Beyond Energy Efficiency: The Emerging Era of Smart Bioenergy

Rachel Armstrong

The Power of Metabolism

> There is in biology a formula called "the equation of burning." It is one of the fundamental pair of equations by which all organic life subsists … All that is living burns. This is the fundamental fact of nature [1]

> … remember what we came for. The fire [2]

> … there is a magic deeper still which she did not know. Her knowledge goes back only to the dawn of time. But if she could have looked a little further back, into the stillness and the darkness before Time dawned, she would have read there a different incantation [3]

William Bryant Logan notices the paradox of the burning bush revealed by God to Moses and reflects on its meaning. He asks himself what it means for something to burn yet not be consumed by the process and concludes that what is being revealed is the fundamental transaction of living things—metabolism. In this process a creature processes the world around it, transforming it into energy to sustain life.

To date, the material narratives of "life" have centred on crystals (nucleotides) and molecular flows (metabolism); however, the material platform that makes them commensurate is the electron, which can combine these principles in a unifying manner that does not homogenise outcomes but enables variation. While electrons are considered classical agents in conventional physics and electronics behaving as flowing particles, they are also quantum phenomena behaving in nonclassical ways such as quantum tunnelling or demonstrating superimposition and entanglement (Einstein's spooky action at a distance).

More than the flow of "electricity" or "energy", the transfer of electrons around charged (or "valent") atomic nuclei is coupled with physical change.

R. Armstrong (✉)
Department of Architecture, Campus Sint-Lucas, Brussels/Ghent, Belgium
e-mail: Rachel.armstrong@kuleuven.be

A. Sayigh (ed.), *Towards Net Zero Carbon Emissions in the Building Industry*, Innovative Renewable Energy, https://doi.org/10.1007/978-3-031-15218-4_3

Electron transport chains enable these unique reduction/oxidation reactions and comprise the oldest systems of “life”. Having freed themselves from the solid structures of the rocks as geochemically produced organic molecules during the Hadean period, these energy-harnessing systems became portable in solution (acid/base couplings) and in the air. Embodying the enlivened reactivity of the living realm, electron transfer chains enabled lively matter to resist reaching the “brute” ground state of relative equilibrium and became enfolded within the internal environment of the earliest cells.

Chemist Ben McFarland emphasises the importance and material creativity of these forces:

> … when molecules fit together, they only care about two things: shape and charge. Shape is familiar—all atoms are spheres that can stack together like a supermarket display of oranges—but charge is unusual. Unless you work with wires or rub your feet across shag carpeting, you don’t normally see charge imbalances at our macro-level. But at the nanometre level, charge moves things around. Each atom is made of heavy protons with a positive charge and light electrons with a negative charge. When these charges are symmetric and balanced, the overall charge is neutral, but when they fall askew, a chain of domino effects can start, and chemistry can happen [4]

The changes produced by metabolism maintain the creature’s own body where downstream products—often smaller, biologically reusable molecules—are released back into the world for other life forms to make use of them.

Over aeons, the first creatures that populated the world such as bacteria and archaea have made developing a robust metabolism their speciality. In the case of bacteria this has happened at the expense of structural organisation, and they have evolved remarkable abilities that keep that electron transfer chain going. The most minimal kind of metabolism is produced by a continual flow of electrons, which prevents enlivened matter from reaching an energetic ground state or functional “death”. The bacterial species *Shewanella* and *Geobacter* directly harvest electrons from rocks and metals to make the universal energy storage molecule called ATP. This pared-down process is quite alien to all other life forms as they don’t need a carbon source (or sugar) for respiration. This means these microbes can thrive indefinitely by eating electrons from one electrode, using them as a source of energy, and then discarding them to the other electrode [5].

Electron transfer is not a solipsistic activity and can connect bodies at a distance from each other, offering a communications medium that enables microbes—and other organisms, like ourselves—to talk at a distance using action-potential mechanisms, which is characteristic of brain tissue. Waves of potassium-driven electrical activity traveling with constant strength enable communities of microbes to propagate signals at around 3 mm/h in tissue-like formations called biofilms, while our own brains work much faster at 100 m/s. In all species, these electrical signals enable the synchronisation of activities across large expanses and are much more powerful than their chemical counterparts as communications systems—which may be likened to “the difference between shouting from a mountaintop and making an international phone call” [6]. The ability to operate at a distance from a locus of metabolism introduces notions of time, space, and anticipation—the foundations of all complex thought.

How we think about and use electricity today is encapsulated by two very different approaches.

"Life" became equated with electricity through Luigi Galvani's (1737–1798) "animal electric fluid" experiments, where he demonstrated the presence of bioelectricity in frog dissections. Regarding this force as responsible for the vitalisation of tissues, his findings were largely enfolded into the life sciences to begin the neurobiological revolution.

Responding to Galvani's experiments, Alessandro Volta (1745–1827) found other ways of producing electricity using metal electrodes and chemical sources which generated high voltages. The catalyst for the electronics revolution Volta's research provided the power and intelligence that underpins the modern industrial age, around which we have imagined and design our relationship with electricity.

Galvani's organic electricity operates through a very different quality of electron flow than Volta's. It is slower, more agile, less forceful, and can be handled by atomic "jugglers",[1] so bioelectrical transactions occur that perform metabolic work, inviting a new set of imaginaries than industrialisation, or modernism. As "life", not top-down control, or consumption, is at the heart of these principles, these electron currencies are constrained by biological principles, establishing the possibility of a new thermoeconomics as the foundation for a regenerative society [7]. When produced metabolically, the natural bioavailability of electrons establishes limits for production systems so that matter and energy are coupled (not cleaved) and are synthesised in a circular context. This means that every material ecology can be strategically metabolised using bioelectrical systems to perform all kinds of useful work, without "borrowing" unlimited resources from next generations or elsewhere.[2]

The Frankenstein Fallacy

The Frankenstein fallacy assumes that if we throw enough electrical power at an inanimate body, then it will spring to life.

