**Article**

# A green theory of technological change: Ecologism and the case for technological scepticism

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**Abstract** Green political theory has a problem: it fails to account for human ingenuity. As a result, it has always struggled to refute the technologically optimistic notion that, in an era of rapid technological development, new technologies will materialise to resolve environmental ills. From ecologism's first emergence, this idea has been its opponents' ultimate recourse. It is especially significant because it denies the constitutive claim of ecologism that environmental problems require political solutions. It is in this claim that the green alternative to modernity and its ideologies is advanced. Yet, green scholars have never successfully refuted technological optimism; indeed, ecologism has always lost the scholarly battles over technological change, even as technology has failed to mitigate environmental catastrophe in the real world. This article's green theory of technological change alters this: it shows that the green belief that technological development is unpredictable is in fact well-founded. In so doing, it buttresses the green challenge to modern political ideologies and justifies the movement for ecologism in the world. In short, it reasserts the claim that the natural is political and reinforces the need for a distinctly green version of political theory.
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Green political theory (GPT) needs a theory of technological change. At stake is the entire notion of a discrete green political theory. Opponents of GPT (or 'ecologism') claim that its problems are not political problems. For these 'Prometheans', environmental emergencies like extinction or climate change are in fact economic problems (Simon, 1996; Solow, 1973). Left alone, or perhaps motivated by tax incentives, the market will correct these faults. They are signals to the technologically ingenious that there is profit to be made. With new technologies fixing problems as they arise, questions of environmental justice – political questions – never need to be asked. What need is there for a green political theory?

This critique will be familiar to any green scholar. It was a major part of the Promethean response to *Limits to Growth*, countering the technological scepticism put forth by the latter and its supporters (Meadows et al., 1972; Eckersley, 1992, p. 120; Dobson, 2007). This clash of technological optimism and scepticism was perhaps the formative debate in green political theory. Despite this, it is not well understood. The recent propensity among scholars has been to treat the dichotomy as either arising from a clash of temperament – modern against romantic – or as the product of competing discourses, premised on differing realities (Dryzek, 2005; Symons & Karlsson, 2015). Attempts have even been made to reconcile the two sides, based on the implicit assumption that neither is meaningfully provable (Brand & Fischer, 2013). This notion that the debate has run its course is premature (Barry, 2017, pp. 111–114). Substantial analytic work remains undone. In particular, the foundation of Promethean optimism has never really been grasped, and, as a result, substantial responses to it have yet to be developed. For Prometheanism is not based on blasé optimism, nor a contempt for nature, but rather on a model of how technological novelties come about. This model assumes that technologies arise endogenously, i.e. in response to constraints on human progress, translated by the market into pricing signals that spur ingenuity. From its vague formulation in Prometheanism, endogenous technological change (ETC) has developed into the backbone of global climate change mitigation policies; indeed, ETC developer Paul Romer was awarded the 2018 Nobel Prize in Economics because of its importance to mitigation policies. Designed to uphold the economic and political status quo, these policies are a powerful defence against the challenge of ecologism (Keary, 2016).

More fundamentally, Prometheanism is the most sophisticated defence yet offered by champions of modernity against the green challenge to its vision of progress. This vision is common to all the political theory traditions that arose out of the enlightenment and amounts to the mastery of nature through science and technology, so as to emancipate human beings from scarcity and environmental hazards (Leiss, 1994; Merchant, 1989; Plumwood, 1993). Greens offer two broad responses to this vision, one rooted in normative theory, the other in positive analysis. First, that it is harmful and wrong: nature ought not to be mastered (Goodin, 1992, p. 185; Plumwood, 1993). Second, that it is impossible: nature cannot in fact be mastered because the effort to do so will eventually exhaust nature's life-sustaining properties and produce ever greater environmental calamities, both of which are beyond the power of science and technology to overcome (Leiss, 1994; Schumacher, 1973). Mastery, as Plumwood tells us, is the 'central dynamic' of the environmental crisis (Plumwood, 2002, p. 131). In response to this crisis, modernity's champions always mobilise technological optimism (Leiss, 1994; O'Riordan, 2000). So, while Prometheanism, as it has been formulated, is a capitalist doctrine, its motivating principle – that human ingenuity will solve the problems of progress – is as much a Marxist idea as it is a liberal one (Eckersley, 1992, p. 94).

Hence, this article's green theory of technological change. This theory is a direct response to Promethean-inspired policy, but more than that, it is the most sophisticated defence yet offered of technological scepticism, which underpins that most fundamental of green aims: halting efforts to master nature. The green theory of technological change does this by showing that these efforts cannot succeed and, therefore, that a different relationship with nature must be pursued.

More specifically, this article's technological change model shows that the green instinct – which cautions against relying on uninvented and unproven technologies to reconcile capitalist production with environmental stability – is well-founded. The point is not to resuscitate technophobia: it is to make the case for a reasoned technological scepticism. The Prometheans' bird's-eye view of the history of technological change presents the process as smooth and controllable; this article's green theory of technological change provides the sobering ant's-eye view, revealing the messy, slow, hit-and-miss nature of the process. It shows that technological futures are inherently uncertain and, therefore, that social, political and economic reorganisation is required, given looming ecological disasters.

I begin by examining the classic environmental disputes over limits to growth. This analysis accomplishes three things: it explores the essence of ecologism; it situates ecologism within political theory as a fundamental challenge to modern ideologies on the grounds of eventual environmental collapse; and it demonstrates the centrality of technological change to the rejection of that challenge. In the second section, I survey the endogenous model as propounded by the two major Prometheans and show that it demands a GPT response. The third section evaluates the success of green responses thus far. It finds three distinct critiques of technological optimism: a direct critique; a critique from ideology; and a critique from complexity. I argue that none of these critiques amounts to a successful rejection of endogeneity. In the penultimate section, I outline an evolutionary model of technological change and demonstrate its superiority to the endogenous model. This model demonstrates that technological change is not predictable: it is substantially random. Far from being a romantic reaction then, technological scepticism is shown to be an analytically coherent position (Barry, 2017). Finally, I explore how this model undermines technologically optimistic positions in contemporary environmental debates. In the conclusion, I note how economics depoliticises that over which it has analytic control; that which it feels is a predictable effect of familiar market forces. A green theory of technological change breaks this analytic control. It shows that the key variable of technological change is not explicable within an economic framework. Absent this depoliticising defence, it cannot be denied that the natural is in fact political.

