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Gambling with our climate futures: On the temporal structure of negative emissions

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Abstract

This paper considers negative emissions—the deliberate removal of greenhouse gases from the atmosphere by human intervention—as a future-oriented imaginary of connected social and technological order. It does so in order to examine how expectations around the development and use of negative emission technologies are managed with the help of integrated assessment models (IAMs). By treating this family of models as a case study for drawing out historical associations between the terminology of risk saturating the discourse of net-zero emissions and the modern conception of the future as an unexplored territory to be profitably colonized, the paper argues that integrated assessment modeling, as a praxis of forecast, structure and organize our experience of the future through standards of risk management and utility maximization. It concludes that to consider risk as a means of navigating between possible futures is to engage with practices that are enacted in the name of a particular understanding of how one ought to act in the face of deep uncertainty. Aside from epistemic questions of how to treat various kinds of uncertainties inherent to IAMs, of pressing concern are thus also normative questions of how its representation of environmental hazards in terms of risk are distinctively writing the contours of our contemporary forms of responsibility toward nature, each other, as well as future generations.

Keywords

Negative emissions, integrated assessment models, climate futures, sociotechnical imaginary, risk management

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Political investment into the sociotechnical imaginary of negative emissions

Future global warming is highly contingent upon the amount of greenhouse gases (GHGs) that will continue to be released through to the end of the 21st century (Allen et al., 2009). Actions that could stabilize the climate as desired have increasingly come to include the deliberate removal of GHGs from the atmosphere by human intervention, also known as "negative emissions" (Viner and Howarth, 2014). Such anthropogenic removals refer to the active withdrawal of GHGs from the atmosphere and include the artificial enhancement of biological sinks of carbon dioxide (CO_2) as well as the chemical and technological engineering of long-term removal and storage. One aspect that is particularly curious about negative emissions is the relatively prominent status that this idea has been ascribed in integrated assessment models (IAMs), especially since expectations of the future role to be played by such technologies far exceed the current state of the infrastructure.

As they provide a means to explore emission scenarios in meeting climate targets, IAMs have been at the heart of the Intergovernmental Panel on Climate Change's (IPCC) assessment of pathways toward keeping average global warming to less than 2°C above pre-industrial conditions within this century (Bui et al., 2018: 1065–1066). In 2014, Working Group Three (WG3) of the IPCC presented four Representative Concentration Pathways (RCPs) developed from over a thousand alternative emission scenarios, where approximately half of them included a significant contribution from negative emission technologies (NETs), potentially to the detriment of more ambitious levels of mitigation in the near-term (Fuss et al., 2014). Although varying widely within a range of 600–3050Gt of CO_2, a model intercomparison project based upon the expectations generated by no less than eighteen different IAMs found that the modeled use of technologies for carbon capture and storage (CCS) was projected to a minimum of 600Gt being captured and stored by 2100 (Koelbl et al., 2014), which is an amount equal to more than half of the emissions reductions required to limit average global warming below 2°C (Bui et al., 2018: 1067). It goes without saying that huge upscaling efforts will be needed to reach this level. Hence, the starting point of this paper is that "negative emissions" is not exclusively the term for a set of proposed technologies for managing climate change, nor for a design-oriented research agenda about the feasibility and efficacy of their deployment. Rather, it is at least as crucial to examine negative emissions as a "sociotechnical imaginary" (Jasanoff, 2015); namely, as an imagined form of social order that center on the expected development and fulfillment of innovative scientific and technological projects, connecting technical concerns about risk assessment and cost-effectiveness to visions about the kind of society we want to live in and how we imagine our relationship to the natural world (Anshelm and Hansson, 2014).

