparison's sake, in 2015 energy production from coal represented only 6.57% of the total UK production, with just 22.6% of electricity generation resulting from the combustion of coal (itself representing nearly 80% of total coal consumption for that year). Press Notice, Department of Energy & Climate Change, UK Government (31 March 2016): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/513244/Press_Notice_March_2016.pdf. Accessed 21 September 2020.

architecture (post 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 (**Figure 3**). Experiments in machine-powered brick manufacturing had not only increased output substantially by the 1850s, but 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 south east and elsewhere.[64] 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 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 methods of machine production

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[64] A specific example of this can be found in the study by Pamela R. Healey and E. M. Rawstron, 'The Brickworks of the Oxford Clay Vale', *The East Midland Geographer*, 4 (1955), pp. 42-48.

continued, but mechanisation of the industry was all but complete by the close of the nineteenth century.[65]

Therefore, in considering the relationship between architecture and energy, we must first contend with buildings as objects, before considering 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.[66] 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.[67] 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 – an infrastructure that, as the architect G. E. Street so aptly observed, gave the middle-class professional no excuse not to familiarise himself with Continental

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[65] See Kathleen Ann Watt, 'Nineteenth Century Brickmaking Innovations in Britain: Building and Technological Change', PhD Thesis (University of York, 1990); Paul Thompson, *William Butterfield* (Cambridge MA: MIT Press, 1971), p. 149.

[66] Stefan Muthesius, '"The Iron Problem" in the 1850s', *Architectural History*, 13 (1970), 58-63. See also, Paul Dobraszczyk**,** *Iron, Ornament and Architecture in Victorian Britain: Myth and Modernity, Excess and Enchantment* (Farnham: Ashgate, 2014), pp. 5-23.

[67] For a recent analysis of this, see Malm, *Fossil Capital*.

art.[68] 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.[69]

What is evident in all of this is the advent of a new and quite peculiar kind of architectural ecology (material and intellectual), one 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 Georgian architecture c.1800 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.[70] 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

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[68] George Edmund Street, *Brick and Marble in the Middle Ages: Notes of a Tour in the North of Italy* (London: John Murray, 1855), p. vii.

[69] *The Printed and the Built: Architecture, Print Culture, and Public Debate in the Nineteenth Century*, ed. by Mari Hvattum and Anne Hultzsch (London: Bloomsbury, 2018), p. 3.

[70] Andrew Barry, 'Technological Zones', *European Journal of Social Theory*, 9:2 (2006), 239. The trailblazing study of this phenomenon was Thomas Hughes's *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore: The Johns Hopkins University Press, 1983).

and realised.[71] The increasing standards, quality, and scale observable in Victorian architecture mentioned above were a result of the performance of 'zones' of this kind. These zones required both technologies and infrastructures to operate effectively, with the infrastructure pulling the various technologies (instrumental and intellectual) 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 was prevalent, ushering 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 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, thus exerting sustained demand within the local economy for technological solutions that utilised these cheap and apparently inexhaustible supplies of energy.[72] 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'.[73] Thus, steam power reordered nature, rather than responding to the world

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[71] This might also be considered part of the wider rise and ideological power of metrology in Victorian Britain, in which new standards of measurement and accuracy brought with them new values relating to order, regulation, and commerce. See Simon Schaffer, 'Metrology, Metrication, and Victorian Values', in *Victorian Science in Context*, ed. by Bernard Lightman (Chicago: University of Chicago Press, 1997), pp. 438-474.

[72] R. C. Allen, 'Why the industrial revolution was British: commerce, induced invention, and the scientific revolution', *The Economic History Review*, 64:2 (2011), 357-384.