What does this mean? To assert that the natural is political is to reject the mastery of nature thesis: that the natural is merely resources to be exploited and hazards to be eliminated. It is to say that the natural is entitled to ethical consideration in the public sphere. It is to say that the natural has been made political; that what it has become is the result of the political power that has acted upon it and thus that the crisis in which it now exists is the result of the anthropocentric and capitalist – modern – institutions and practices that currently prevail. It signals a political, rather than technocratic, approach to resolving environmental degradation, one in which these institutions and practices will be fundamentally reassessed.

## The origins of GPT

GPT developed from the green movement, whose key texts were *Silent Spring* and *Limits to Growth* (Carson, 1962; Meadows et al., 1972). It asked: what does this movement mean for existing political thought? It was argued that existing political theory was incapable of representing this movement because it was underpinned by cornucopian and anthropocentric assumptions (Eckersley, 1992, p. 4). Thus, ecologism's political theory challenge arose from an empirically minded debate: *Limits to Growth* was the real catalyst. Its opponents were the 'Prometheans' – predominantly economists – who maintained that economic growth is limitless (Simon, 1996; Solow, 1974). This debate has often been rehearsed and its main details will be discussed below (Dryzek, 2005; Homer-Dixon, 2010). However, two things are worth noting now. Firstly, at the crux of the debate was the idea of human (technological) ingenuity and the extent to which it could alleviate pollution and resource depletion (Carter, 2001). Secondly, after much activity between the early 1970s and early 1990s, 'the debate', as Homer-Dixon notes, became 'sterile' (Homer-Dixon, 2010, p. 235).

This article argues that this sterility ensued because technological change, despite being a major concern, was under-theorised. Empirical work indicated that the role technological change *might be* performing in the space between the economy and the environment, but data about cost increases/decreases, species-loss, etc. reflected proxies whose connection to the underlying process was never close enough to prove either interpretation. In other words, human ingenuity *may* be the reason why a commodity's price declined, or its absence *may* be the reason why species continued to disappear, but too many other variables were potentially responsible. The inadequacy of this debate reflects significant gaps in GPT's foundations.

To understand this, we must explore green political thought's more fundamental challenge to ideas about freedom that emerged with modernity: firstly, GPT argues that freedom/flourishing is not just for humans; but secondly, it maintains that freedom actively produces scarcity (Eckersley, 1992). That is, even as it (arguably) maximises the efficiency of an economy, the free pursuit of self-interest ensures that resources are maximised as efficiently as possible from the point of view of those with power over them. If this hurts the natural world and future generations, then so be it. The result is an economic vision very different from that of the classical liberal thought from which Prometheanism arose: where liberalism sees progress, ecologism sees decay.

This is one of GPT's two original contributions: an attack on the widespread idea that consumption can grow indefinitely. The earth, say greens, cannot provide this. As Carter notes, 'the concept of *finitude* which underpins the "limits to growth" thesis is unique to ecologism' (Carter, 2001). For greens, the goods the world provides, like metals or water, are limited in quantity and its services, like photosynthesis, are limited in scope. They can accommodate certain demands, but more than these will exhaust the goods and collapse the services. So even ignoring nonhuman flourishing, humans are obliged to respect biophysical limits to material gain.

GPT also contends that nonhuman life must be considered more than just a resource though. While greens differ about the ideal relationship between humans and nonhumans, ecologism declines to dichotomise people and nature, arguing that humans are merely part of an intensely complex 'interrelated biotic and abiotic community' (Dobson, 2007, p. 3). Thus, trade-offs cannot always favour humans. Moreover, nature's complexity warns against incautious human intervention, especially large-scale technological action (Eckersley, 1992, p. 59). The consequences of the latter, greens argue, are unknowable because the effects in a complex world defy forward extrapolation.

These two contributions shake the assumption in modern political thought that the environment is an economic matter rather than a political one. GPT says that *the natural is political*, both because it has independent worth and because the harms and benefits that come from humanity's use of nature must be distributed fairly. In other words, because economics cannot manage finitude, politics must intervene. For finitude to count, though, it must be close in time: negative consequences for CE 3000 are unlikely to matter today. In *Limits*, Meadows *et al.* argued that scarcity and political crisis could occur within two generations (Meadows et al., 1972).

This explains why ecologism was such a significant challenge to the political traditions of modernity. The most forceful response came from Promethean economists defending classical liberalism. Separating the economic from the political has been part of the liberal tradition since Smith and Ricardo. However, by arguing that the market can resolve ecological crises – that the environment is part of a self-correcting economic system – the Prometheans in effect argued for the separation of the environmental and political realms also. At the heart of these claims lay a conception of human ingenuity, one that asks of ecologism the most fundamental question: is the environment a sphere proper to politics at all? Or is it no more than a mildly disruptive element of the economic sphere? Let us examine this now.

## Prometheanism

Eckersley argues that *Limits* 'spawned a plethora of counter-arguments to the effect that the problems were susceptible to "technological fix" and pricing solutions that would alleviate the negative ecological externalities of economic growth without need for any fundamental changes in political values or the pattern and scale of economic activity' (Eckersley, 1992, p. 12). This sums up how greens remember the *Limits* dispute and the Promethean response. Less clear is the mechanism by which pricing and technological change are supposed to bring about solutions. In other words, if the normative analysis insists that little action needs to be taken in response to the problems identified by *Limits*, what positive analysis of world processes supports this conclusion? To answer we will focus on the two most significant Prometheans: Robert Solow and Julian Simon.