When a forceful river of new electrons is launched at a troupe of jugglers, however, it puts the juggling act off balance and may stop it altogether. Electrotherapies only work when the influx of juggling objects (electrons) can boost the actions of dysfunctional jugglers that have dropped too many balls and are not performing at all well. The power to respond to the influx remains with the jugglers, as they are still motivated, and sudden bombardment with new juggling objects may persuade

[1] The "juggler" metaphor is used to indicate the dynamic orbits within an atom that enable the movement of electrons.

[2] For example, through their combustion fossil fuel-based systems overwhelm contemporary ecosystems with "old" sources of carbon.

them to keep going. The moment that the jugglers give up, then no matter how forceful the flow new objects into the system is, they will not start again.

As Galvani's dissections were recently prepared and the creatures newly deceased, the atomic jugglers were still willing to move objects around for a while, proving his animal electricity hypothesis. However, the force of electrons used in Volta's setup is not designed for organic bodies but brute[3] metal ones. Forming a matrix through which outer electrons can move freely instead of orbiting their respective atoms, metals are excellent conductors of electricity and heat, but their electrons are not in a context where they can perform the work of life (where atoms are spontaneously transformed by electron flow). Massive unsustainable flows of energy in conductive materials are therefore needed to animate "brute" matter, and once the circuit is turned off, this vigour is not sustained.

The Long Latency of the Bioelectrical Revolution

Galvani's organic electricity operates through a very different quality of electron flow than Volta's. It is slower, more agile, and less forceful. It can be handled by atomic jugglers, so bioelectrical transactions occur that perform metabolic work, which invite a new set of imaginaries than industrialisation or modernism. As "life," not top-down control, or consumption, is at the heart of these principles, then these electron currencies are constrained by biological principles, establishing the possibility of a new thermoeconomics. When produced metabolically, the natural bioavailability of electrons establishes limits for production systems so that matter and energy are coupled (not cleaved) within a circular context. This means that every material ecology can be strategically metabolised using bioelectrical systems to perform all kinds of useful work, without "borrowing" unlimited resources from next generations or elsewhere.[4]

Significantly, bioelectricity can cross the mechanical and organic divide, permeating both platforms, but operates at much lower power levels than generated by fossil fuels or renewables. What it lacks in quantity, however, it makes up for in the quality of its operations, inviting an era of low-power (bio)electronics.

In 1911, Michael Cressé Potter brought these organic and mechanical electrical worlds together in a "living" battery, or microbial fuel cell (MFC), that used the vital processes of *Saccharomyces* bacteria to produce several hundred millivolts of energy [9]. Acting as biocatalysts, the microbes convert the chemical energy of organic matter from waste streams into electrons for as long as they continue to be fed. Each "cell" consists of two compartments, the anode and the cathode, which are separated by a proton-exchange membrane. Bacteria anaerobically oxidise the

[3] In a letter to Richard Bentley, Isaac Newton uses the term "brute" to refer to an inert body [8].

[4] For example, through their combustion fossil fuel-based systems overwhelm contemporary ecosystems with "old" sources of carbon.

organic matter in the anode chamber to release electrons that flow through an external circuit to provide electrical power. Acidic protons are also produced, dissolve into solution, and pass through the membrane into the cathode, where they react with oxygen to produce fresh water. This highly mediated relationship sets up a power-sharing relationship across mechanical and natural bodies that is neither entirely biological nor exclusively mechanical. Constituting the essence of zoë, the microbial fuel cell blurs the relationship between organism and machine to form a type of cyborg "being" with microbial flesh that thrives on different types of organic fuel. Supported and directed by a technical environment, they perform a range of metabolic tasks at room temperature such as cleaning wastewater, generating bioelectricity, and detoxifying pollutants.

While bioelectrical systems like the microbial fuel cell (MFC) cannot compete with the sheer power of other electricity generating systems (renewables, fossil fuels), their (material) circularity is unsurpassed providing essential natural limits to our consumption. Metabolic transactions have helped build the soil and air, creating the biological economy that founded a carbon-based exchange between living things. Life has sustained itself thus since the dawn of biogenesis. These are not, however, the principles on which modern society and the building industry are based.

Buildings are designed to shelter us from uncertainty and danger outside. In the modern world we spend 90% of our time in these spaces. While buildings are erected as barriers that control what comes in and out of our artificial worlds, the natural world necessarily interpenetrates them. Fluid elements leak through windows and doors while shifting layers of metabolism that comprise our very acts of daily life consume resources. In deep time, urban ecosystems turn over the many bodies and buildings that form its landscapes, complicating the relationships between them and rendering impermanent the very notion of a city. Percolated by the flow of space and time, no walls can stop our lives from being changed by the world's events. Spending about 2% of the total economic value of our homes per annum, we maintain the illusion of security through distributed acts of building maintenance. Drawing comfort from our separatism and human exceptionalism, we've grown blind to those systems and resources beyond the domestic sphere that we consume daily. Measured and capitalised, a variety of natural utilities and services appear in our kitchens and bathroom, seemingly from nowhere, making themselves available for our consumption. Placing only financial demands upon us, they never ask to be replenished. So, our distance from nature grows, and our exclusively human bodies seem ever more secure in their integrity, identity, and independence from the world outside.