Considering that the current rate of CCS deployment is already falling short of the 2°C pathway (IEA, 2016: 67–69), all the while they are yet to be demonstrated on a commercially viable scale, policymakers are entering a terrain of significant uncertainty and considerable risk should they come to rely upon this sociotechnical imaginary. To begin with, none of the NETs that figure in IAMs with the explicit purpose of balancing emissions currently exist anywhere near the scale required to meet the projected amount of GHGs to be captured and stored as per the IPCC's RCPs. Secondly, many of these technologies are likely to face a range of economic, institutional, and social hurdles to large-scale adoption (Buck, 2016; Muratori et al., 2016; Muri, 2018). This suggests that we are still at the stage in the development of NETs in which the management of expectations constitutes the main battlefield upon which our climatic as well as political economic future on this planet is now being decided (Carton, 2019: 751–752). Even more striking, then, is the prominence ascribed to CCS in scenarios assessed by WG3, and the magnitude of the expected role to be played by NETs in the projected de-carbonization pathways of the IPCC. Something that ought to concern us is thus how NETs have been mobilized within IAMs, particularly in relation to the discursive structure that governs their production of knowledge, but also with regards to their impact on the global governance of our planetary environment. It is arguably at the interface between science and policy that the question of the influence of non-epistemic values on knowledge production, and the normative dimension of future making, is most striking. Yet, the discursive conditions for the construction of the sociotechnical imaginary of negative emissions in IAMs have received surprisingly scant attention. When it comes to global environmental assessments in general, the link between foresight and governance—such as the implications of an increasingly future-oriented and explorative mode of producing knowledge for the structure of the political process of decision-making—has been insufficiently researched, remains badly understood, and consequently requires further exploration (Lövbrand, 2004; Vervoort and Gupta, 2018). It is this absence in the existing literature on negative emissions that the present paper seeks to address.

Integrated assessment models as epistemic technologies

In order to clarify what is at stake in this paper, it might be useful to draw upon a slightly modified version of Carton's (2019: 751–752) analytical distinction between (1) technical concerns with the potential risks, opportunities, and trade-offs of specific NETs; and (2) interpretative concerns with the discursive construction of a so-called "horizon of expectation" (Koselleck, 2004: 255–275) against which such a technological fix may be framed as a solution to a warming climate, and the social implications of global warming subsequently made intelligible in terms of *risks*, *opportunities*, and *trade-offs* (See also Schneider, 1997: 230). To insist on the latter of the two—which I will do herein—is to stress that whenever one is immersed in technical concerns, there is already a terminology in use; and moreover, that such terminology draws upon the semiotic well-spring of a larger discourse. A pressing albeit yet under-researched avenue is thus the question concerning the discursive formation of a coherent set of techniques and technologies that defines integrated assessment modeling as an epistemic community (Haas, 1990: 349–354). Granted that such assessments produce explorative projections of the future, they do so based on a set of discursively inscribed rules that govern the "temporal structure" (Koselleck, 2004: 93–97) that policymakers then must relate to. Indeed, leaving aside the ontological question about the ubiquity of the nature of time, human experiences of temporality are culturally specific. As has been argued by the geographer David Harvey, our conception of time is not merely a framework of material practices but an essential element of the constitution of political action and social reproduction. Rather than a universal a priori form of sensible intuition, there is a cultural dimension to temporality that is dependent upon collective action and interaction. "Each social formation," Harvey (1990: 419) writes, "constructs objective conceptions of space and time sufficient unto its own needs and purposes of material and social reproduction and organizes its material practices in accordance with those conceptions." In other words, the cultural structuring of the experience of time generates certain social patterns and relationships, with consequences for the values held and the prospects perceived (Harvey, 1989: 201–210).

To understand the role played by integrated assessment modeling in the construction of the sociotechnical imaginary of negative emissions, the aim of this paper is to examine the relationship toward the future established by IAMs in their role as epistemic technologies. This is to acknowledge that negative emissions, as an imaginary, has taken shape in a scientific—as well as, partly, a legal, political, and administrative—culture (Hulme, 2015: 9), and therefore has an intellectual history that forms the substrate out of which beliefs, claims, and disputes about the feasibility and desirability of NETs emerge (Hulme, 2017). As a set of social practices, such knowledge-producing techniques and technologies do not merely offer useful information but mobilize the future as a strategic resource for the sake of shaping present-day arrangements—be they social, cultural, political, technological, or economic (Jasanoff, 2020; Saltelli et al., 2020). "What is of interest here," to quote Beck and Mahony (2017: 2), "is the performativity of scientific assessment – that is, the ability of particular descriptions of the world to act upon, transform or bring into being the objects they describe, not just through the direct informing of policy decisions, but through the wider conditioning of the world[.]" Such an approach takes interest in how the negotiation of the role of negative emissions in IAMs is governed by a particular way of looking at the world, a particular understanding of how to grasp the world scientifically, and a particular understanding of how it is fundamentally constituted. It requires taking seriously on its own terms the *raison d'être* of integrated assessment modeling so as to carefully examine the conditions upon which NETs become a meaningful vehicle for political decision-making—thereby opening a field of possibilities for social change, albeit simultaneously also restraining the same field in accordance with its underlying rationale.