Solow's intervention is the earliest and responded directly to the publication of *Limits*. It is framed as the response from the discipline of economics and gets to the heart of the Promethean argument:

> It is clear without any technical apparatus that the seriousness of the resource-exhaustion problem must depend in an important way on two aspects of the technology: first, the likelihood of technical progress, especially natural resource saving technical progress, and second, the ease with which other factors of production, especially labor and reproducible capital, can be substituted for exhaustible resources in production (Solow, 1974, p. 10).

The latter ultimately runs into diminishing returns, so it is really the former that matters to the question of limits. The problem revolves around predictability. Technological change will occur long into the future. However, will it occur in the direction and at the pace needed to overcome limits, be they resource or pollution, as they arise? In implicit response, Solow argues 'when natural resources become more and more valuable, the motive to economize those natural resources should become as strong as the motive to economize labour. The productivity of resources should rise faster than now – it is hard to imagine otherwise' (Solow, 1973). Later in that paper he argues for 'user taxes' on pollution: a similar idea, wherein taxes incentivise the development of sufficiently clean technologies (Solow, 1973). This is an endogenous conception of technological change and it is central to answering the question of direction and pace (Solow, 1957). If technological change occurs in direct response to pecuniary incentives within the economy, be they high prices, subsidies or taxes, then it can overcome environmental problems. In effect, ingenuity is collapsed into rationality: a tricky new variable converted into an economist's stock-in-trade. Prometheanism cannot have key variables powered by noneconomic motives: they would be unpredictable, and the problem of limits would then reassert itself.

There is nothing in Solow to guarantee that technological solutions will arrive before serious damage is done though. This problem is addressed by Simon. He states that technological change is behind his rejection of *Limits* and similar arguments from other sources:

> we do not say that a better future happens *automatically* or *without effort*. It will happen because men and women…will address problems with muscle and mind, and will *probably* overcome…the solutions will leave us better off than if the problem had never arisen; that is the great lesson to be learned from human history (Simon & Kahn, 1984, p. 3).

Moreover, it is clear from this and other similar statements that he sees the process of technological change as endogenous:

> Throughout history, individuals and communities have *responded to actual and expected shortages* of raw materials in such fashion that eventually the materials have become more readily available than if the shortages had never arisen (Simon & Kahn, 1984).

Simon is thus certain that individuals respond to constraints with ingenuity. From his earlier book, we can be sure he thinks they do so for money (Simon, 1996). Here, Simon explicitly adheres to the price model as outlined by Solow, thereby ensuring economic predictability. Simon is also not averse to market-based regulation. He thinks that regulation must be used sparingly and be designed to replicate free-market incentives (Simon, 1996, pp. 302, 308). His example is carbon dioxide emissions-permits. Doubtlessly he expects that, like free-market incentives, these state-created incentives will spur ingenuity.

Simon is the archetypal defender of modernity. Humans, through their technological ingenuity, can master nature, and progress is the result: 'a "technical fix" is the entire story of civilization', he says (Simon, 1996, p. 299). He is, though, only the most overt defender. Prometheanism, in all cases, defends the modern institution of capitalism and thus, for greens, the mastery of nature. It does this through an understanding of technological change that collapses ingenuity into rationality. The provision of incentives, whether automatic – through natural price-increases – or artificial – through taxes – leads to an immediate and sufficient ingenious response. Otherwise, there is reason to believe that limits are a political issue, one threatening to growth and liable to require political, as opposed to economic, responses. If true, this would vindicate the position of green political theory. If ETC is correct though, ecologism is redundant. As Dryzek notes, '[if the] Prometheans are right then all other discourses of environmental concern are rendered irrelevant and unnecessary' (Dryzek, 2005, p. 70). We should thus examine how GPT challenges the optimism ETC inspires.

## Critiques of technological optimism within green political thought

An examination of the treatment of technological change within green political thought offers one inescapable conclusion: there is no consistent understanding of the process by which it works. Ecologism has no model of technological change. Indeed, it lacks clear conceptual distinctions, such as between technology and technological change, invention and innovation, and so forth. This perhaps explains the weakness of green critiques of technological optimism. This section discusses the three forms of critique in turn: direct, but mostly asserted, criticisms of technological solutions; an undeveloped recourse to ideology; and a cautionary logic, premised on the concept of complexity, that is stricter even than the precautionary principle. In many places, it is difficult to believe that greens fully grasp just how corrosive the logic of the endogenous model is to green thought.

### Strategy

Firstly, though, a brief digression into argumentative strategy. It is commonly accepted that ecologism lost its early debates about technological change (Homer-Dixon, 2010, p. 234; Sabin, 2013). These episodes have likely discouraged green thinkers from arguing on technological grounds. However, other grounds have significant strategic drawbacks. The promise of technological change pushes ecologism's other arguments onto the margins of their objections and very far from 'human-prudential' arguments (Dobson, 2007, p. 46). In other words, while not without merit, these arguments are unlikely to convince sizeable numbers because they are overwhelmingly buttressed by references to the rights of nonhumans. That such arguments *should* be convincing does not allow us to escape from pressing environmental crises. Hence, many greens take argumentative strategy extremely seriously (Dobson, 2007, p. 52). However, a theory of technological change can pull other arguments back from the margins and put human well-being back into play.

### The green critique of technology

We will first consider arguments that directly critique the substance of Promethean technological optimism. *Limits'* judgement was that 'technology can relieve the symptoms of a problem without affecting the underlying causes': it merely delays ecological collapse (Meadows et al., 1972, p. 154). Technological solutions that relieve a problem in one area then add pressure to another, leading to collapse. This criticism begs the endogenous model: ‘a “technical fix” is the entire story of civilization’, as Simon puts it (Simon, 1996, p. 299). This model explicitly rests on specific technological solutions, motivated by financial reward, arising in response to each new pressure. So, when *Limits* says these fixes do not address the underlying causes, it is stating a fact upon which both sides agree. *Limits* is silent about the process of technological change that underlies Promethean claims and thus adds nothing further to the debate. The most that can be taken from *Limits* is a suspicion of the hyperbole surrounding technological fixes.