Tearing up the anthropocentric order of things, the climate crisis shatters these cosy architectural conventions and fully exposes us to the actual "outside". Although such an outcome has been inevitable for many decades, we remain woefully unprepared. The Anthropocene, a cultural epoch of our own design, has force fed carbon-industrial foie gras[5] on the world's ecosystems in the name of progress, extinguishing

[5] *Foie gras* means "fatty liver".

the very forms of life that we depend most on. The most vulnerable and smallest agents have suffered first: pollinators, reefs, fertile soils, “weeds”, clean air, and oceans, setting in motion a system of collapse that characterises the Sixth Great Extinction and has damaged the planet’s fundamental capacity for self-repair. With collapsing ecosystems, the comforts of modernity are no longer available in the way they used to be, and the systems by which we trade and govern no longer apply. “Freedom, justice, equality, truth—all these things are distant memories by now, as is an age where people took such things for granted. The idea of civilization as we know it has come to an end” [10]. Masked by our extreme exploitation of every resource, with few gestures of re-investment, we have crippled planetary resilience to the point where geosystems are transitioning into new kinds of order that are not of human design. More than increasing outbreaks of extreme weather events, pandemics, wildfires, quakes, heatwaves, droughts, mudslides, and tornadoes—all heightened by the climate crisis—they embody a “profound mutation” in our relationship with the world [11].

> When I was around bustling crowds of people, I saw death and destruction. When I walked on dry land, I saw floods. I imagined wild animals, especially snakes, getting out of the zoos in the aftermath of natural disasters. I worried about how we would treat each other in the face of such calamity. I doubted it would be kind [12].

Although we are consuming our planet at such a speed that it cannot renew itself, our response to this situation is shockingly feeble, and this paralysis is deeply troubling.

> I think in many ways that we autistic are the normal ones and the rest of the people are pretty strange. They keep saying that climate change is an existential threat and the most important issue of all. And yet they just carry on like before. If the emissions have to stop, then we must stop the emissions. To me that is black or white. There are no grey areas when it comes to survival. Either we go on as a civilisation or we don’t [13].

There are far more questions than answers to this predicament. While we’ve stolen untold resources from the planet and even from our own children [14], it’s not too late to start giving our descends their future back. When it once appeared that total global warming should be kept below 2 °C or as close as possible to 1.5 °C above pre-industrial revolution levels, it seemed reasonable to simply reduce our emissions as well as reusing and recycling resources at “sustainable” levels within the present economic order. Governments and businesses have even promoted Green New Deals of various descriptions, but even the most radical of these operate from within the systems that continue to contribute to climate change. Expressing sympathy for the cause is an empty gesture as their capacity for radical change is limited. With our present trajectory set to go above 3 °C or 4 °C, “tipping points” in our planetary system are visibly being reached, which means that radical breaks from the current system of production, consumption, and economic order are urgently needed. Exactly how long we have before the world becomes unliveable is unknown: for some, that point is already here. In the best-case scenario, we may only have 10 years to transform global society to reasonably limit the catastrophic impacts of climate change [15].

> Things are already bad. They are already getting worse. This report reveals—and, for many of us, confirms—that we're not doing nearly enough to stop things from getting damn apocalyptic [16].

The scale of the challenge is immense. Rather than being able to take actions ourselves, it appears the ways of dealing with the crisis are somewhere out there where "moonshot" technofixes abound. Geoengineers aim to prevent glaciers from collapsing using scaffolding made from sand; oceanic fertilisation is set to absorb vast quantities of carbon dioxide by stimulating the growth of phytoplankton; stratospheric mirrors and cloud manipulators strive to prevent sunlight from reaching the ground, and innovators have developed a whole range of products including ocean trash-eating robots, carbon-fixing materials, and artificial trees. While exciting and welcome, all these developments rely on institutions and agencies that operate beyond our own realm of influence.

> The dominant narrative around climate change tells us that it's our fault. We left the lights on too long, didn't close the refrigerator door, and didn't recycle our paper. I'm here to tell you that is bullshit. If the light switch was connected to clean energy, who the hell cares if you left it on? The problem is not so much the consumption — it's the supply. And your scrap paper did not hasten the end of the world.
>
> Don't give in to that shame. It's not yours. The oil and gas industry is gaslighting you [16].

Since our house is on fire [13], we must start the reconfiguring of our lives in the home. While we already limit our domestic energy consumption, recycle our waste, and reduce our consumption, as in the case of the Green New Deals, all these approaches are inescapably entrenched within our present economic frameworks and comfort zones. Even from the comfort of the domestic realm, we are treading the same pathway towards planetary destruction that has already been mapped out by industry—albeit more slowly, self-consciously, and considerately. To achieve a radical break from our present trajectory, a reimagining of those activities of daily life that maintain us, zoë, is needed, alongside a reappraisal of the values that uphold the good quality of life we seek, bios.

As citizens of modern societies, we are bound by those frameworks that shape how we live and work. Our non-innocence in the present situation means we must consider allies in the more than human world to meet the present challenges. While applications of fire powered by fossil fuels have brought great innovations into our homes, they have not conferred the kind of wisdom needed to bring about planetary enlivening. To step beyond these malignant processes requires a new kind of technology and fundamental metabolism that is not built on consumption but tempers the production of work with environmental enlivening. Such a technological system seems far away, corporate, or even magical, but, in fact, it is so close, obvious, and reliable that it is taken for granted. While everyday events within our living world seem commonplace—leaves seasonally sprout and fall, food is digested, wounds heal, the young become old—when considered from a cosmic perspective, each and every one of them are extraordinary.

How We Will Incorporate Nature into Our Homes and Cities

Only by working with the biological processes of metabolism can we close the loop of consumption to stay within the resource limits of a site, with the benefit of actively managing our waste. We are not the masters of this knowledge domain, but microbes are.

Microbes have a unique individual identity, as well as a larger collective one. Some are commensals, some symbiotic, and around 1400 species are pathogens. While this may seem like a large number, they account for much less than 1% of the total number of microbial species on the planet [17]. The most remarkable characteristic of a microbe is not their form but their fluid metabolism, which is modulated via the environment through redox chemistry, which is the environmental program that enables microbes to rapidly alter their metabolic (and genetic) networks that they can use to completely transform their environment.

