CHAPTER 4

SOCIOTECHNICAL TRANSITIONS: A SIXTH WAVE

Before tackling the details of the green shift insofar as it affects energy transformations, resources, food production and water, we want to ask what is the character of the transition overall. Is it simply a process of substitution of one material or technology for another, as maintained by the models and policy prescriptions of neoclassical economists? Or do we need to dig deeper, to engage with the Schumpeterian dynamics of one industrial system or paradigm superseding another?

Focusing on the technoeconomic drivers of change in our industrial system, we can draw from a Schumpeterian literature to identify five transitions in the period since the Industrial Revolution – with a sixth putatively under way in the current period. The point is that each transition involves major social, technical and business upheavals that go well beyond mere economic substitutions effected by relative price movements. In my 2015 book *Greening of Capitalism*, the five transitions were outlined as follows.

FIVE WAVES OF SOCIOTECHNICAL TRANSITION

A first wave was created by the diffusion of the improved steam engine, which for the first time created a universal power source independent of natural constraints like river courses, wind or horse power. This wave went through an upswing from the 1780s to around 1810 and then into a downswing into the 1840s. It is what is conventionally known as the Industrial Revolution.[1] A second wave was initiated by the railway investment craze, with thousands of kilometres of track being laid in the emerging industrial powers – and creating

1. The timing and sources and impact of the Industrial revolution are of course all contested. For a comprehensive overview, see Allen (2009).

a second upswing from the 1840s to the 1870s, followed by a downswing into the 1890s. A third wave was launched by the new applications of electricity, in electric motors fed by new power grids, combined with the advances in steel and chemical technologies, culminating in the 'modernist' wave from the 1890s to the period of the First World War and a downswing lasting through the Great Depression and the Second World War. The post war period then saw a fourth upswing, driven by oil and the internal combustion engine, with all the features of suburbanization, with new consumer products and services that characterized this new wave, in upswing from the close of the war to the late 1960s and downswing up to the early 1980s. The fifth wave, driven by microelectronics and IT with its numerous applications across the economy (except in energy and transport), saw an upswing from the 1980s to the early 2000s followed by a downswing expected to last until the 2020s. The great debates of the 1980s over how well the world was accommodating to the imminent arrival of a fifth wave are now giving way to debates over the world's accommodation to a sixth such transition.

This periodization of five Schumpeterian upswings and downswings since the Industrial Revolution is relatively widely accepted.[2] The real issue is whether there is a sixth wave now appearing earlier than anticipated, and being driven by renewable energies and the application of IT to energy and transport where it had been prevented from exercising its revolutionary effects during the period of tight oligopolistic control during the fourth and emerging fifth wave periods.[3] If it is real (and I have no doubt of its reality) this sixth wave would be based on the revolutionary impact of a shift in the underlying energy foundations, from fossil fuels to renewables, with all the associated applications of IT, microelectronics and the Internet. It can be expected to create the dominant technological wave of the twenty-first century.

SIXTH WAVE TRANSITIONS: FOOD, WATER, RESOURCES, ENERGY

We may characterize a series of transitions as being 'sixth wave' (6W) processes where they share the feature that they promise to substitute traditional open-air

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2. See the successive works by Freeman, by Perez (e.g., Perez 2010) and by Freeman and Perez (1988) as exemplary. Freeman and Louçã (2001) provide another perspective on the same theme. In their discussion of energy, climate change and sustainable development, Grubb et al. (2014) emphasize the role of strategic investment and innovation as shaping emerging markets for renewables.

3. See the exposition in my *Greening of Capitalism* (Table 7-1) based on Korotayev and Tsirel (2010), Tables 1, 2, p. 2.

operations dependent on natural cycles or on natural resources with closed-environment operations or operations involving manufactured products utilizing technologies that are clean, cheap, abundant – and safe. In the most general terms possible I agree with the authors of the *Ecomodernist Manifesto* that this is a shift from processes that are coupled to nature to ones that are not so coupled (i.e., they are decoupled). Let us follow through how this works.