Of course, building a coupled climate–economy model inevitably involves normative judgments—judgments that are paramount in articulating the kind of futurity that we are then held accountable toward. The amendment of NETs to the coupled climate-economy models' technology portfolio is an excellent case in point, for the problem of investment project selection evidently necessitates a prospective as well as a prescriptive view. Which projects, for instance, should be implemented to maximize intergenerational welfare? Clearly, the solution to this problem relies, among other things, on a particular understanding of, and on certain beliefs about, the social and material dynamics of our late capitalist societies and their underlying drivers of global change (IPCC, 2014: 364–385). It also requires an implicitly agreed upon definition of sustainable development (IPCC, 2014: 292), as well as a shared methodology to translate such concepts into operational rules for asset pricing (IPCC, 2014: 225–234). Exploring the cost-optimal pathways to reach set targets, such models are constrained not only by climatic parameters and dynamics, nor even by a wide range of assumptions about the global price of carbon and a perfect global market, but also by a horizon of expectation against which future emissions may become governable in financial terms of a carbon budget and made available for practices of risk management. Hence, my objective is neither to offer solutions nor to propose definitions, but rather, in the words of Daston (1994: 284), to raise "[…] the Kantian question about the preconditions that make thinking this or that idea possible." In short, given that IAMs establish a certain experience of time by means of a discursively inscribed relationship toward the future, I am interested in the temporal structure of negative emissions. Against the background of which "time horizon," to borrow an expression from Harvey (1990: 420), do negative emissions become a meaningful imaginary?

Computer-based simulation and the significance of subjective probabilities

So, what kind of knowledge is it, then, that IAMs produce, and what are its implications for the temporal structure of negative emissions? Well, we may begin by noting that IAMs are a family of computer models that have sought to couple biophysical with socioeconomic systems to capture the interaction between climate and economy (IPCC, 2014: 50; IPCC, 2018: 100). Although integrated assessment modeling as a designation is often used to describe the development of a wide range of models that may vary considerably in the ways in which they work and the questions that they can answer (Kelly and Kolstad, 1999; Parson and Fisher-Vanden, 1997), there have nevertheless been, broadly speaking, two main types involved in articulating the sociotechnical imaginary negative emissions. Firstly, a type of highly-aggregated cost-benefit IAMs modeled to calculate the so-called "social cost of carbon" (SCC); that is, the quantifiable costs and benefits of carbon dioxide emissions in monetary terms, so as to estimate the optimal mitigation level utility-wise, relative to economic costs of climate impacts. Secondly, a process-based type of stochastic IAMs that link modules representing the social and economic factors that drive GHG emissions with the atmospheric and biogeochemical factors that determine its resultant effect on human welfare (Weyant, 2014; Wilson et al., 2017). These two types of IAMs differ in their degree of complexity as well as in their intended use (Weyant, 2017: 116–124). The former will always produce the same output from a given starting condition or initial state. Often, they use a particular type of Monte-Carlo simulation: Drawing values for a set of uncertain parameters from a joint distribution, simulating each draw in the model, and then averaging results and presenting mean, variance, percentiles, etc. It is crucial to recognize that these models are essential technologies for exploring possible future outcomes for a given policy, not to prescribe an optimal policy (Crost and Traeger, 2013). Meanwhile, the linkages built into the latter type of IAMs means that they are, on the contrary, able to simulate large ensembles of scenarios in order to explore poorly understood or previously unanticipated consequences—such as co-benefits, policy synergies, and cascading effects—and thereby generate policy options whose performance is maximally insensitive to various associated uncertainties. Their objective is to give as good estimation as is presently possible of the probabilities characterizing the residual risks of deciding what mitigation strategies to invest in and when (Lempert et al., 2004: 4–5).