Suspicion has been a prominent feature of green thought ever since, though without sufficient justification (Dobson, 2007, p. 13). John Dryzek’s (2005, p. 51) effort rests on the claim that Prometheanism ‘can only stand…with a theory of nature’s abundance’; he thus labels it ‘Promethean/cornucopian’ to signify the idea that Prometheans also believe in the earth’s unlimited capacity to recover from ecological punishment. He has no textual support for this, and it is not an argument Prometheanism needs to make. If the price mechanism can solve all environmental problems, then there is no requirement for a theory of ecological resilience.

Dryzek’s only additional critique is to observe that ‘there is no guarantee’ that new technologies will continue to appear as Prometheans predict (Dryzek, 2005, p. 67). However, without further elaboration, this assertion again merely begs the Promethean response: ingenuity collapsed into rationality operating under profit incentives, something that, in their reading of history, has always worked. To counter this, one needs to go further: to engage the model and the historical reading on which it is based.

Thomas Homer-Dixon does go further. In *The Ingenuity Gap*, he implicitly shows us why GPT needs significant additions if it is to respond convincingly to Prometheanism (Homer-Dixon, 2010). He makes a key contribution to the literature in, for the first time, explicitly recognising the endogenous model and its importance. Yet he is not a green political theorist and his critique of technological optimism does not provide a sufficient platform for it.

Homer-Dixon concedes much to the Promethean position: the thrust of his case is that problems in a free market do indeed bring about solutions through the application of ingenuity for profit. There is, however, a gap. Often our ingenuity does not keep up with the quantity and extent of our problems. It is thus dangerous to rely on it (Homer-Dixon, 2010, pp. 4–6). This argument is important, but how Homer-Dixon sustains it offers little to ecologism.

His focus is on the difficulty of establishing the right market conditions for ingenuity, especially in the developing world (Homer-Dixon, 2010, pp. 240–246). However, none of the problems he mentions – such as rule of law – are irresolvable in principle. They point inexorably to improvements in regulation, transparency and development, not to significant changes in our patterns of production and consumption. Indeed, the whole market-barrier case has been considered at length by mainstream economics and solutions to the problem are part of their approach to climate change (Newell, 2009).

Homer-Dixon's critique of Prometheanism is also unhelpful. He claims, using a quotation from Solow, that Prometheans believe natural resources to be dispensable, such is their faith in ingenuity. He goes on to critique this position (Homer-Dixon, 2010, p. 241). In fact, the quote is misleading. In it, Solow merely presents one extreme position, and later he presents the other, before concluding his more measured stance, as discussed above (Solow, 1974, p. 11). Homer-Dixon's critique is therefore irrelevant and cannot help us challenge technological optimism.

Beyond *Limits,* Dryzek and Homer-Dixon, no green thinker has really engaged the environment-technology dynamic at the heart of Prometheanism and certainly not the endogenous model itself. However, even if one ignores the model, there are additional grounds for claiming that Prometheanism is an inadequate response to ecological concerns.

## Ideology

Bypassing direct engagement with the processes and history of technological change is the argument from ideology. This argument arises from a specific version of the mastery of nature thesis, in which the world is dominated by 'technocentrism': an ideology grounded in post-enlightenment hubris regarding humanity's capacity and right to control its environment (Eckersley, 1992, p. 3; Carter, 2001). Technocentrism is contrasted with ecocentrism, an ideology-in-waiting, where the nonhuman has a value of its own and human intellect is far from boundless in its capacity to reconcile its material desires with the planet's well-being. Technological optimism is central to this clash and is defined as 'the confident belief that with further scientific research we can rationally manage (i.e. predict, manipulate and control) all the negative unintended consequences of large-scale human interventions in nature' (Eckersley, 1992, p. 51). Unfortunately, the critique from ideology does not go beyond this, merely inviting us to accept the charge of hubris.

Certainly, Prometheanism thinks that technological change will mitigate negative consequences to the point that they are outweighed by the gains of the intervention on an anthropocentric cost–benefit analysis (Simon, 1996, p. 227). However, as a standalone critique, the notion of endogeneity as the production of a hubristic ideology begs an empirical question about the capacity of technological change. Such empirical debates have not been kind to greens (Sabin, 2013).

Still, greens add the claim that technology cannot solve environmental problems as long as it is produced under an instrumental rationality (Bookchin, 1971, p. 133; Eckersley, 1992, p. 116). Doing justice to the concept of instrumental rationality is beyond the scope of this article; however, we can say that ecocentrists have not used it to much effect against technological optimism. Their argument goes little further than the judgement that only an ecocentrist rationality can produce the small-scale, 'soft path' technologies that can enable sustainable human flourishing (Bookchin, 1971; Eckersley, 1992; Schumacher, 1973).

Proponents of the endogenous model would disagree, at least by an anthropocentric metric, arguing that economic production can be decarbonised, for instance, and that environmental degradation exists because endogeneity has not been allowed to fully operate (Chakravorty et al., 1997; van Vuuren et al., 2010). Large-scale deployment of solar power and carbon capture and storage is behind these claims. It is not clear from the ecocentric critique why these should fail an anthropocentric test of environmental protection, or even possibly an ecocentric one, if the endogenous model's logic is taken to its conclusion. In short, the argument from ideology is under-developed, and completing it would be a nontrivial task. The first step would be to demonstrate the flaws in the theory of technological change upon which technocentrism is founded, thereby dissolving a key truth-claim. The green theory of technological change (GTTC) outlined in the next substantial section does this, and it also supplies theoretical substance to the claim that only under a green ideology can truly green technology arise. The GTTC, therefore, may well reinvigorate the green critique from ideology.