Food production

The production of food has remained more or less tied to the great innovations that we associate with the Agricultural Revolution of 10–12,000 years ago such as, domestication of plants, breeding of superior varieties, regular planting, watering, fertilizing and harvesting. It is a process that in its open-air form is subjecting larger and larger areas of the planet to intensifying agriculture, with all the negative impacts like soil degradation and overuse of water resources, leading to overreliance on fertilizers, herbicides, pesticides, use of antibiotics in farmed animals and all the runoff involved, resulting in the 'silent spring' effects in killing off biodiversity.

Take vegetables production first. The ecomodernizing approach is to decouple agriculture from its open air form with all its sources of insecurity such as being subject to variations in factors like rainfall, soil salinity and fertility, and to produce food instead in what can aptly be described as 'plant factories' or 'vegetable factories' or more generally 'controlled environment agriculture' (CEA). [I will not use this term because 'ager' as the root word for agriculture refers to open fields. It is better to coin a term like 'controlled environment food production'.] This alternative means of producing food is one that brings principles of manufacturing to food production, controlling all the parameters such as water flow, air flow, acid–base balance and gaseous mix (including carbon dioxide levels) in a controlled environment generally known as a greenhouse. But 'plant factories' extend the notion of greenhouse so far as to become unrecognizable – including stacking rows of plants in vertical frames, rotating them to receive light and water mist, dispensing with sunlight altogether through use of energy-efficient LED lamps with their wavelength outputs tuned to the needs of growing plants, and dispensing with soil altogether in what is called aeroponics.

Such plant factories are ultra-clean, thus eliminating pests and microbes from the growing environment and producing leafy vegetables such as lettuce that are so clean that they do not need to be washed by the consumer. Such an approach to 'farming' (better, food production) is obviously associated more with cities than with the countryside, and hence has given rise to terms like 'urban farming', or 'vertical farming' and other descriptors that seek to capture the artificial or decoupled aspect of the process. The key driver of such systems (which already exist in Japan, Taiwan and China and are penetrating elsewhere) is that they are vastly more productive than traditional farming (in terms of yield per hectare); their costs are coming down to attain parity with costs of traditionally farmed vegetables (a convergence that we might term 'food market parity', by analogy with the term 'grid parity' used in the energy sector). Since the inputs are minimal we can expect the costs to continue to fall, as per the experience curve that is characteristic of manufacturing processes.[4]

Likewise we can envisage an ecomodernizing alternative to traditional livestock production of meat, utilizing tissue culturing methods scaled up to huge vats and reactors that resemble nothing so much as a brewery. The vats would be producing real cultured meat as well as other traditional animal products like the proteins found in milk and eggs. Already the world has witnessed a cultured meat hamburger cooked and eaten at a public demonstration in London in August 2013 – to widespread acclaim. Again, costs can be expected to plummet as the market expands.

Water production

Likewise in the production of clean water, we see a trend associated with urbanization and industrialization where increasingly intolerable pressures on 'natural' water usage are being countered by artificial water production via new techniques of desalination and water recycling. Methods of water extraction that are coupled to natural phenomena like seasonal rainfall and exploitation of ground water are being stressed beyond their limits, through intensification of agriculture and its dependence on irrigation and ground water. There are also water-dependent industrial processes such as oil refining and other water-hungry processes that have been conducted without regard to natural water limits and now pose severe threats as water shortages loom.

Again, a solution presents itself in the form of decoupling the water usage from its natural setting – as in water extraction from dirty water recirculation and desalination via new technologies such as 'multiple effect distillation'

4. It must be conceded that 6W methods of food production so far are limited to vegetables and horticultural production plus aquaculture – but no successful cases as yet of broad-acre production of grains have been demonstrated. This remains a major technical 'reverse salient' to be resolved.

or new forms of membrane-based desalination via forced osmosis. These innovations liberate cities from traditional water supply sources and open up new possibilities of recycling water, decoupling the process from dependence on natural water cycles. Sources of power to drive the requisite desalination processes can increasingly be derived from renewable sources including sun and wind, so reducing the costs of desalination and facilitating its wider adoption through the power of the learning curve.