> Life loves redox chemistry because it is mild and controllable [18]

More than the flow of "electricity" or "energy", electron transfer is coupled with physical change. The loss or gain of electrons, or change in the charge of a molecule, alters its physical properties. Comprising the oldest systems of "life", biological electron transport chains freed themselves from the solid structures of the rocks during the Hadean period. Taking the form of geochemically produced organic molecules, these energy-harnessing systems became portable in solution (acid/base couplings) and in the air. Embodying the enlivened reactivity of the living realm, electron transfer chains now enabled lively matter to resist reaching the "brute" ground state of relative equilibrium to become enfolded within the internal environment of the earliest, leaky compartment of cells, resulting in the kinds of dynamic chemical interactions that comprise the living realm.

Introducing an Emerging Platform: Microbial Technology

You may not think of nature as a technology, but radical new insights about the microbial foundations of the living world means we can understand and work with them as a creative and regenerative force.

> Although the tiniest bacterial cells are incredibly small, weighing less than 10^{-12} grams, each is in effect a veritable micro-miniaturized factory containing thousands of exquisitely designed pieces of intricate molecular machinery, made up altogether of one hundred thousand million atoms, far more complicated than any machinery built by man and absolutely without parallel in the non-living world [19]

Consequently, a new age of "living" technologies is emerging. Powered by microbes, these "living" technology platforms can process our waste, turning it into electricity and cleaned water and can detoxify our surroundings. Orchestrated microbial activities can therefore form the utilities systems of our buildings, generate new, organic materials [20], and dramatically alter the impacts of human development, so our collective daily activities are bioremediating rather than harming the environment.

Historical Relationship with Technology Frames Our Future Trajectories

Dancing with the demon of fire, the sacred being that gave us the first artificial metabolism, we could exceed the wet heat of the flesh experienced through proximity to metabolising bodies. Fire is a demanding god that consumes all it is fed to ashes and in return gives us power far beyond our biological means. It's greedy, dry, harsh combustion readily transformed organic substances such as fuel and food, from one sort into another. Gathering around this magical transformer and its unnatural light, early human societies sought to instrumentalise its multiple powers and set out to direct its actions towards specific tasks—from generating heat to finding their way in the dark and making food more palatable and digestible. While raw foods yield just 30% or 40% of their nutrients, cooked food releases everything. Suddenly, having a large brain stopped being an evolutionary liability and became an asset. By gaining the necessary nutrients more easily, people could start to imagine better ways to hunt, live, develop culture, produce art, and invent early technologies—all the things that made us who we are now [21]. Nomadic peoples quickly acquired the knowledge for making open fires, while settlers formalised these spaces within the area of communal activity that became known as the kitchen—the traditional and symbolic heart of the home.

Increasingly instrumentalised by regulating the flow of air, organising space, selecting the right materials, and designing implements to instruct fire in different ways, each culture developed their own processes and rituals. Using heat to prepare food was most the important activity for communities, being associated with rituals of gathering, preparation, cooking, dining, cleaning, socialising, ablutions, and the disposal of leftovers. While powerful, fire was also a voracious entity demanding food—predominantly wood, maintenance, and regulation so that in its voracity, it did not leap from its place in the home to burn the entire house down—which it frequently did. Early hearths were therefore made of clay or stone, their main purpose being to enclose the fire. Looking after this beast was a commitment. Demanding constant attention, it needed stoking in the morning, modulating during the day and turning safely back into glowing embers at night. Entangled with the preparation of food, the complexity of these activities was balanced by what those people responsible for them could achieve in a day. Tempered by a baseline liveability that varied from home to home, the activities around the fireplace shaped the designs of hearths and ovens, informed where kitchens were located, and spawned the development of other important household areas associated with the preparation of food such as the pantry, orchard, garden, larder, icehouse, root cellar, and medicinal herb garden. Like electrical capacitors, the kitchen fire's work could also be stored, and the earliest containers of its cooked products were animal skins, woven baskets, or gourds.

Traditionally a matriarch ran the household economics and domestic affairs, where the kitchen was central both as a workshop but also a meeting place between classes and organisational power structures. For ancient Greeks and Romans, the kitchen was designed as a separate house, with clearly defined preparation areas for turning food from city gardens into meals. By medieval times, wealthy European homes had large kitchens with dedicated rooms such as for storing utensils, pantry, cold storage, and a buttery. More commonly, kitchens were the centre for communal cooking, dining, and social activities. During the Renaissance, a range of technologies of food preparation flourished for new types of cooking that coaxed fire's participation in different ways using the spit, gridirons, ewers, salvers, and huge cauldrons. These innovations catalysed new methods for food preparation and storage during the winter months using a range of desiccating techniques like curing, drying, smoking, pickling, and salting.

Nineteenth-century kitchens embraced the Industrial Revolution, whose fire thrived on a new kind of concentrated energy obtained from fossil fuels. This freshly unleashed demon lurked in petroleum basins formed from decomposed flesh still dreaming of tarry insurrection against the rotting Sun. [22] Its capacity for intense burning intensified the demands of fire and made possible new materials such as cast iron, which could tolerate drastic temperature swings and was an ideal medium for casting into complex, prefabricated parts decorated with surface ornament. Benjamin Thompson, better known as Count Rumford, revolutionised the technology of fire and design of the kitchen by taking the open cooking fire from the hearth and constraining it within a cast iron box. Topped by a flat, perforated surface, accessed through round ports of different sizes, the fire contained below could be spatially directed to heat specially designed pots and pans that were designed for these new ranges. Requiring less surveillance and space, the machine-like fireplace, however, obliged an industrial metabolism to catalyse its intense activities. Natural gas, used by the lighting industry, followed by advanced in electrical power sources, enabled the development of lighter, smaller, and even more effective appliances that could burn beyond the full fury of an open hearth—even in the smallest of homes [23]. Even from within their boxes, the twin demons of fire and fossil fuel continue to indulge their appetites. Assumed to be securely under human control, their endless demands began to consume our world.