Epitomized by the IPCC as an organization operating at the interface between climate science and international policymaking (Miller, 2004), such a mode of producing knowledge has conventionally been termed "post-normal" (Funtowicz and Ravetz, 1992; Haikola et al., 2019a: 47–49). In fact, reasoning based upon subjective probability has increasingly come to be recognized as an indispensable tool for dealing with issues "[…] where facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz and Ravetz, 1993: 744); and seeing as climate change is the quintessential wicked problem of our age, the post-normal is more likely, in this case, to become accepted as the new normal. For while it is certainly true that objectivity remains the ideal even for the climate sciences, the fact that the knowledge we can gain from these models has enormous public policy implications thereby also necessitates an entirely different kind of responsiveness to policymakers' needs for expert judgment, whom are in such a position that they do not have the luxury of putting off decisions indefinitely (Nordhaus and Popp, 1997; Ravetz, 1987). Since these are questions that involve scientific knowledge and its present limits, modelers are encouraged to provide assessments that are built on highly uncertain findings of the best available research "[…] at a particular time, given the information currently available, even if those judgments involve a considerable degree of subjectivity." (Moss and Schneider, 2000: 36). This is made especially palpable in regard to the kind of knowledge that IAMs produce; namely, projections which, as integrated assessment modelers themselves have been keen to point out (Haikola et al., 2018: 22–23), are subject to varying degrees of structural and parametric uncertainty (Foley, 2010: 651–653; Gillingham et al., 2018; Winsberg, 2010: 100). Since such model-outputs can be evaluated only in comparison with other models and in conjunction with historical data (Oreskes et al., 1994), integrated assessment modeling has been characterized as a pragmatic effort to map out the sample space of possible climate futures (Ackerman et al., 2009: 297; Weyant, 2017: 117). By assuming that a distribution from members of the ensemble of models will asymptotically approximate the probability of random variables by indexing the dimensions of a recursive blind-spot (Saltelli et al., 2015: 81–82; Van Vuuren et al., 2014: 383–384), the aim is to explore the structural difference between the various modeled climate-economy systems.

Although the distinction between structural concerns on the one hand and parametric concerns on the other is a simplification of the distinct types, nature, and nuances of uncertainty that scientists and policymakers must deal with in the context of global environmental assessments (See, for instance, Beck and Krueger, 2016; Haikola et al., 2019b; Mehta et al., 2021; Mehta and Srivastava, 2020), a more comprehensive treatment of the diverse understandings, politics, and implications of uncertainty in such assessment processes lies outside the scope of this paper. Instead, it suffices to note that IAMs are built in the face of pervasive uncertainty and that modeling choices determine how the current state of knowledge about the elements and processes of various systems is represented. "Most fundamentally," the authors of WG3 of the IPCC acknowledge in their technical summary:

> integrated models are simplified, stylized, numerical approaches for representing enormously complex physical and social systems, and scenarios from these models are based on uncertain projections about key events and drivers over often century-long timescales. Simplifications and differences in assumptions are the reason why output generated from different models – or versions of the same model – can differ, and projections from all models can differ considerably from the reality that unfolds. (IPCC, 2014: 58).

While output may vary greatly depending on the characteristics of the models—reflecting their translation of concepts into operational variables as well as the underlying assumptions they proceed from—the idea is that their simulation *en masse* nevertheless may provide indications of findings that are "robust" across models and different assumptions (IPCC, 2014: 172–173. See also Lempert et al., 1996, 2004; McJeon et al., 2011). Robustness, in this context, is a technical criterion that designates a formal response to conditions where experts disagree about structural choices in the construction of models or the prior probability distributions for the key input parameters to those models. In such cases, the pragmatic solution is understood to be one of characterizing the vulnerabilities of various strategies to evaluate the trade-offs between them (Lempert et al., 2006; Van Bree and Van Der Sluijs, 2014). For the purposes of IPCC's Fifth Assessment Report (AR5), there were thus no less than 1888 scenarios collated from integrated modeling teams around the world (IPCC, 2014: 8n12, 10, 51). In this manner, precisely by taking advantage of the marriage of calculus with probability through the aid of sophisticated computer technology, the idea is that IAMs, although they are not built to confidently prescribe specific requirements for climate goals to be met, may nevertheless provide policymakers with a "map" to probabilistically navigate the trade-offs and consequences related to various scenarios based upon an iterative and adaptive process of robust decision-making (Edenhofer and Kowarsch, 2005; Haikola et al., 2019b; Workman et al., 2020). In the words of WG3, summing up their contribution to the AR5, the task of integrated assessment can thus be understood as an "[…] explor[ation] [of] the solution space of climate change mitigation drawing on experience and expectations for the future," wherein one of the "[…] four major pillars to this cartography exercise" consists in "risk management" (IPCC, 2014: ix).