Resources reproduction – circular economy

Industrialization has been associated with intensive use of resources – extracting them from the earth (mining, drilling) and then dumping them in the earth again (waste disposal). This traditional, linear approach to resource extraction and disposal is even older than agriculture – and just as unchanged. As the scale increases to encompass the planet as a whole, the disasters associated with more intense and larger-scale mining are getting worse – such as coal mining disasters that are reported every year in China and collapses of tailings dams as occurred in 2015 in Brazil. Now of course some resources have to be burned and as such are not recyclable – and so we call them 'fuels' and discuss them separately, under the rubric of energy. But all other resources are subject to conditions of increased scale of use, increasing intensity, increasing pollution, and increasing insecurity as nations and companies fight for access to the dwindling resource supplies. China as the latest arrival in this industrializing process and the world's largest manufacturer is also the world's largest exploiter of resources in this 'take, make, dump' mode and the world's largest producer of waste. But it is also developing the world's most radical and successful approach to solving the problem – a solution consistent with other ecomodernizing trends that taken together are called the *Circular Economy*.

The Circular Economy (CE) decouples resource use from its natural setting and aims to recirculate resources, allowing them to be regenerated by extraction from waste flows. This is what is aptly called 'urban mining' which may be characterized as (re)production of resources by artificial means, through closing industrial loops and turning outputs into inputs for other processes – emulating the cycles of nature where waste is made into food. The CE as a national goal is most advanced in China, where successive Five Year Plans (FYPs) devote major sections to achievement of CE targets to bring China's material intensity levels closer to those of OECD countries overall. What is driving its uptake in China is mainly legislative and planning requirements, including the channelling of investment into CE initiatives via use of state development banks that follow FYP targets in making their loans contingent on meeting green targets. But what ultimately will drive the supersession of the linear economy by the circular economy – a process that can already be seen – will be the reducing costs of regenerated resources (urban mined resources) as opposed to 'open air' traditional mining and associated waste disposal costs. I have suggested that this process could be accelerated if commodities futures markets were to introduce traded contracts that differentiated between virgin resources and regenerated resources – allowing the traders to create a price differential between the two.[5] There are also clear productivity gains as resource intensity is reduced and waste disposal is almost completely eliminated. There is an urgent need for econometric estimates of these cost and productivity advantages to be anticipated from CE initiatives.

Energy production/generation

When we look at energy issues, we see the same processes at work. Taking the burning of high carbon containing resources (termed fossil fuels) as the prevailing 'business as usual', with its tight coupling between power generation and natural resources of these fuels (mined, drilled), with price fluctuations depending on availability of accessed deposits, we can see that a sixth wave remedy again presents itself. The remedy is to divorce energy generation from these natural moorings, and to generate power utilizing devices manufactured for the purpose. These machines would include wind turbines or solar photovoltaic cells or arrays of mirrors and lenses as in concentrated solar power systems, together with energy storage systems to accumulate the energy generated and release it as needed. This is best described as energy generation using artificial or manufactured systems as a sixth wave transition.

The *Ecomodernist Manifesto (EM)* complicates its otherwise clear discussion of these matters by calling it 'energy extraction', which retains a link back to fossil fuels. A clean terminological break – energy generation from renewable sources – is what is called for. I surmise that the *EM* authors use the nebulous term 'energy extraction' because they want the focus to be on 'extracting' energy from nuclear processes like fission and fusion. But I have no such constraint: the best term is clearly 'energy generation utilizing artificial measures', as opposed to remaining tied to natural deposits of fuels and being subjected to all the geopolitical uncertainties as nations and corporations fight

5. See Mathews (2008b). This contribution is framed in terms of a putative sustainable biofuels contract, but is easily extended across to commodities futures contracts in general.

for access to these fuels (including uranium) and their pricing. By contrast, manufacturing their way to energy security by shifting to renewables is a promising way forward, consistent with the other ecomodernizing trends discussed so far.[6] Again it is China that is in the lead in this endeavour, driven no doubt by concerns over energy security which can be mitigated by manufacturing the (means to produce) the energy needed – rather than depending on 'natural' supplies.

What drives this shift in energy systems is cost reduction – down to and beyond 'grid parity'. Some energy scholars depict the driver as decarbonization, which runs through the sequence: wood, to coal, to oil, to gas – and then to hydrogen (derived from fossil fuels) and nuclear.[7] But in my argument the driver is not decarbonization; it is cost reduction, which derives from the learning curve that is in turn linked to manufacturing. Some scholars seem to emphasize decarbonization at the expense of cost reductions – perhaps because they view the decarbonization process as one that moves directly from one fossil fuel to another and then to the hydrogen economy, with nuclear reactors being deployed to split water to produce the hydrogen at colossal scale. This is a very different vision of energy systems evolution from the one that I discuss in this text.