The rise of modern agriculture and modern manufacturing fuelled the twentieth century marketplace, rendering obsolete the need for self-sufficiency in food production. By the 1930s, the number of kitchen staff as well as the size of kitchens and pantries was reduced in most homes. A rapidly changing modern workforce spent less time in the home and more at various kinds of workplaces, where convenience foods were bought and consumed, eliminating the need for the socially productive role of the kitchen. While it remains the symbolic centre of the home, the twenty-first century kitchen's foundational technology of fire is assimilated into global power grids, and no longer draws us like moths, to its flame. If we are to curtail its consumption of our planet, then we must find new kinds of energy, or power, with which we can ally that enable us to live better with the available resources of the word and unmake our pact with demons.

MFCs directly contribute towards sanitation improvement and double up as remote energy sources, fuelled by waste, for low-power applications in rural, off-grid settings. The potential for simplifying complex processes, through digitisation and interactive decision-making apps, could result in wider interest, enhanced public acceptance, demand for, uptake of, and investment in large-scale development of the technology in the market.

This overall approach of harnessing microbial metabolisms also opens up new frontiers in low-power electronics that can be run by bioelectricity produced by the system, as well as the science of programming microbial biofilms[6] and consortia,[7] which establish the principles for designing metabolic "apps", where microbes that do not normally work together are able to collaborate for the first time, enriching the potential for metabolic design.

Living Architecture's combined effects can alter the character of our living spaces—from environments that merely consume resources—to spaces that link the webs of life and decay to provide for our needs, refresh our atmosphere, and reduce the circulation of toxic compounds, such as detergents in our waterways. Like the exchanges between the first forms of life, the way that webs of biochemical exchanges are orchestrated can increase the liveability of a space by, for example, sequestering heavy metals and breaking down nitrous oxide. Beyond their capacity to act as remedial systems, by actively transforming domestic wastes into useful outputs they generate resource, which enables them to be accordingly revalued within the domestic economy.

The ability to choose and nurture the specific metabolism of our living spaces will alter our lifestyles and the way we inhabit our homes. As "living" architecture is founded on the mutual relationships between microbes and humans, how we care for our living spaces will deeply influence their performance. With the advent of many more "apps", residents will be able to select and nurture a unique character for their homes that—in exchange for being sensitive to the system's wellness—is capable of meeting specific needs such as producing medicines, recycling organic matter into edible biomass, or producing liveable amounts of electricity and heat. While local conditions and resource availability will constrain the performance of metabolic "apps", innovative combinations may enable a small range of possibilities to achieve unexpectedly desired outcomes, such as generating bioluminescence to provide low-level, mood-elevating lighting. In whatever way "living" architectures are deployed, they will require our conscious engagement with them, so they can learn about and respond to our needs. "Living" architectures will wake up with us, go to sleep when we do, will cope with our intimate habits, and will even be

[6] A biofilm is a mixed cohabiting community of microorganisms.

[7] Microbial consortia are populations of one kind of microorganisms and are not mixed as in biofilms.

re-enlivened by our return after a holiday break—"as if" they are "pleased" to see us. Through the care and conscious design of their metabolisms, inhabitants of living architectures will differently understand the character of our homes, what they can do, and establish our responsibilities for them.

Domestic buildings will no longer be a projection of our own desires upon them but beings in their own right that belong as much to a community as we do. Through a choreography of material relationships, different degrees of freedom for metabolic "apps" will be increasingly able to carry out different kinds of functions within homes and community spaces. Capable of evolving through space, time, and alongside their relationships with other beings, their metabolic exchanges will be at the heart of an environmentally concerned architectural practice that gives rise to an increasingly lively world.

The existence of these metabolic approaches and programmable, "living" technologies that can be incorporated into domestic spaces, as in the Living Architecture project, has implications for the development of our homes and cities, since they change the concept of sustainability. Exceeding the conventional disciplinary limits of architecture in making a building, they expand the practice to restore the health of the biosphere through the incorporation of living technologies into our homes, buildings, and cities. No longer designing for bounded plots, architects are concerned with the impact of their designs and interventions on whole bioregions.

Citizens are empowered to customise and modulate the impacts of their lifestyle choices from a diverse range of metabolic apps, which are a form of economy and key to customising the performance of microbial colonies to meet people's needs, while enabling significant changes in energy flow, water, and waste through homes and cities. By adopting such technologies, buildings will require richer networks of elemental infrastructures that modulate the flow of water, air, and material resources, to become sites of nutrient recycling and resource processing. When networked together, these combined, programmable metabolic processors have the potential to alter the nature of resource utilisation in cities.

As the technology develops, specific building metabolisms will be available from a diverse range of microbial and bioreactor choices. The aim is not to homogenise or universalise the ways that cities and their people live but, through the programmability of microorganisms, diversify approaches in ways that enhance the quality of urban environments. We also need to look at much larger-scale applications of microbes and extend our understanding of them, so they violate binary divisions and distinctions between the built and natural environments—like artificial reefs and mangroves—that increase biodiversity, clean the water, and stabilise land erosion. With the right governance, networks of bioprocessing units will begin to benefit ecosystems, remediate our ailing atmospheres, and, ultimately, improve the health and well-being of our cities and their inhabitants.

Benefits for generations to come may include increasing the biological quality of urban environments through the production of microbial biomass, eventually even replacing all fossil fuel-based appliances with organic systems. The major "waste" outputs of such "living" cities are the antithesis to modern cities such as cleaner waterways and composts. Enabling more green plants in metropolitan locations, which are climate moderators, in turn conserves water, improves soil and air quality, produces oxygen, absorbs carbon dioxide, and traps dust particles. In effect, the incorporation of "living" metabolic technologies into our daily routines gives us a chance to make human development more compatible with nature.

The "Living" Home: Our Households Become a Circular Economy

> We ate the birds. We ate them. We wanted their songs to flow up through our throats and burst out of our mouths, and so we ate them. We wanted their feathers to bud from our flesh. We wanted their wings, we wanted to fly as they did, soar freely among the treetops and the clouds, and so we ate them [24].