What is astonishing about the above description is that it manages to tick most of the boxes of what sociologists of modernity, such as Beck (1992: 50), have found characteristic of "[…] the change in the […] views of reality and in the norms of knowledge" that defines the emergence of so-called "risk society." In order to grasp what is discursively at stake in the knowledge production of integrated assessment modeling, we shall therefore do well to first put this set of epistemic techniques and technologies in the context of the cultural shift to the experience of the future that pertains to modern developments to computation. In particular, we will focus on the concomitant success of a quantitative attitude that subverted futurity's heretofore end-oriented trajectory in favor of the metaphor of an unexplored territory to be pragmatically charted through the art of probabilistic navigation.

Charting out futures against a time horizon of risk

The intellectual history of risk management is situated at the intersection between mathematical and statistical experimentation on the one hand and commercial interests on the other (Bernstein, 1996, 1998). What sets the notion of "risk" in risk society conceptually apart from premodern practices of mitigation is that it acquired, in modernity, a profitable or expedient sense. For throughout most of Western history, the notion of the future as a frontier to be potentially exploited has been the exception rather than the rule. Up until late-medieval society, mitigation was limited to external risks; that is, to buffers against the capriciousness of nature, such as improvements to the surpluses of agriculture and the fortifications of townships, reinforced by piecemeal advances in areas such as crop specialization, rotation systems, and new methods for managing wind and water, all in order to offset natural disasters like famines, droughts, and storms (Merchant, 2016: 64–67). A noticeable absence of the profitability of risk prior to the 16th and 17th centuries is telling because it is contingent upon an impossibility, similarly prior to this juncture, to conceive of unanticipated long-term benefits or costs associated with the notion of certitude as, at best, an approximation (Moynihan, 2020b: 234–235).

Late-medieval commercial bookkeeping is often cited as an explanation of this kind of shift, and so too is Fibonacci's 13th-century explication of *Modus Indorum* arithmetic alongside the introduction of place-value notation (Devlin, 2011). Nevertheless, it also concerns a wider ontological step away from the organic lifeworld, with its tangibly apparent intervals of cyclical time, and toward, in its place, abstract formalizations suitable to the iterative mechanism of time-stepping procedures. Articulated in the new fields of probability and statistics, the de-semantification wrought by number as an operative scheme stimulated a gradual move away from belief in fate and divine providence. With its roots in the 16th-century polymath Gerolamo Cardano's proficiency in gambling and his interest in the odds of the dice game of hazard (Beck and Kewell, 2014: 18; Hacking, 2006: 122–133), the concept of equipossibility rendered what had previously been apprehended as impenetrable *fortuna* subject to mathematical experiment (Reith, 2004: 388). What the historical intersection between the emergence of probability and the newly attendant willingness to speculate on the future indicates is that the future could only be rendered instrumentally useful after it had been relinquished from the fetters of qualitative contentfulness and instead submitted to the purely quantitative computability of formal systems. In short, the future could become intelligible as an open-ended frontier first in the wake of having been stripped of self-presenting meaningfulness.

Noteworthy, here, is the wider reconfiguration of the subject's relation to the future; namely, one wherein the concepts and norms in accordance with which futurity comes into view themselves become subject to risk assessment, precisely because the future is imagined to be inherently indifferent to value-laden meaning. Although first inaugurated by the 17th century mathematician Jacques Bernoulli as "subjective probability" (Hacking, 2006: 146–147), there had already been a growing interest—at least since Blaise Pascal's famous Wager extrapolated Cardano's conception of a sample space beyond the domain of dice games to conduct risk-benefit analyses concerning issues of religious belief—with how, in general, to accurately assign, from observed effects, probabilities as the precise measurement of one's confidence in reasoning upon unobserved causes. Using "uncertainty" to refer not to things but rather to the mechanics of inference itself (Daston, 1988: 226–295), the 18th-century articulation of subjective probability expedited this *longue durée* loss of epistemic foundations. It indicated that one does not reason, analytically, from secure certitudes, but only infinitely approximates certitude by employing numerical values to track one's confidence or degrees of belief regarding the unknown, and then pragmatically update one's opinions relative to the incoming data (Carnap 1962: 182–187). Thusly, the Presbyterian minister Bayes (1763: 392–393) later wrote of the need for a rule of inference