## Complexity

The most substantial green critique of technological optimism is the argument from complexity. It is, in essence, a risk argument. The premise is that the environment is made up of any number of overlapping ecosystems, each containing countless variables. Given such complexity, the impact of further variables – meaning human interference – is difficult to construe in advance with any great degree of reliability. Hence, we should be cautious and doubt our ability to either enhance utility or to solve problems through significant interventions, such as the use of sophisticated technology (Carter, 2001; Dryzek, 2005, p. 70). Humans tend to lack this caution though. Rather, action is based on 'a misconceived belief in our capacity to fully understand biospherical processes' (Eckersley, 1992, p. 28). In other words, humans can master nature. For Greens, problems like climate change are the consequences of this hubris. I refer to these sorts of problems as 'revenge effects' (Tenner, 1996). Let us examine what they mean for technological optimism.

The argument from complexity has two distinct streams. The first is merely cautionary: we should direct scientific research towards problems that might arise from technical changes and require a high degree of sophistication from supporting studies (Wolfenbarger & Phifer, 2000). This stream does not necessarily support GPT against technological optimism. In the second, more radical stream, complexity is a standalone critique of technological optimism. At its strongest, this second stream functions as a pillar of finitude, one of the two key ideas of ecologism discussed earlier.

Complexity gives finitude much more immediacy because it suggests that we cannot know when limits are approaching. Complexity means that humans can 'never be fully cognizant of all the interrelationships between the human and nonhuman worlds' (Eckersley, 1992, p. 113). Hence, limits are not something that we must manage our distance from; instead, they are something beyond our ability to know. Due to complexity, humanity could conceivably cross a vital threshold without being aware it has done so until it is too late. *Limits to Growth* gave us some idea of what this might mean when dividing the world into sectors – population, food, etc. – where growth in one caused deterioration in another; but with complexity, the interactions are far less aggregated and the possibility of negative ramifications infinitely multiplied. In principle, the deterioration of a seemingly minor element of an ecosystem could have far larger, potentially catastrophic, revenge effects.

How risky does this make the endogenous model? Complexity indicates that solutions to environmental problems may not be a net benefit, given the unforeseeable consequences, so relying on them is foolish. We can imagine extreme examples, such as geoengineering the climate, as well as less extreme interventions, like the proposed diversion of the Volga to rehabilitate the desiccated Aral Sea (Elhance, 1997). Either could result in an outcome at least as bad as the problem. Thus greens have argued that 'technological fixes' give rise only to the further need for solutions and do no more than 'perpetuate or, at best, contain rather than solve, environmental problems' (Meadows et al., 1972, p. 39). The endogenous model cannot work because, being unable to fully understand ecological problems, humans cannot ensure a thorough solution to them. Nature cannot be mastered.

The problem with this perspective is that it appeals to a risk-aversion beyond even the precautionary principle. The latter obliges safe-guarding the environment when the facts of a proposed intervention are still uncertain and there is an *a priori* case that serious harm might result (UN, 1992, Principle 15). The argument from complexity is more cautious still, effectively arguing that the environment be privileged in the presence of unknown-unknowns. This is a problematic burden: it requires actors to prove more than the absence of evidence of harm, though logically this is the most anyone can do. In effect, complexity requires that growth and capitalist prosperity be jettisoned because environmental interventions involve the unknowable chance of unforeseeable, irresolvable consequences. Moreover, it is fair to state that progress in understanding environmental systems has occurred – computer modelling, for instance, can increasingly account for a daunting number of variables – and thus that the risk of intervention has lessened. In the end, since even the precautionary principle is under significant threat, it is unrealistic to expect the wider public to buy the complexity case unless climate change, the ultimate revenge effect, can make it persuasive (Read & O'Riordan, 2017).

 

Its power to do so depends on the endogenous model. As indicated by Simon – 'a "technical fix" is the entire story of civilization' – Prometheans are content *not* to thoroughly solve environmental problems (Simon, 1996, p. 299). If the profit–ingenuity relationship works, there is no reason why it should not continuously mitigate revenge effects, each technology spurring a side-effect and vice versa. While for greens this is the very crux of the hubristic mastery thesis, Prometheans accept this scenario, considering it part of progress. They also minimise its scope. Simon argues that even as technology has increased our capacity to harm nature, it has offered ever better solutions, thereby minimising the potential for revenge effects (Simon & Kahn, 1984, p. 12). Even resolving the greatest revenge effect – climate change – costs a fraction of the welfare gains made by industrialisation, according to supporters of endogeneity like Nicholas Stern (Stern, 2006).

This is the great test of the complexity argument. The human-prudential significance of climate change cannot be doubted. If analyses like Stern's are correct, then the argument from complexity is of little strategic value. If, however, Stern is wrong, and climate solutions are beyond what financial incentives can engender, then complexity, portending potential future disasters like climate change, is of the greatest significance. The achievability of estimates like Stern's rest on predictions powered by ETC (Stern, 2006, p. 360; van Vuuren et al., 2010). A viable critique of endogeneity is thus crucial if the argument from complexity is to have its full effect.

In sum then, GPT has several important arguments that refute the notion that nature can be mastered and support its assertion that the natural is political. Technological scepticism is central to these arguments, yet none successfully critiques the endogenous model. This model gives us a plausible reason to believe that the natural need not be politicised: that the market resolves environmental problems in a way that would satisfy human-prudential metrics. Moreover, as discussed further below, Prometheanism has recently been buttressed by sophisticated computer modelling (Keary, 2016). Quite simply, these models bring ingenuity under complete analytic control within an economic framework. An essential goal of green political theory must be to break this analytic control.

## A green theory of technological change

So ecologism, to be defensible, must justify its scepticism of the capacity of humans to dictate the pace and direction of technological change. To attain this, the endogeneity of technological change that justifies Promethean optimism must be undermined. With an evolutionary theory of technological change, the fully endogenous becomes partly exogenous. The key act of creation itself is shown to be partly random, immune to economic incentives and thus utterly unreliable from an economic standpoint. Rationality and ingenuity are forcefully separated. Hence, shorn of the expectation that technology will solve environmental problems, politics must intervene.