Our modern lifestyles promote a culture of obligate consumption. In our homes we produce almost nothing for ourselves, and as producers of this world we are obsolete being responsible not only for widespread environmental destruction—from deforestation to industrial-scale agriculture and mining practices—but also for the associated loss of biodiversity that our insatiable appetites promote.

How might a bioelectrically centred culture of life that works with the creative constraints of metabolism appear?

The *Living Architecture project* is a "living" combined utilities infrastructure that can turn liquid household waste, like urine and grey water, into valuable resources (electricity, biomass, water, reclaiming phosphate from washing-up liquids and removing poisonous gases from the air) that can be reused in the household (Fig. 1). This movie envisages the prototype's installation into a modern building. Here, it cuts down on electricity and utilities bills, as well as the amount of untreated waste we put into the environment. Potentially replacing fossil fuels as the main source of energy in a home, this series of linked bioprocessors can charge a 12 V battery supply.

When combined with renewables, microbial technologies create value by bioremediating our waste and even produce an ecological currency for exchange, just by the activities of daily living. So by eating, going about our routines, and doing our ablutions, the wastes we produce have economic value—even when our lives are spent at home. How a home could be constructed from a posthuman household inhabited only by microbes and the digital ghosts of the past, present, and future was prefigured in the installation 999 years, 13 sqm (the future belongs to ghosts), a collaboration between Cecile B. Evans and Rachel Armstrong (2019), using a microbial fuel cell array to power the infrastructure of the space and projecting a way forward through which the transformation towards our emerging ecological era can begin (Fig. 2).

Valuing the contributions by all who carry out the work of life—the different microbial units that make up the Living Architecture system—enables those that are not usually regarded as economically productive in a capitalist economy to take part in an ecological economy. Re-centring the site of value creation within the domestic

Fig. 1 Fully inoculated Living Architecture “wall” and apparatus installed at the University of the West of England, Bristol. (Photograph courtesy of the Living Architecture project (2019))

sphere, our homes become wealth generators. Inhabitants now have choices to make about how they use this ecological resource—perhaps they can reduce their own living costs, but, maybe too, they can donate some of their well-earned resource (formerly called “waste”) to help others and activate the commons.

Active Living Infrastructure: Controlled Environment (ALICE)

While Living Architecture establishes a metabolic economy for transactions between humans and microbes, the Active Living Infrastructure: Controlled Environment (ALICE) prototype (2019–2021) generates the foundations for collaboration with microbes. Using electrons produced by the anaerobic biofilm of microbial fuel cells as “data” provides a direct link between bacterial metabolism and electronic systems that can interpret and visualise this data. Possessing a very particular kind of environmental intelligence, bacterial data can reveal a great deal about the character of a place, where a technologised approach can generate a relatable communications interface (Fig. 3).

Fig. 2 The installation 999 years 13 sqm (the future belongs to ghosts) is a collaboration between Cecile B. Evans and Rachel Armstrong for the Is This Tomorrow? Exhibition at the Whitechapel Gallery, London. (Photograph courtesy Rolf Hughes (2019))

Typically, microbial activity is deciphered using the tools of biochemistry, but in human terms the interpretation process is quite slow. Tapping into the much faster electron flows within biofilms, however, provides a direct way of understanding the behaviour of a microbial population at any given moment and, depending on the sensitivity of electrodes, creates the possibility of developing a communications platform between human and microbe (Fig. 4). Electrical activity from the biofilm was a source for both power and data, which was translated by software into animations that conveyed the overall status of the biofilm in relatable terms. Audiences could, therefore, respond to the microbial behaviour—not by looking at unpleasant "slime" (the natural "face" of microbial colonies)—but by interacting with appealing forms on a familiar screen-based interface. Participants could play with resident microbes through data and performance in an exploratory exchange—as if they were a pot plant or even a pet. This world of "Mobes"—a characterful term coined for the data-based representations of microbes—offers a simple, probiotic approach to interspecies communication within the highly situated realm of microbes, in a relatable manner that could even become part of our everyday routines. Being in conversation—rather than "exploiting" microbes—means we may start to learn along with them through their ability to generate clear and direct signals and data that relate to shared concerns, like transforming waste streams into household resources based on new value systems that invite different kinds of (house)work and domestic routines for our living spaces.

Fig. 3 ALICE installation at the Digital Design Weekend, Victoria and Albert Museum, London, 26–7 September 2021, a cyborgian entity powered entirely by microbes with a concurrent online "life" which embodies the bio-digital platform through the integration of microbial and artificial intelligences with biological and technical bodies. (Courtesy of the ALICE consortium: Ioannis Ieropoulos, Julie Freeman, & Rachel Armstrong)

The "Power Plant": Activating the Commons

While *Living Architecture* shows that a circular economy of the household is implementable, we have not yet figured out the economies of scale. It is likely more efficient for many households to contribute to a shared resource through their waste and what better site to process this than a garden—turning them, literally, into *power plants*? By scaling microbial operations in ways to serve a whole community, we can provide access to resources that can be allocated according to need. Working with Hungarian company Organica Inc. that designs urban wastewater gardens for municipal use, starting with human sludge, which is passed through a series of vats that break down the organic matter using the microbes on the roots of plants, our group proposes to introduce the electricity-generating microbial technology called the microbial fuel cell—a "living" organic battery—into this system, which can also be powered by the organic waste. This means such an installation could not only treat the human residues for between 5 and 30,000 residents with no access to a formal sewage system but that sludge could also generate enough bioelectricity to power mobile phones, provide LED street lighting, power Wi-Fi transmitters, and activate screen displays that enable citizens to access—for example—websites to online council services, while also enjoying the benefits of a public garden and