REVERSE SALIENTS

Thomas Hughes is the source for much of our understanding of how large-scale technoeconomic systems evolve. His paradigm case was the electric power networks that were developed at the end of the nineteenth century and into the twentieth century, as analysed in his magisterial work *Networks of Power* (1983). This study tackled the first of the technological innovations that constituted a whole system – even more so than the railways and the gas and water utilities of the earlier nineteenth century. The electric power networks involved innovation at the level of units and installations – such as electric motors, generators, and dynamos – but even more significantly at the level of the distribution system with its famous 'battle of the systems' between AC and DC power. The DC power system was developed and championed by Edison

6. The reference is to the article in *Nature* published by Hao Tan and myself in 2014.

7. See for example the arguments mounted by Jesse Ausubel (e.g., Ausubel 2007), which draw from a long tradition developed by others such as Marchetti. I provide a critique of this school of thought in Mathews (2016a).

and his General Electric company – but its fatal flaw was that it was very limited in its range of distribution. The solution to this was provided by the Serbian genius Nikola Tesla with his invention of AC power and the polyphase generator that provided it, working in alliance with the Westinghouse company – the eventual victor in the war of the systems.

In taking a systemic approach to the issue, Hughes worked with the concept of *reverse salient*. He introduced this concept as a means of accounting for the concentration of effort on certain technological problems and less on others.[8] The term is a military one, depicting 'that section of an advancing battle line, or military front, but which has fallen behind or been bowed back' (1983: 79). The term had been a household word during the First World War when it was used to describe the German efforts to eliminate what was for them the reverse salient at Verdun. Hughes explained that the term is preferable to others like 'disequilibrium' or 'bottleneck' because of its connotations of complexity involving individuals, groups, material forces, historical influences and other factors. Ultimately the reverse salient is a subsystem that is underperforming and holding back the advance or development of the system as a whole. Hughes argued that the idea of a reverse salient 'suggests the need for concentrated action (invention and development) if expansion is to proceed' (1983: 79) – that is, concentrated attention devoted to solving the issues raised by the underperforming subsystem.

The DC power system developed by Edison and GE had many reverse salients all of which were solved – except the overwhelming problem of its rising cost of transmission as the distance from the power station increased. Likewise the AC system had its own reverse salients which were also solved, making the AC system in the end overwhelmingly superior to the original DC system. Edison had early on identified the issue of the rising cost of transmission of the DC system as its major reverse salient. To his frustration he and his engineers could not find a solution within the DC paradigm.[9]

Now the point of introducing this discussion of 'reverse salient' is to deploy the concept in our discussion of the diffusion of new, green technological systems – with renewable energy systems and smart grids taking over from

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8. I would like to acknowledge discussions on this point with my colleague Dr Mei-Chih Hu, a professor at National Taiwan University.

9. As described by Hughes, the solution was found eventually by Gaulard and Gibbs in the form of an alternative AC paradigm, involving polyphase generators, with high-voltage utilized for distribution (achieved via transformers) and low voltage for local distribution. See Hughes 1983: 86.

fossil fuelled, centralized, non-intelligent grids, and circular economy networks (closed loops) taking over from the linear economy, and new food production systems taking over from traditional, open-air, irrigated systems. How does the concept work in these cases?

For the case of renewable energy, there is a clear reverse salient in the form of energy storage subsystems. Until recently there was no sense of there being a strong technological process of innovation bringing costs and prices of batteries and storage systems to the level where mass production could take over. This situation is now changing and the one remaining reverse salient standing in the way of rapid diffusion of renewable energy systems is now closing.

In the case of the shift to a circular economy, the reverse salient is doubtless that of companies in a supply chain failing (or refusing) to act on their common interests in sharing resources such as energy, heat and power and waste disposal. But the case of China is different since CE initiatives are targeted on existing industrial parks and export processing zones where there is already a governing body or representative council that embodies the interests of all participants, and is better able to recognize where firms might have common interests. It also helps that these representative bodies also carry local authority and have the means to require firms to act where their interests are seen to coincide.