"[…] in the case of an event concerning the probability of which we absolutely know nothing antecedent to any trials made concerning it," leading him to produce the first domain-agnostic rule for reasoning under uncertainty.

Crucially, this procedure marks uncertainty as epistemically informative rather than something to be eliminated. For if one can find a way to estimate one's own ignorance, then one can also reason productively upon threats entirely beyond experience, precisely because a lack of experience can be grasped as itself a measurable threat. Risk, thereby, is conceptually detached from the frequentist concern with bounded objective regularities and instead expands to become the subject's comprehending optic in accordance with which the future comes into view. By gradually rendering unknown unknowns into known unknowns—or, at the very least, by acknowledging that the subjective position of observation is itself bound up with risk (Moynihan, 2020a: 9)—such a break with circumspect foundations empowers the human only in exact step with ever further immersing it in a field of global risk. In this self-reinforcing manner, the internal dynamics of an increasingly future-oriented culture tend to generate new and ever more intractable, encompassing, and complex forms of hazard—a phenomenon that Giddens (1999a: 4–10) has called "the manufacture of risk." As opposed to external risk—experienced as coming from the outside and caused by nature, such as bad harvests, floods, and famine—manufactured risks are generated by the activities of humans. This is why Beck (1992: 21) similarly defines risk as "[…] a systematic way of dealing with hazards and insecurities induced and introduced by modernization itself." As the subject seeks to elucidate, to itself, the extent of its own incertitude, the modern acknowledgment of limits to knowledge reformulates "finitude" from that of ignorance about external risks to that of insight about internalities (Ewald, 1991: 199). Given these newly strengthened sensitivities to the scope of limitations upon its own experience, the subject institutes the conditions that motivate, on its part, a pragmatic and self-correcting pursuit of increasingly efficient problem-solving (Lyotard, 1984: 41–47).

In the modern sense, risk thus denotes the usefulness for the subject to track its confidence in its own predictions of strategic utilities and affordances. As opposed to confidence in a world completely insulated from hazards, a risk society seeks instead to render itself sensitive to the internality of threat to mitigation. "To know risk, to find a capacity to calculate uncertainty, in these terms" is, to quote Amoore (2013: 71–72), "not at all the same as knowing dangers, recognizing threats, or averting uncertain futures. […] [Because] to achieve complete security, absolute knowledge of the future and all it holds, would be to fail to capitalize on the potential rewards." Whereas the ideal of a perfect forecast seeks to eliminate the unpredictability of futural events under infallible anticipation and thereby to cancel risk altogether, a risk society is on the contrary one which is not only keen to, but fundamentally reliant upon, harnessing ever new uncertainties and insecurities as domains for further expansion. To view the future against a time horizon of risk is not to seek security but to render the future *securable*; namely, to embrace futurity's riskiness in order to afford sufficient *securability* for rewards to be realized even in the face of a constantly lingering possibility of loss (Baker and Simon, 2002: 1–22).

Along with the birth of calculus and probability, then, the future suddenly became subject to entirely novel mechanisms of power. For by treating the future as a colonial outpost, it can either be utilized as a temporal dumping ground for negative externalities—such as environmental degradation and public debt—or as a potential source of profit by establishing a futures exchange that allows for the creation and transaction of derivatives (Boden, 2005: 190–192; Giddens, 1991: 133; Lysandrou, 2016). As the maximization of profit became an increasingly important exercise of power, the future, in step with epistemic techniques of knowledge production bent on rendering it functionally useful for instrumental exploitation, was thus mapped out in a manner akin to that of a trade route. Since economic benefit lay in insuring one's business against, as well as speculatively seizing upon, futurity's riskiness, it was henceforth unavoidable that such a mapping would become increasingly comprehensive and sophisticated. In order to gain a competitive advantage over others on the market, economic concerns such as rates of profit, interest, and wages thereby rationalized the heterogeneous time of the medieval scholastics and encouraged the conception of it as something homogenous and universal instead, bringing about a revolution "[…] in mental structures and their material expressions." (Le Goff, 1980: 35). With its new location in the abstract institutions of commerce, the future was liberated from the symbolic representation of higher meaning and separated from its interdependence with place (Reith, 2004: 388).