[73] George Edmund Street, 'The True Principles of Architecture and the Possibility of Development', *The Ecclesiologist* (Aug. 1852), 250.

as given; from then on advanced economies began to shape themselves around the opportunities and demands of steam power.[74]

It is important to remember, however, that 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, and was concerned primarily with the control of labour and efficiency gains in the modern capitalist economy. As Andreas Malm sees it, 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.[75] 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.[76] 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. Indeed, 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.[77]

This had effects for what Jane Hutton has called 'reciprocal landscapes', both in Britain and abroad, responsible for the supply of food and materials – what, in this case, might otherwise be described as Britain's production footprint, local and exported.[78] For

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[74] The emergent nature of these relationships and the nexus between coal, steam, and capital that they created are discussed at length, for instance, in Malm, *Fossil Capital*, pp. 121-222.

[75] Andreas Malm, 'The Origins of Fossil Capital: From Water to Steam in the British Cotton Industry', *Historical Materialism*, 21:1 (2013), 15-68 (18).

[76] For instance, see Jason Long, 'Rural-Urban Migration and Socioeconomic Mobility in Victorian Britain', *Journal of Economic History*, 65:1 (2005), 1-35.

[77] Daggett, *The Birth of Energy*, pp. 83-103.

[78] Jane Hutton, *Reciprocal Landscapes: Stories of Material Movements* (Abingdon: Routledge, 2019). This production footprint also extended to materials such as timber in the case of Britain. See Graham Wynn, *The Timber Colony: A Historical Geography of Early Nineteenth Century New*

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.[79] 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.[80] 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 if not surreptitious forms of slave labour. 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

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Brunswick (Toronto: University of Toronto Press, 1981); Pallavi V. Das, 'Railway fuel and its impact on the forests in colonial India: The case of the Punjab, 1860-1884', *Modern Asian Studies*, 47:4 (2013), 1283–1309. This also related to Costa Meyer's evocation of the theoretical categories of ontology and scale. See Costa Meyer, 'Architectural history in the Anthropocene', 1205-09.

[79] E. J. T. Collins, 'Food supplies and food policy', in Collins (ed.), *The Agrarian History of England and Wales*, VII, *1850–1914*, 2 vols (Cambridge: Cambridge University Press, 2000), I, p. 37; Rebecca J. H. Woods, 'Breed, culture, and economy: The New Zealand frozen meat trade, 1880-1914', *Agricultural History Review*, 60:2 (2012), 288. This production footprint also extended to materials such as timber. See Graham Wynn, *The Timber Colony: A Historical Geography of Early Nineteenth Century New Brunswick* (Toronto: University of Toronto Press, 1981).

[80] Malm, 'Who lit this Fire?, 223-48. See also, Andreas Malm, *The Progress of this Storm: Nature and Society in a Warming World* (London: Verso, 2017), pp. 19-20. For British coaling stations in practice, see Steven Gray, 'Fuelling mobility: coal and Britain's naval power, c.1870-1914', *Journal of Historical Geography*, 58 (2017), 92-103; G. A. Bremner, 'Tides that Bind: Waterborne Trade and the Infrastructure Networks of Jardine, Matheson & Co.', *Perspecta*, no. 52 ('Ensemble') (2019), 42.

inventions'.[81] 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.[82] Waterhouse's extensive use of machine-manufactured products such as terracotta and encaustic tiling are evident in most of his major commissions, including Manchester Town Hall (1868-77), and the Natural History Museum (1865-80) and 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.[83] This transformation in Britain resulted from the fundamental shifts in energy consumption outlined in the introduction. But the conceptual leap in terms of industrial science and technological innovation was equally significant. As the economic historian Joel Mokyr had 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.[84]

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[81] George Edmund Street, *An Urgent Plea for the Revival of True Principles of Architecture in the Public Buildings of the University of Oxford* (Oxford: John Henry Parker, 1853), p. 4.

[82] For Butterfield, see Thompson, *William Butterfield*, pp. 149-150; for Waterhouse, see Colin Cunningham and Prudence Waterhouse, *Alfred Waterhouse 1830-1905: Biography of a Practice* (Oxford: Clarendon Press, 1992), pp. 165-172.