## An evolutionary model

An evolutionary theory of technological change rests on 'the idea of directed selection imposed upon an exogenous and stochastic supply of innovations' (Mokyr, 1996, p. 113). In other words, the appearance and form of technological novelties are significantly random, and their survival depends on their fit within the prevailing environment. Technological change is thus unpredictable (Basalla, 1989; Constant, 2002; De Bresson, 2013; Smith, 1993).

I will explain this using the theoretical work of Campbell (1965) and Arthur (2009). Though unknown to each other, Arthur's work on technological change is a perfect application of Campbell's more general account of how knowledge advances. To explicate this abstract framework, I draw predominantly on Nobel Prize lectures. As Arthur (2009, p. 107) also notes, there is surprisingly little research on the creative process in technological development. It is hard to find detailed accounts of how specific, modern novelties arose. Nobel lectures are one of the few places where such details can be found. They chime well with the framework I shall outline (Akasaki, 2015; Dubochet, 2018; Geim, 2010; Nakamura, 2015; Shirakawa, 2001).

What separates Campbell's and Arthur's work from endogenous technological change is that, whereas ETC leaves 'ingenuity' as a vague and uninterrogated concept, the former supplies the process by which the creative act takes place: blind variation and selective retention, to use Campbell's terminology (Campbell, 1965). Blind variation means trial-and-error. The creative act, whereby a novelty is brought into being, is a process wherein the creator repeatedly varies the elements she is working with, be it in her imagination or in the lab, until hitting upon a combination that meets 'internalized selective criteria' (Campbell, 1965, p. 389; Arthur, 2009, p. 112). A key part of the development of light emitting diodes (LEDs), according to Nakamura, was the period of a year and a half which he spent modifying his equipment every morning, and growing gallium nitride (GaN) crystals every afternoon, until eventually producing GaN of sufficient quality (Nakamura, 2015, p. 7772). As Campbell tells us, the 'presence of a fundamental trial-and-error process in individual learning needs no elaboration or defense. Suffice it to say that recognition of such a process is found in all learning theories which make any pretense of completeness' (Campbell, 1965, p. 382). In general then, this process involves a potentially enormous number of failed trials and a successful one that the creator stumbles into blindly. This is the messy reality of ingenuity.

What prevents this process from being hopelessly inefficient is understandable from the precise definition of 'blind' within 'blind variation'. When developing the laser, Maiman did not choose the ruby at random: he had experimented with it on an earlier project (Bromberg, 1988, p. 30). If the process were completely random, nothing would ever arise from it except by fluke. As Arthur (2009, p. 121) explains, technologists create novelties by combining elements from their 'store of functionalities'. Hence, knowledge matters insofar as it narrows the parameters of the search. This should not be understood, though, to make the process trivial. Almost every scientist pursuing LEDs had abandoned GaN by the 1980s due to decades of failed experiments (Akasaki, 2015, p. 7752). Logically, if a novelty has yet to be created, no one can know in advance the number of trials required to satisfy the creator.

Hence, 'blind' means that 'variations are produced without prior knowledge of which ones, if any, will furnish a selectworthy encounter. An essential connotation of blind is that the variations emitted be independent of the environmental conditions of the occasion of their occurrence' (Campbell, 1965, p. 381). By 'environmental conditions' Campbell is referring to the second key element of his model: selection. One criterion commonly associated with successful variations is profitability. Examining the role this plays in selection shows us how effectively an evolutionary theory critiques Prometheanism.

To take an example, a strong, conductive and uniquely light material has always been of great interest to modern manufacturers and thus a profitable patent to hold. To use evolutionary terminology, variations (or mutations) like this tend to be adaptive. Materials that boast the first two of these criteria already exist, so a variation that fails in the final category would likely not be adaptive. In this case, manufacturers who desire, say, ever smaller transistors constitute the environment. Countless physicists have begun trials over the years aiming to satisfy these criteria – which thus become the 'internalized selective criteria' (Campbell, 1965, p. 389) – and reap the likely rewards. However, with each trial, the physicists cannot know if it will meet the criteria until it is completed. The trials continue until a result thought to be adaptive is found, though this usually turns out to be an incorrect judgement. As Geim (2010, p. 315), co-discoverer of graphene, puts it, 'eventually, you get a feeling – rather than an idea – about what could be interesting to explore. Next, you give it a try, and normally you fail'. Indeed, the overwhelming majority of attempts at technological creation fail (Mokyr, 1990, p. 284). Graphene was an exception.

Of course, ample funding can increase the likelihood of an adaptive result. One can employ more people to search or tighten the parameters of the search by hiring more knowledgeable searchers. Crucially though, even with these advantages, any search may have a tremendous number of possible variations. Thus, while knowledge and numbers help, and the creator may have some idea of what an adaptive variation is when they see it, the trial process itself is blind to the selective environment. This is the random, exogenous element within the creative process that endogenous theory misses. It entirely escapes human desires and control.

  

How does ETC compare to this model of creativity? It tells of ingenuity responding to human needs, be they resource shortages or harmful pollution. The need translates into a monetary incentive, either through the market or through the government replicating market mechanisms. The inescapable implication of this is that creation is automatic. As such, there can be no random element in the mix. Significantly, we have no further details from the proponents of endogeneity on how they understand the act of creation. Implication and limited possibilities allow us to guess though.

Taking endogeneity at its most reasonable, there must be a theoretical minimum level of profit-incentive beyond which one is able to draw at least the minimum number of people from the pool of creators necessary to generate a novelty with the desired attributes. These persons must also generate the novelty in an amount of time that is of no practical importance, since delays beyond a certain length are alike to failure and would necessitate political action. Novelty creation for the end of problem-solving is simply an ability at these persons' disposal. The only idea within the technological change discourse that chimes with this description is the idea of 'insight' (Campbell, 1965, p. 384). Indeed, this is surely the most powerful idea about creation in society generally.