Accordingly, the mid-16th century represents the first time that "risk" entered the English lexicon. First used by long-distance maritime explorers as they set off on an expansive search for new territories to feed burgeoning capitalism, the modern concept of risk then infiltrated the professional lexicon of seafaring traders and their financial benefactors (Nacol, 2016: 2). Indeed, "risk" seems to have entered the English vocabulary through either Spanish or Portuguese, where it was employed to refer to hazards specific to the context of sailing into previously uncharted waters. Since its inception, risk in the modern sense thus had an orientation to geographical space, tied to the business of marine insurance (Ewald, 1993: 226; Giddens, 1999b: 1). As this spatial image was transferred to the temporal domain—primarily through its usage "[…] in banking and investment, to mean calculation of the probable consequences of investment decisions for borrowers and lenders," and from which it "[…] subsequently came to refer to a wide range of other situations of uncertainty" (Giddens, 2000: 38–39)—the practice of risk management became a carrier of a built-in tendency to spatialize time (Gross, 1981). Suddenly, with a coeval explosion of insurance industries, alongside the maturation of financial markets and practices of speculation, the very "space" of the future had become a profitable territory and risk a lucrative business (Moynihan, 2020a: 8). From thereon, the institution of insurance exploded during the late medieval commercial revolution, finally reaching its full development as a commercial concept in the 18th century (Bernstein, 1998: 92). Parallel to a new protestant ethic flowing out of the Lutheran reformation (Maier, 1987: 154; Weber, 1992), the future increasingly came to resemble a *terra incognita*—one to be mapped out for the sake of profit-seeking.

Constituting the social cost of carbon as a bundle of securable assets

Institutionalized in the burgeoning insurance industry, it was this particular notion of risk that, as the 19th-century economist Léon Say (quoted in Ewald, 1991: 199) noted, became "[…] the very object of [the] type of contract" that the modern subject as *homo economicus* entered in the market for security. It was through this shift toward an economic conception of the human as an atomistic individual making investment decisions based on rational calculations of how to maximize utility from a point of self-interest, that Foucault (2008: 283), in his lectures on the modern reorganization of governmental practices, identified the associated emergence of novel techniques and technologies designed specifically to exploit the internality of threat to mitigation by means of a logic of insurance. Such a conception places a particular philosophical anthropology of the human as an economic subject at the basis of politics, and then, with reference to our human nature, it refigures the operative terms of society from that of rights and laws to interest, investment, and competition. Accordingly, the discourse of risk management "[…] becomes an entire way of life, a common *sense* in which every action can be charted according to a calculus of maximum output for minimum expenditure." (Read, 2009: 31, my italics). In short, everything comes into view as a potential asset (Foucault, 2008: 267–268). As resonating forms of power, these techniques and technologies transformed risk from that of a mere impediment to a potential prospect, which would prove highly innovative since it offered a means of harnessing the profitability associated with uncertain futures. By interpreting the logic of insurance as a general "[…] scheme of rationality, a way of breaking down, rearranging [and] ordering certain elements of reality[;] […]

[namely,] a certain type of rationality: One formalized by the calculus of probabilities," Ewald (1991: 199) has observed that the modern concept of risk is intimately tied to a wide-ranging cultural shift whereby "[…] gaming becomes a symbol of the world." According to Ewald, such insurance technologies do not only passively administer risks; they actively generate them as economic opportunities in accordance with a speculative marketplace of asset-backed securities (Dillon, 2008; Ewald, 1991: 198–200). "By objectivizing certain events as risks," he notes, "insurance can invert their meanings: It can make what was previously an obstacle into a possibility. Insurance assigns a new mode of existence to previously dreaded events; *it creates value*." (Ewald, 1991: 200. See also Martin, 2007: 67).