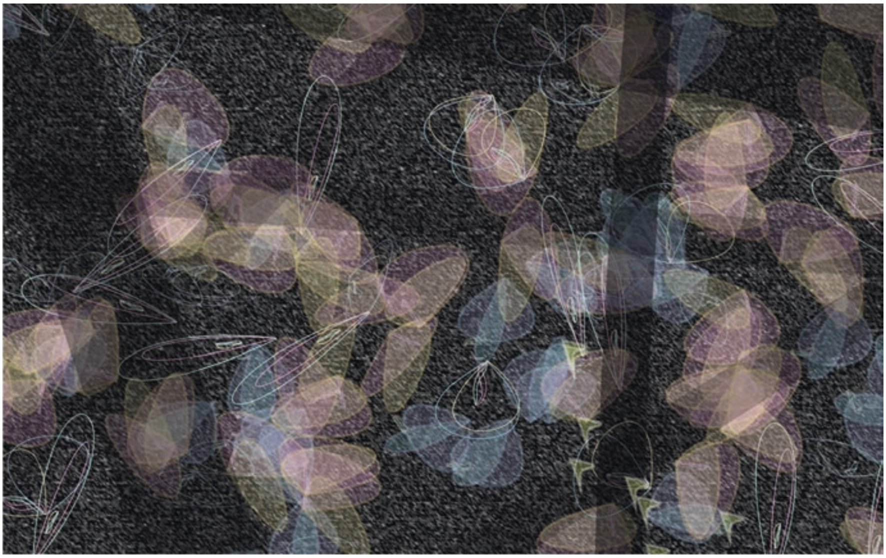

Fig. 4 "Mobes", from the ALICE website (http://alice-interface.eu) showing dynamic, interactive, graphical representations of microbes. (Courtesy of the ALICE consortium (2021))

harvesting the organic produce it provides as you would in an allotment. By creating an opportunity for citizens to share space and find things in common with each other, this platform is a big stepping point towards activating the commons, where the organic matter we call "waste" becomes a shared and flexible resource. Through harnessing those natural processes, which are taking place continually in the soil, this sludge can be turned into useable end products (vegetables, cleaned water, electricity) as well as provide a pleasant public space.

Microbial Sentinels: Keeping Us Safe

One of the intriguing aspects of working with our waste is that microbial technologies can not only make it useful but safe. During the coronavirus pandemic, one way of testing the prevalence of the virus in the broader population was to sample material from the sewers. As you have just seen, microbial technologies are powered by this very waste and, as it were, can keep an "eye on" its composition. Even more importantly, these stable communities of microbes can intervene when needed. This graph shows that when organic waste is recirculated through a microbial fuel cell, it not only produces bioelectricity but also removes pathogens, becoming a first-line, external immune system comprising a breakthrough for the sanitation industry, with very interesting possibilities for how we manage viral circulation during times of pandemic, and in the longer term, these same systems can play an active role in monitoring our health—either at both the individual level and also in the community [25].

Natural Bioremediation in Urban Spaces: Revitalising Brownfield Sites

If we take these microbial technologies out into other parts of the city, we can also strategically use them to remove toxic substances like heavy metals and noxious organic compounds from post-industrial sites. By laying down a membrane and washing the soil in situ, microbes can do the cleaning for us while contributing to the natural environmental healing process. As contamination is just another form of "food" to microbes, we harvest their bioelectricity to power sensors while they metabolise toxins, and using artificial intelligence to observe the cleaning process, we can gather data, link it to other "smart" systems, and so enable the entire bioremediation process to be computationally regulated.

Towards the Off-Grid City: Empowered and Mobile Communities

Ultimately, microbial technologies free us from the static infrastructures of modern cities and the utilities they provide. At a time of climate crisis and the displacement of peoples everywhere—such as during times of severe flooding—having access to clean water, shelter, power, and sanitation can literally save lives. Bill Gates' vision for microbial technologies is to build mobile settlements that are entirely off grid and can house up to 30,000 people—and the underpinning technology Pee Power has demonstrated this potential at Glastonbury for the last 5 years. So, while Gates' vision is specifically for refugees in developing countries, these principles are also transferrable to our Western homes, communities, and commons. Perhaps the most radical step suggested by these microbial technologies is to challenge our basic assumptions about the baselines of what we need to live comfortably and healthily. Imagine the reduced impact of human development if every home that is now connected to a 230 V grid could operate comfortably on a 12 V battery supply. While this would require innovation in some of the things that we do every day that we solve by consuming a lot of energy, like washing machines and fridges, these same tasks could be done differently, such as using advanced new materials to help with refrigeration and finding alternatives to mechanical agitation like ultrasound to carry out this housework. The hardest part to altering our impacts is changing our thinking, our habits, and our concepts of what a "good life" actually entails. Whether we like it, or not, the rules for living on this planet have changed. The good news is that microbial technologies can help us make the necessary adjustments to work within the carrying capacity of our lands, draw on our collective creativity, and help us find much, much ways of better working alongside nature. The bad news is that as yet, nobody has demonstrated at scale that this is possible in Western communities, and so this requires the participation of adventurous and bold pioneers.

Conclusion

Whether we accept it or not, we're all in mourning. For the futures we wanted to leave our children, for the children we opted not to have, for the devastation of countless species, for lost savings, loved ones or homes, which may have already been taken away from us. In such troubling times, liveable ways forwards are needed that are within our power to enact.

By considering the nature of life through a dynamic system that is capable of uniting material and ephemeral realms, electron flow enables the design and implementation of new approaches for addressing our ecological stressed world by making matter livelier. Beyond the conservationist notions of reducing consumption, such necessary activities of survival are transformed into regenerative acts where the materiality of metabolism itself becomes the arbiter of what activities we can perform—previously called our carrying capacity. Setting such natural limits to our daily routines is not about reducing our quality of engagement with the world but establishes new rituals of care where we do not just consume our surroundings but, in every living act, can give something priceless back to our incredible, vibrant world.