[83] On this point the economic historian Joel Mokyr has observed that the conversion of heat energy into work via the steam engine was one of the most crucial advances ever made. See Joel Mokyr, 'Editor's Introduction', in *The British Industrial Revolution: An Economic Perspective*, ed. by Joel Mokyr (Boulder: Westview Press, 1993), p. 20.

[84] Mokyr, *The British Industrial Revolution,* pp. 19-20. On this point he adds that the breaking through of the separation between thermal and kinetic energy in the form of the steam engine was 'truly radical' (p. 20).

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, providing 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 6,000 miles had been constructed.[85] 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'.[86] 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'.[87] 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, for instance, just how crucially the development of the Victorian stone industry (to take but one example) relied on these technologies and networks, and thus just how much embodied energy its products contained. The rather sudden appearance of a hitherto near unobtainable array of decorative and common building stones, not just from within Britain, but from across Europe and the Mediterranean basin, in quantities and of a quality and at a cost that made them available for general use for the first time, was entirely dependent upon

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[85] Wrigley, *The Path to Sustained Growth*, p. 146.

[86] Wrigley, *The Path to Sustained Growth*, p. 150.

[87] *Dictionary of Energy*, ed. by Cutler J. Cleveland and Christopher Morris (Amsterdam: Elsevier, 2009), p. 191.

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.[88] This applied as much to marble and granite as to other common building stones.[89] It was also recognised at the time. 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'.[90] 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 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 coalesce, as Sigfried Giedion noted, with explosive force (i.e., the 'zoning' effect).[91] 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

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[88] For the rise and economic impact of steamship transportation in this period, see Charles K. Harley, 'The shift from sailing ships to steamships, 1850-1890: a study in technological change and its diffusion', in *Essays on a Mature Economy: Britain after 1840*, ed. by Deirdre McCloskey (London: Methuen & Co., 1971), pp. 215-237.

[89] Further specifics relating to marble can be found in, see G. A. Bremner, '"In bright tints … nature's own formation": the uses and meaning of marble in Victorian building culture', in *Radical Marble: Architectural Innovation from Antiquity to the Present*, ed. by J. Nicholas Napoli and William Tronzo (New York: Routledge, 2018), pp. 78-84. For Aberdeenshire granite, see T. Donnelly, 'Structural and Technical Change in the Aberdeen Granite Quarrying Industry 1830–1880', *Industrial Archaeology Review*, 3:3 (1979), 228-238.

[90] A. J. B. Beresford Hope, *The English Cathedral of the Nineteenth Century* (London: John Murray, 1861), p. 249.

[91] S. Giedion, *Mechanisation Takes Command: A Contribution to Anonymous History* (New York: Oxford University Press, 1948), p. 5.

effect was one of the key features of the energy revolution resulting from the industrial-scale combustion of coal during the Victorian age.[92]

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, on the whole, may 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 that 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, London (1866-77).[93] 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 (**Figure 4**). The facing

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[92] The issues and consequences of speed and time in this context are also dealt with in 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 forever. This was represented in the difference between what Mumford was wont to call 'eotechnic' versus 'paleotechnic' civilisation (alternative ways of expressing the difference between 'organic' and 'fossil-fuel' economies). As Mumford observed: 'During the paleotechnic period the changes that were manifested in every department of technics rested for the most part on one central fact: the increase of energy. Size, speed, quantity, the multiplication of machines, were all reflections of the new means of utilizing fuel and the enlargement of the available stock of fuel itself. Power was at last dissociated from its natural human and geographic limitations'. Lewis Mumford, *Technics and Civilization* (New York: Harcourt, Brace and Co., 1934), p. 196.

[93] For instance, for relations between the steamer economy and warehouse construction in the China Trade, see Bremner, 'Tides that Bind', 39-40.