## Critique of insight

The notion of 'genius' and, particularly in the nineteenth and twentieth centuries, the 'emergence of the inventor as hero', wrapped around mythologized figures like Archimedes, da Vinci, Brunel and Edison, indicate that certain people are simply possessors of the intangible but distinct gift of insight (Basalla, 1989, p. 57). So powerful is this view that Arthur makes a point of denying the existence of genius (Arthur, 2009, p. 123), and Campbell frames his work around attacking the 'insightful problem solving' model and what he calls the 'ideology of creativity' more generally (Campbell, 1965, p. 390). Given the dominance of this idea in society, and the absence of a suitable alternative, it seems certain that endogenous theorists had this idea in mind when constructing their model. Presumably, so prevalent is it, they felt it needed no elaboration.

However, despite this prevalence, insight does not hold up well under analytic and empirical scrutiny. For a start, it is intangible. We have no idea how it works and thus why it takes an indefinite interval to occur. For instance, it took Shirakawa ten years, a new research partner and a move to the USA to develop the electrical conductivity of the polyacetylene he had discovered in 1967 (Shirakawa, 2001). Moreover, we do not know why only certain people possess it, besides being vaguely associated with high intelligence or 'talent' in a field. And we cannot account for why it does not occur: General Electric have created myriad technologies and yet neither they, nor numerous other companies, have yet managed to satisfactorily develop hydrogen fuel cells, despite investing seventy years and countless dollars (Eisler, 2009).

Blind variation better explains the history of technological change, especially the predominance of failure. For instance, it anticipates uneven and often lengthy timescales of development. The trial process continues until an adaptive variation is produced or the searchers give up. Being random at this point, some adaptive variations will be produced very quickly and others not at all. So, the Eureka! moment-of-insight trope is really the end of a trial-and-error process. Indeed, the myth itself implies this: Archimedes was considering the problem in his head, effectively trialing different variations, before eventually identifying one that works due to the fortune of being in the bath. Also, blind variation requires no rigid separation between 'creative' and 'uncreative' people and can thus account for a person continuously failing to create before finally succeeding. It explains how unusually knowledgeable and intelligent people can lose a race for an adaptive variation. It comes down to luck: the variations they produced simply were not adaptive. Perhaps most importantly, blind variation explains far better, even if only partially, why despite the predictions of Prometheans, the world has 'not succeeded in reversing adverse environmental changes' (UNEP, 2012, p. 6). It tells us that ingenuity is too random to justify Promethean faith in the market mechanism.

## Technological possibilities and impossibilities in contemporary environmental debates

The preceding section has demonstrated that the evolutionary model is a more convincing account of technological change than the endogenous model. What does this resolution mean for contemporary environmental debates?

The publishing of the ecomodernist manifesto in 2015 added a new strand to the debate about technological change (Asafu-Adjaye et al., 2015; Symons, 2019). The ecomodernists are a loose collection of thinkers who marry environmental action with an interventionist, pro-growth and techno-optimist platform (Shellenberger & Nordhaus, 2011). They oppose degrowth, techno-sceptic thinkers who advocate a sustained reduction in 'throughput' – the quantity of material our economic system processes – and an ideological shift away from our growth-centred political economy (Kallis, 2011, p. 874).

The technological optimism of ecomodernism is different from that of Prometheanism. This is unsurprising since they come from competing traditions. The intellectual heft behind ecomodernism is heterodox economics, inspired by Polanyi and Schumpeter (Mazzucato & Semieniuk, 2017, p. 32). Prometheanism is orthodox economics. Ecomodernism also lacks scholarly depth. Academic justification for their policy positions comes almost entirely from economist

Mariana Mazzucato (Symons, 2019, p. 117). Mazzucato, though, is not an ecomodernist and her work is not prepared for the weight they put on it.

Mazzucato's big idea is 'mission-oriented' policy, where the state manages major technological changes (Mazzucato, 2018; Mazzucato & Semieniuk, 2017). The state thus plays a central role in ecomodernism; in contrast to Prometheanism, where the market is king. Mazzucato draws on examples of state-based innovation hubs, like the USA's DARPA and NASA, to show how organisations with a clear mission can spearhead technological development (Mazzucato & Semieniuk, 2017). She challenges the orthodox prejudice against the state 'picking winners', arguing that the state can play a major role in innovation.

Ecomodernists employ these findings to claim that all states can follow a western development path, without environmental consequences (Symons, 2019, p. 104). Mazzucato's theory does not support this though. She cites climate change as ideal for the state's 'mission-oriented' activities but only says that the 'entrepreneurial state' can identify areas that are 'ripe for development' (Mazzucato & Semieniuk, 2017, p. 34). Her work does not provide a predictive model of technological change, that is, a mechanism to judge how much development will occur for a given outlay. Ecomodernism therefore lacks evidence for the possibility of its decarbonised, consumerist utopia. States might deliver improvements, but to what degree? We have no way of knowing.

This chasm in their chain of justification does not appear to trouble ecomodernists. They may not understand that technological change is a poor subject for argument by analogy. Ecomodernists regularly cite Project Apollo and other famous state-sponsored technology programs (Asafu-Adjaye et al., 2015; Shellenberger & Nordhaus, 2011; Symons, 2019). However, as the preceding section indicates, no two processes of technological development are identical. Randomness means different timescales of development, but the level of difficulty can be wildly different also. As noted, most efforts at technological creation fail. The comparatively few successes are no proof of inevitable triumph.

Ecomodernism lies within the mastery of nature tradition. Say Shellenberger and Nordhaus: '[the] solution to the unintended consequences of modernity is, and has always been, more modernity – just as the solution to the unintended consequences of our technologies has always been more technology' (Shellenberger & Nordhaus, 2011). The message is that nature is entirely under control and always will be. The GTTC helpfully undermines this faith. Even technological change is not under control, so nature certainly is not. The mastery vision is a mirage.