Acknowledgements Living Architecture is Funded by the EU Horizon 2020 Future Emerging Technologies Open programme (2016-2019) Grant Agreement 686585 a consortium of six collaborating institutions—Newcastle University, University of Trento, University of the West of England, Spanish National Research Council, Explora Biotech, and Liquifer Systems Group. The Active Living Infrastructure: Controlled Environment (ALICE) project is funded by an EU Innovation Award for the development of a bio-digital "brick" prototype, a collaboration between Newcastle University, Translating Nature, and the University of the West of England (2019–2021) under EU Grant Agreement no. 851246. 13sqm, 999 years (the future belongs to ghosts), installation by Cecile B. Evans and Rachel Armstrong at the Whitechapel Gallery at the group exhibition "Is this Tomorrow?", London (2019), was possible with contributions by bioengineering team: Ioannis Ieropoulos (lead; University of the West of England), Simone Ferracina (University of Edinburgh), Rolf Hughes (Newcastle University), Pierangelo Scravaglieri (Newcastle University), Jiseon You (University of the West of England), Arjuna Mendis (University of the West of England), Tom Hall (University of the West of England), and Patrick Brinson (University of the West of England); microbial fuel cell bioreactor brick installation design: Pierangelo Scravaglieri and Jiseon You, under the guidance of Ioannis Ieropoulos; structure designer: Dominik Arni; structure fabricator: Weber Industries; contributing writer: Amal Khalaf; animator: Tom Kemp; composer: Mati Gavriel; research and production assistance: Anna Clifford; installation team: Richard Hards, Hady Kamar; sponsorship from Personal Improvement Ltd. and Living Architecture (EU Grant Agreement no. 686585); in-kind support provided by Andrew Hesketh; Audioviz (UK FogScreen), the Bristol BioEnergy Centre at the Bristol Robotics Laboratory, and their research into alternative, sustainable sources of power for the home and infrastructure.

References

1. Logan, W. B. (2007). *Dirt: The ecstatic skin of the earth* (p. 3). W. W. Norton & Company.
2. Golding, W. (1954). *Lord of the flies* (p. 161). Faber and Faber.
3. Lewis, C. S. (1961). *The lion the witch and the wardrobe* (p. 148). Geoffrey Bles.
4. McFarland, B. (2016). *A world from dust: How the periodic table shaped life* (p. 3). Oxford University Press.
5. Brahic, C. Meet the electric life forms that live on pure energy. *New Scientist*. July 16 2014 [online]. Available at: https://institutions.newscientist.com/article/dn25894-meet-the-electric-life-forms-that-live-on-pure-energy/
6. Popkin, G. Bacteria use brainlike bursts of electricity to communicate. *Quanta Magazine*, September 5 2017. [Online]. Available at: https://www.quantamagazine.org/bacteria-use-brainlike-bursts-of-electricity-to-communicate-20170905/
7. Garrett, T. J., Grasselli, M., & Keen, S. (2020). Past world economic production constrains current energy demands: Persistent scaling with implications for economic growth and climate change mitigation. *PLoS ONE, 15*(8), e0237672.
8. Newton, I. (2007). Original letter from Isaac Newton to Richard Bentley. *The Newton Project*. [online] http://www.newtonproject.ox.ac.uk/view/texts/normalized/THEM00258
9. Potter, M. C. (1911). Electrical effects accompanying the decomposition of organic compounds. *Proceedings of the Royal Society B, 571*(84), 260–276.
10. Haque, U. The age of shock: Why the coronavirus should be a wake-up call about how our civilisation ends. *Medium, Eudaimonia*, 2 April 2020. [online]. Available at: https://eand.co/the-age-of-shock-81e56c7a7699.
11. Latour, B. (2018). *Down to earth: Politics in the new climactic regime* (p. 8). Polity Press.
12. Heglar, M. A. The big lie we're told about climate change is that it's our own fault. *Vox*, Volume 27 November 2018 [online]. Available at: https://www.vox.com/first-person/2018/10/11/17963772/climate-change-global-warming-natural-disasters
13. Thunberg, G. *Our house is on fire. Greta Thunberg, 16, urges leaders to act on climate*. Edited version of DAVOS speech, p7, The Guardian, 25 January 2019 [online]. https://www.theguardian.com/environment/2019/jan/25/our-house-is-on-fire-greta-thunberg16-urges-leaders-to-act-on-climate
14. Berry, W. (1971). *The unforeseen wilderness: An essay on Kentucky's Red River Gorge* (p. 26). The University Press of Kentucky.
15. Robinson, M. (2018). *Climate justice: Hope, resilience and the fight for a sustainable future*. Bloomsbury Publishing.
16. Heglar, M. A. The big lie we're told about climate change is that it's our own fault. *Vox*, Volume 27 Nov 2018 [online]. Available at: https://www.vox.com/first-person/2018/10/11/17963772/climate-change-global-warming-natural-disasters
17. Editorial, N. (2011). Microbiology by numbers. *Nature Reviews Microbiology, 9*(9), 628.
18. McFarland, B. (2016). *A world from dust: How the periodic table shaped life* (p. 25). Oxford University Press.
19. Denton, M. (1986). *Evolution: Still a theory in crisis*. Discovery Institute Press.
20. Armstrong, R. (2022). *Safe as houses: The more-than-human home*. Lund Humphries.
21. Mott, N. ,*What makes us human? Cooking, study says*. National Geographic. 26 October 2012. [online]. https://www.nationalgeographic.com/news/2012/10/121026-human-cooking-evolution-raw-food-health-science/
22. Negarestani, R. (2008). *Cyclonopedia: Complicity with anonymous materials*. Re.Press.
23. Bock, G. *The history of old stoves. Old house*. 3 Aug 2012. [online]. Available at: https://www.oldhouseonline.com/kitchens-and-baths-articles/history-of-the-kitchen-stove.
24. Atwood, M. (2006). *The tent*. Bloomsbury.
25. Ieropoulos, I., Pasternak, G., & Greenman, J. (2017). Urine disinfection and in situ pathogen killing using a microbial fuel cell cascade system. *PLoS One*. https://doi.org/10.1371/journal.pone.0176475