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 (Figure 5).[94] 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.[95] There were some, for various reasons, who 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.[96] Pollution, too, was a key concern. Later, misgivings over industrial manufacturing and its effects on craftsmanship would become the *cause*

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[94] Ronald Firman *et al*, 'Brick, Stone and Iron: Building Materials at St Pancras', *British Brick Society Information*, 96 (April 2005), 5-20.

[95] For instance, see Malm's reference to Charles Babbage in Malm, 'The Origins of Fossil Capital', 15-16. Babbage referred to carbon dioxide as 'carbonic acid'.

[96] E.g. Vicky Albritton and Fredrik Albritton Jonsson, *Green Victorians: The Simple Life in John Ruskin's Lake District* (Chicago: University of Chicago Press, 2016), pp. 32-33; John Ruskin, *The Queen of the Air* (London, 1869). This moral concern might also be linked to Georges Bataille's observations on surplus energy within industrialised economies, which, when such economies reach their temporary limits, lead to enervating and potentially destructive consequences via 'luxury'. See Georges Bataille, *The Accursed Share: An Essay on General Economy*, vol. 1 'Consumption' (New York: Zone Books, 1988 [originally published in French in 1949]), pp. 35-37.

célèbre of William Morris and friends, as the Arts & 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. 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, generally speaking, but also significantly 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

> *Nous déclarons que la splendeur du monde s'est enrichie d'une beauté nouvelle: la beauté de la Vitesse.*
>
> –Filippo Tommaso Marinetti, 'Manifeste du Futurisme', *Le Figaro* (1909).

So announced Marinetti in perhaps the most famous line of his exciting, overheated, violent Futurist Manifesto of 1909. 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 40, 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.[97]

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.[98] He wrote of the 'new synthetic substances' that had contributed to the genesis of modernism, singling out 'steel, concrete, glass'.[99] 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

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[97] Italy's imports of coal rose rapidly from the 1870s to the start of the First World War. 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 15 May 2019.

[98] Germany's total energy consumption rose on an approximately exponential curve from the 1850s to 1914. See graph elaborated by Ben Gales , Paul Warde and Sofia Henriques for Kander et al, *Power to the People*: https://sites.fas.harvard.edu/~histecon/energyhistory/graphs/Total_Energy_Consumption_Germany.pdf, accessed 21 September 2020.

[99] Walter Gropius, *The New Architecture and the Bauhaus* (1925), trans. by P. Morton Shand (Cambridge, MA: MIT Press, 1965), p. 25.

intervening millennia.[100] 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 US, 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 tonnes in 1900 to nearly 15m by 1914, and over 30m in 1928.[101]

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 you use, 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.[102]

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[100] Effective metallurgy, glass-work, and mortar/cement technologies were in fact available for prestigious architectural projects during some pre-industrial periods (all three are present in every medieval Gothic cathedral, for instance, including the use of iron (not steel in this case) tensile reinforcement on a large scale at Bourges and elsewhere: Stephanie Leroy, Maxime L'Heritier, Emmanuelle Delqué-Kolic, Jean-Pascal Dumoulin, Christophe Moreau, and Philippe Dillmann, 'Consolidation or initial design? Radiocarbon dating of ancient iron alloys sheds light on the reinforcements of French Gothic Cathedrals,' *Journal of Archaeological Science*, 53 (2015), 190-201 (195-9).

[101] Thomas D. Kelly and Grecia R. Matos, 'Historical Statistics for Mineral and Material Commodities in the United States: Cement', US National Minerals Information Center: https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states. Accessed 21 September 2020.

[102] Iron production required temperatures of more than 1300^{0}C. Typical iron-smelting furnaces in the early 1700s in England produced in the region of 300 tons per annum of pig iron, having burnt an amount of charcoal that required 12,000 tons of wood. To produce that weight of wood sustainably required an area of hardwood coppices the equivalent of a circle 5km across. Overall annual production in 1720s was under 20,000 tons, requiring 1,100km^2 of coppiced hardwood to sustain it. The annual national production of pig iron of the 1830s, around 1m tons per year, would have required at least ¼ of the British Isles to be coppiced wood exclusively for smelting. See 'World history and energy', in *Energy Encyclopedia*, ed. by Cutler J. Cleveland, 6 (Amsterdam: Elsevier, 2004), pp. 549-561.