In the case of water regeneration and food production in enclosed spaces, the reverse salient has been heavy use of energy and high costs of power, particularly for lighting in enclosed-space horticulture using greenhouses. This situation is neutralized by the use of solar sources for power and seawater, as in the Sundrop farms concept discussed below, and by use of LEDs for lighting that offer cost-effective solutions that can improve yield through tuning the wavelengths of their outputs. Reverse salients thus slow down diffusion of innovations, but do not block them forever.

Interconnections

The four dominant processes that may be viewed as constituting the core of ecomodernization (or what I call 6W processes) are expounded here, together with their reverse salients. But of course they are interconnected – and we shall explore such interconnections when we discuss the concept of the 'triple nexus' between water, energy and food production below. No doubt we could extend the list of 6W processes. Transport is increasingly being decoupled from natural moorings as the urbanizing world moves towards electric vehicles (both pure battery powered and hybrid vehicles), high-speed rail, metro subway systems, air transport as well as electric powered sea transport. In fact the case can be made that the invention and commercialization of the automobile at the end of the nineteenth and beginning of the twentieth century was the original version of 'decoupling' (leaving aside the issue of fossil fuel dependence) that provides the template for all the subsequent cases being discussed under the rubric of ecomodernization. The automobile (as the name implies) liberated humans from natural constraints on mobility, measured in terms of range or speed or acceleration. Likewise steam-powered vessels liberated sea craft from the natural constraints of wind, and aircraft set a new standard of naturally unconstrained transport that had no known antecedents. Of course the analogy breaks down when one introduces constraints associated with fossil fuels – which are themselves being mitigated as private transport moves towards electric vehicles and fuel cell vehicles with battery charging networks as the new infrastructure.

What is demonstrated here is that these 6W changes are both feasible and real, and the reverse salients that have been holding back their diffusion are being resolved. The new systems are already being implemented, albeit sometimes at small scale, but in a way that lends itself to scaling up to global level. This is the challenge being met by China and India, with powerful benefits for themselves and powerful repercussions for the rest of the world.

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Where I differ from the authors of the *Ecomodernist Manifesto* is that I see the diffusion of 6W technologies as being likely to be driven by their reducing costs – which are ensured by the fact that products embodying these technologies are all manufactured. As such they benefit from increasing returns and reducing costs because of the learning curve effect. Their diffusion will also be driven by the wide applicability of these technologies – taking over from traditional operations in such diverse areas as food production, water production and resource (commodity) production as well as energy production. This is truly an economy-wide technoeconomic transition – which is why I call it the sixth wave disrupting the industrial system since the original Industrial Revolution.

Now other authors have addressed themselves to these questions but with differing emphases. Jeremy Rifkin is convinced that there is an industrial revolution involved here, but he sees it as the third such revolution – telescoping everything that has happened since the eighteenth century into two simple turning points, a first (industrial revolution) and a second (electrification). He insists that there is a third such transition underway, driven by technological changes with a principal focus on the Internet of Things (IoT) and Zero

Marginal Costs as the driving forces.[10] Now the IoT will surely have a profound impact in enabling people to take charge of many operations that have been the province of large corporations. But the IoT can also be viewed as enhancing the power of other large corporations – particularly of those that are investing large funds in the IoT like GE, Microsoft, Google and Intel. So while energy prosumers might be able to locate each other in a 'sharing economy' exchange of energy, I do not see this as the reason that will drive the diffusion of 6W processes so much as the fact that the technologies involved are manufactured to be cheap, clean, abundant – and safe.[11]

As for zero marginal costs (or more accurately, close-to-zero marginal costs), these too must certainly be viewed as a profound driver of the uptake of 6W technologies and products. There is no doubt that generating solar and wind power eliminates the cost of fuel from the energy equation and thereby makes such technologies much more attractive than their fossil fuelled competitors. The fact that sunshine and wind are free and can be harvested by devices that we build, and are operated with low marginal costs, is a profound advantage. But is it the principal driver of the uptake of 6W energy devices?