Ecomodernism, with no model of technological change to substantiate its extremely optimistic claims, should be dismissed out of hand. Prometheanism, however, has recently developed extremely sophisticated models of technological change. The impetus has been IPCC Working Group III's mitigation scenarios (Intergovernmental Panel on Climate Change, 2014; Keary, 2016). These 'New Prometheans' ought to be the object of far more scrutiny because theirs is by far the most sophisticated and prestigious extant 'green growth' scholarship (Keary, 2016). Their computer models are predictive and appear to reconcile growth with environmental stability (Chakravorty et al., 1997; van Vuuren et al., 2010). Both the degree of incentive required and the timescale of development are illustrated. Given properly calibrated carbon taxes, New Prometheans project the market will deliver near-total decarbonisation by 2050. This sophistication and influence underscores the importance of an alternative model, like the evolutionary one above, that can critique the Promethean understanding of technological change.

The GTTC thus justifies green caution about technological change. It also justifies green positivity though: the notion that if produced under a different ideology, technological changes could improve human lives without damaging the environment (Goodin, 1992; Kallis, 2011). What would these changes look like? Greens usually focus on energy technologies, preferring them clean, small and local, as well as relatively uncomplex, so meaningful local control is possible and humans are not mere cogs in their operation (Schumacher, 1973; Goodin, 1992, p. 188). The phrase 'convivial technology' is increasingly used to capture this outlook (Kerschner et al., 2018). The GTTC shows that movement in this direction is not fanciful.

First, an ecocentric ideology would make the social environment quite different. Fracking would no longer be adaptive, whereas other neglected technologies suddenly might be. Most technologies would still fail, but, for instance, a technology thought inefficient for centralised power-generation systems might become desirable. The idea that changing the ideology can change the technology, the social dimension of technological change, is thus supported by the GTTC.

Second, it would alter the technologist's internalised selective criteria. From the social construction of technological change literature, we learn that in any technology's development there are moments when the form of that technology is decided (Bijker, 1995). A technology could conceivably develop to serve either centralised power-generation systems or local, small-scale, sustainable systems. When trialling variations, the internalised selective criteria revolve around the novelty's adaptivity. So, with a radically different ideological environment, trials are less likely to end with environmentally damaging forms and more likely to produce eco-friendly forms. There is no guarantee, and this prospect should be considered a bonus rather than a necessity, but there are grounds for cautious optimism.

Hence, we see that the GTTC performs two functions in contemporary environmental debate: it exposes major weaknesses in the arguments of the technological optimists; and it supports the green notion that technological change can help make an eco-friendly world more comfortable and fulfilling for humans.

## Conclusion

Greens have long been sceptical of technological fixes for environmental problems. They have never had strong grounds for being so. Theorists have explained this scepticism as either an instinctual distrust or the product of a particular discourse. This article both explains and justifies this scepticism. It explains that the sense among greens that technological development is unpredictable is in fact well-founded and thus justifies the movement for ecologism in the world.

It also buttresses the green challenge to modern political ideologies. The utopian visions of a Smith or a Marx rest on the assumption that the controlled environment offers unlimited abundance; that nature can be mastered by science and technology. Green thought has never just objected to the morality of this, it has always also denied the possibility. *Silent Spring* and *Limits to Growth*, for instance, both make the positive case of impossibility, thereby enabling the normative case that another path must be sought. Technological scepticism is crucial to green thought because, without it, the mastery of nature thesis cannot be rejected. This article's green theory of technological change is crucial to green thought because it is the only theory of technological change that justifies green technological scepticism.

It also reinvigorates other green critiques of Prometheanism. First, the commonplace green assertion that technological solutions merely bring upon the world new problems. This Prometheans do not deny, instead arguing that new technological fixes would appear for each new problem. The GTTC shows this confidence to be unwarranted. Second, the claim that Prometheanism is the emanation of a technocratic ideology. While this claim needs development, technological optimism is clearly not common sense. The GTTC also supports green positivity about what might be accomplished technologically if an ecocentric ideology can attain prevalence. Finally, if human ingenuity cannot be relied upon, then interfering with a planet complex beyond human understanding is a far riskier prospect. Even by a human-prudential metric, these critiques become weighty in light of the GTTC.

It also gives greens a commonsensical way to talk about technology. Many prominent scholars urge greens to adopt policies that appeal to public reasonableness (Barry, 1999; Dobson, 2007; Homer-Dixon, 2010). The public would probably repudiate an anti-technology platform. However, green over-positivity about technology risks helping those who would advocate technological, as opposed to political, solutions to environmental degradation. The optimist–sceptic fault line remains a major one in green scholarship (Kerschner et al., 2018).

Indeed, green scholars, especially in the degrowth literature, are increasingly identifying technological imaginaries – positive visions of sociotechnical futures – as important tools of popular persuasion (Jasanoff & Kim, 2015; Kerschner et al., 2018). However, they can be harmful if they encourage unrealistic expectations of technological change, which may boost Prometheanism. Moreover, ecologism probably cannot offer imaginaries as popularly appealing as those of Prometheanism. If imaginaries must be a feature of public debate, then ecologism should strive to ground them in realistic expectations of technological change.

The GTTC thus resolves significant difficulties in green thought by enabling greens to tread a clear, cautiously optimistic line regarding technological change. Greens can accept that some problems will be alleviated by technology, thereby avoiding hostages to fortune, while also arguing that technology reliance is a major gamble. We cannot know if technologies will arise to mitigate specific problems. Political solutions should be the first, not final, recourse.

Overall, the green theory of technological change allows us to say that orthodox economics does not have ingenuity under analytic control; it is not reducible to rationality so their model – and indeed all technological optimism – fails as a result. Attempts to master nature will never succeed; the natural is political.

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## Notes

1. Though this article is concerned with defending GPT, it does not aim to uphold any particular version of it. As explored below, all green political theories broadly agree on a few core premises. It is these premises that the article focuses upon. Since endogeneity denies these premises, all interpretations of GPT are threatened by ETC.

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