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'.[103] 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 be 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.[104] 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.[105] 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.[106]

Le Corbusier was just as stimulated by the other revolutionary new energy carrier that was taking off in France in the 1920s, electricity. The chapter frontispiece of the final

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[103] Le Corbusier, *Towards a New Architecture*, trans. by Frederick Etchells (New York: Dover, 1986), p. 63.

[104] 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 (318, n.5).

[105] Jerry Garrett, 'Voisin, Auto Innovator, Gets a Show of His Own', *New York Times* (3 June 2012).

[106] Thanks to Mark Crinson for pointing this out to us.

chapter of *Towards an Architecture*, 'Architecture or revolution', depicts a 40MW electrical turbine.[107]

Oil could replace coal-driven steam engines, manual labour or draft animals piecemeal, distributed initially 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 and, by the 1920s-30s, could link up separate electricity generators and users into networks spanning many hundreds of miles.[108]

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.[109]

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

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[107] Le Corbusier, *Towards a New Architecture*, p. 267. Other illustrations in the chapter continue the hymn to the revolutionary new industrial energy sources, including a racing car, an aeroplane, a battleship, a crane, a vast coal depot, an electricity turbine disc, an industrial ventilator, a Bugatti engine, and the electric-powered Lingotto car plant.

[108] Hughes, *Networks of Power*, pp. 363-364.

[109] Jacques Sbriglio, *Le Corbusier: The Villa Savoye* (Basel: Birkhäuser, 1999), p. 138.

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.'[110]

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.[111] The US-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, and additionally 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.[112]

Le Corbusier's 1920s and '30s 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, Portland OR, in the 1940s, and was indeed for decades important to effective control of mechanical ventilation.[113] Le Corbusier's preferred

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[110] Tim Benton, *The Villas of Le Corbusier 1920-1930* (New Haven and London: Yale University Press, 1987), p. 65.

[111] Rosa Urbano Gutiérrez, 'Le pan de verre scientifique: Le Corbusier and the Saint-Gobain glass laboratory experiments (1931–32)', *ARQ*, 17:1 (2013), 63-71; Harris Sobin, 'From l'Air Exact to l'Aerateur: Ventilation and Its Evolution in the Architectural Work of Le Corbusier," in *The Green Braid*, ed. by Kim Tanzer and Rafael Longoria (Abingdon: Routledge, 2007), pp. 140–152.

[112] Urbano Gutiérrez, 'Le pan de verre scientifique', 65.

[113] Meredith Clausen, 'Belluschi and the Equitable Building in History', *Journal of the Society of Architectural Historians*, 50:2 (1991), 109-129. Thanks to Daniel Barber for drawing our

glazed façade would have had a double skin, with heated or cooled air circulated through the cavity to maintain a steady 18C indoors. Urbano-Gutierrez 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.[114] The most famous of Le Corbusier's reverses with this idea was at the Paris Cité de Refuge, where 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.[115]

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.[116] The reality of their implementation in many of Le Corbusier's inter-war 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 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

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attention to Belluschi's importance to the story of energy and twentieth-century architecture, and to this article.

[114] Urbano Gutiérrez, 'Le pan de verre scientifique'.

[115] Luis Manuel Diaz and Ryan Southall, 'Le Corbusier's Cité de Refuge: historical & technological performance of the air exacte', Polytechnic University of Valencia Congress, LC2015 - Le Corbusier, 50 years later, http://dx.doi.org/10.4995/LC2015.2015.796 (p. 552). Accessed 21 September 2020.

[116] The concept of 'systems cultures', where demand, expertise, investment and infrastructure are required to drive and support adoption of a new technology, is set out in Hughes, *Networks of Power*, p. 15.

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 post-war decades.