The feature that all 6W products and technologies have in common is that they address age-old issues of insecurity – food insecurity, water insecurity, energy insecurity and resource insecurity – and pose novel means of alleviating these insecurities. In their different ways they all substitute manufactured and artificial environments for traditional open air environments subject to adverse weather, physical conditions and dependence on water, soil and natural processes. Insofar as this is the message of the *Ecomodernist Manifesto* I agree with it and applaud the authors for putting their finger on the key issue.[12]

SIXTH WAVE TRENDS – DECOUPLING ECONOMIES FROM NATURAL CONSTRAINTS

There are many trends that drive the evolution of our global civilization – one being the processes of globalization themselves. There is elimination of ancient prejudices, and liberation of women from practices and ideologies that tie them

10. See Rifkin (2013; 2014).

11. I discuss these matters further below in the chapter on energy, where the case is made for a Global Energy Interconnection (GEI) that has greater salience than the IoT.

12. Here I am contrasting the *Ecomodernist Manifesto* with the arguments of other commentators like Jeremy Rifkin or Gaia-author James Lovelock.

to the home and to child bearing and child rearing (and prevent the onset of the demographic transition). What underpins many of these welcome shifts is a broad process widely known as modernization.

The features that all these 6W processes share is that they are products of manufacturing – in that they are clean and operated within a closed environment. They are *practicable* (in that the technologies already exist), *scalable* and *replicable* – and hence can be utilized in cities everywhere as the world population expands and urbanizes.[13] Above all, they present as favourable options for China, India and other emerging industrial giants, providing them with the means to resolve their issues of security of energy, water, food and resources supplies.

Another way of characterizing these processes is to describe them as shifting towards a design ethic of biomimicry or biomimesis – taking the biological world as fashioned through millions of years of evolution as guide to introducing and designing new technologies. Renewable energies are biomimetic, as are circular resource flows and water regeneration and desalination utilizing heat-driven processes that biomimic the evaporation-driven water cycle. Even synthetic meat culture and creation of artificial dairy products can be said to be biomimetic in that they are guided by nature in their ways of constructing muscle tissues and blends of proteins that can substitute for the animal-derived originals.[14]

In this book I am focused on the dominant technoeconomic trends of our time, which may be called ecomodernizing trends, and I ask to what extent the successful industrialization of large countries like China and India and Brazil depends on the strategic choices they make as they embark on their modernizing journey. Along with South Africa these may be called the BICS countries, with reference to what Goldman Sachs christened the BRICS – an acronym which included Russia. (Let us agree to exclude Russia because it remains tied to fossil fuels and shows little inclination presently to develop energy alternatives like renewable power or resource alternatives like the circular economy.) The BICS countries are becoming the centre of gravity of

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13. These features of being practicable, scalable and replicable are those used explicitly by the administrative committee of the joint Sino-Singapore eco-city of Tianjin – as discussed in the penultimate chapter. I am taking these features as characterizing 6W processes generally.

14. I discussed biomimicry at length in *Greening of Capitalism* (Mathews 2015). My sister Freya Mathews has discussed the philosophical underpinnings of biomimicry (F. Mathews 2011).

world manufacturing (Great Convergence) and are now becoming the drivers of investment in new 6W technological processes, through their creation of new investment vehicles such as the New Development Bank on the one hand (a BRICS initiative) and the Asian Infrastructure Investment Bank (AIIB) on the other. These banks are expected to take over from the World Bank as sources of green infrastructure funding in the next couple of decades.[15]

The major trends worth focusing on are those that decouple economies and economic processes from natural constraints. It is China and India that appear to be driving the uptake of these new systems, with strategic choices that are distinctive and differ in many ways from those outlined by the authors of the *Ecomodernist Manifesto*. Their choices impact both on their own economies and on the rest of the world as their actions drive the expansion of markets and hence the downward trend of costs and therefore prices. It is little wonder then that these countries are greening their economies as fast as they can manage the process – with all the technological, economic and geopolitical constraints (such as trade conflicts) involved. There really is no secret as to why China, India and other industrializing countries are choosing the green growth option with distinctive strategic choices that reflect their historic positions. We start by seeking to analyse just why they are making these particular choices – and what the impact is likely to be.

15. See the argument of the paper 'The AIIB and investment in action on climate change', by Darius Nassiry and Smita Nakhooda, ODI, April 2016, at: http://www.odi.org/publications/10374-aiib-and-investment-action-climate-change.