The graph below (**Graph 1**) shows that 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 post-war period: 34% between 1959 and 1973 alone. 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.[117]

In cities around the world in the post-war 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

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[117] Kander, Malanima and Warde, *Power to the People*, p. 307.

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 1,943-seat concert hall could be used as a public square and outdoor sculpture gallery.

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 changed the relationship between construction and labour, reducing very sharply the amount of labour required and increasing the amount that could be achieved. A bulldozer today can replace around 10,000 preindustrial labourers.[118] 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 next door tower, roughly doubling the speed of their rival contractors there.[119] 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 20 times more productive than muscle-powered raising of components.[120]

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

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[118] Calder, *Architecture* (forthcoming).

[119] 'You could have your lunch while you waited for the lift to come up… If they [the contractor Myton's with the slow cranes] were earning a pound, McAlpine's should have been earning £2 per hour, because they were way faster'. See *Building the Barbican 1962 – 1982: Taking the Industry Out of the Dark Ages*, booklet published as part of 'Constructing post-war Britain: Building workers' stories 1950-70', University of Westminster, led by Christine Wall, p. 17.

[120] The Real Estate Record Association, *A History of Real Estate, Building and Architecture in New York City During the Last Quarter of a Century* (Record and Guide, 1898), p. 370.

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 light-wells, 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 post-war office: the economic pressure to redevelop was immense in any area with moderate or high land values.[121]

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 much other housing 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, preserving 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 post-war 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.[122]

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[121] Oliver Marriott, *The Property Boom* (London: Hamish Hamilton, 1967).

[122] 'One covered car parking space is provided for every flat in the South Barbican area. By present standards this is a generous provision and may be in excess of the demand during the first few years. Taking into account the ever increasing number of cars on the road and the type of tenant for whom the flats are designed, we have judged it wise to provide for this large

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, that keeps out the road's ill effects, but 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.[123] Most now also reject early High Tech's enthusiasm for planned rapid obsolescence, which would have seen major building components scrapped like rusty cars every few years and replaced. Yet if one looks at the trajectory of change over the previous two centuries in Britain, America or Japan, the tendency was clear: often 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, the disasters of Three Mile Island and Chernobyl and even the oil crises of the 1970s were still far in the future, and before the environmental impacts of fossil fuels we widely understood. 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.[124]

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number of vehicles. All car parking is situated beneath the podium out of sight of the flats. In all cases access from cars to flats is under cover and involves the minimum walking distance'. Chamberlin, Powell & Bon, Architects, 'Barbican Redevelopment', April 1959, quoted in: http://www.barbicanliving.co.uk/barbican-story/the-grand-plan/garages/, accessed 15 May 2019.

[123] Cedric Price and Joan Littlewood, 'The Fun Palace', *The Drama Review: TDR*, 12:3 (1968), 127–134 (132).

[124] Lewis L. Strauss seems to have been the first to say this in 1954: 'It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter.' See 'Remarks

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 the energy curve shown above 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 post-war 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 the extent to which our contemporary notions of what is 'normal' in architecture is 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 in the period 2011-13 than the global economic superpower, the USA, had used in the entire course of the twentieth century.[125]

Prepared by Lewis L. Strauss, Chairman, United States Atomic Energy Commission, For Delivery At The Founders' Day Dinner, National Association of Science Writers, On Thursday, September 16, 1954, New York, New York.' https://www.nrc.gov/docs/ML1613/ML16131A120.pdf (p. 9). Accessed 21 September 2020.

[125] https://www.washingtonpost.com/news/wonk/wp/2015/03/24/how-china-used-more-cement-in-3-years-than-the-u-s-did-in-the-entire-20th-century/?noredirect=on. Accessed 21 September 2020.

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 1870s-1930s New York, and 'mechanisation' in interwar Modernism, were all much discussed, and celebrated in architectural writing and practice, though 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 it is expressed in terms of cost of materials or labour, as a problem of lighting or heating, or framed as 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.