Now, looking at the temporal structure of negative emissions, and at how this sociotechnical imaginary has been constructed in IAMs, the modern concept of risk is crucial for understanding why and how NETs have been modeled therein as the potential realization of the idea of carbon neutrality; that is, net-zero emissions. In the context of contracting carbon budgets, including the rate and scale of mitigation required to remain within these budgets, the ability to remove CO_2 from the atmosphere and store it for extensive periods of time theoretically also enables overspending (Mander et al., 2017: 6038); and to overspend, in turn, is to wager on a certain expected rate of future economic growth to pay for mitigation and adaptation. "Negative emissions," as Carton (2019: 758) has noted, therefore:

> take the carbon budget concept to its inevitable conclusion, by accounting not just for carbon "expenditures" (that is, emissions), but also a range of proposed carbon "incomes." This idea takes its inspiration from a number of biological (e.g. photosynthesis) and chemical (e.g. weathering of rocks) processes that remove CO_2 from the atmosphere, and imagines that these could be deployed at a massive scale in order to make a limited carbon budget stretch further.

It is the option to overspend a carbon budget that has made NETs attractive as a means of delaying and thereby discounting mitigation costs, because it potentially enables more ambitious targets to become feasible at the same cost—or less—than presently possible (Friedlingstein et al., 2011; Huntingford et al., 2012; Rogelj et al., 2015; Van Vuuren et al., 2013; Van Vuuren and Riahi, 2011). Progressively "buying time" by borrowing GHG emissions from the future, the conceptualization of negative emissions may in this manner justify a delay in peak emissions or even facilitate an overshoot of atmospheric GHG concentrations (Huntingford and Lowe, 2007: 829). Importantly, this is because integrated assessment modelers rely upon a utilitarian understanding of value (Ackerman et al., 2009: 300). In order to maximize it across generations, they then invoke subjective-probabilistic estimations about the relative returns on a set of alternative investments, which, when weighted against an expectation of compound interest, can be likened to a risk assessment of how much utility may be gained or lost by further delaying mitigative repayment in the face of uncertain futures. "The logic," to quote the climate economist Nordhaus (2007: 687):

> is straightforward. In a world where capital is productive, the highest-return investments today are primarily in tangible, technological, and human capital, including research and development on low-carbon technologies. In the coming decades, damages are predicted to rise relative to output. As that occurs, it becomes efficient to shift investments toward more intensive emissions reductions.

Resorting to a technique of discounting, a lot of the ensuing disagreements in the modeling community have ultimately come to hinge upon the appropriate rate against which to calculate the real return on capital (Arrow et al., 1995: 1–2; Emmerling et al., 2019; Stanton et al., 2009: 173–175). While a larger discount results in a greater return, a higher rate of interest paid on debt also equates with a higher level of risk. In order to judge whether the present value of a bond is either over or underestimated, the SCC calculated from these priors must thus be informed by simulating it against the background of the coupled climate–economy system to explore any unanticipated outcomes, and then, in a Bayesian manner, update the priors accordingly (Moss and Schneider, 2000: 36; Rogelj et al., 2013; Rotmans and Van Asselt, 2001: 48).

At first glance, this does not seem to constitute a challenge to the classical scientific ideal of value-neutral theory. It even underlines that the role of integrated assessment modelers is not to validate or reject scenarios but merely to assign probabilities to them (IPCC, 2014: 40). Once modelers have assigned probabilities and communicated this information to "rational agents," it is up to these agents themselves to decide whether the scenario is worth acting upon. What is more, IAMs have also been intentionally kept exempt from the task of indicating the *feasibility* of emission pathways, because pathways are constrained not only by economic costs and technological development but also by the controversial question of political acceptability (Jewell, 2019: 349). However, in spite of such a first impression, is not the discourse of risk management complicit in making sense of the kind of future in relation to which negative emissions as a sociotechnical imaginary is constructed in the first place, even before modelers may begin to agree or disagree on technical concerns with specific NETs? For if the aim of risk calculus is to exploit the internality of threat to mitigation, it does so indirectly to the detriment of a precautionary attitude toward "[…] 'tail risk,' that is, the likelihood or possible impact of a catastrophic climate outcome." (Pindyck, 2017: 101). As a matter of fact, critics who have argued that IAMs are "the wrong tools" (Anderson, 2019: 348; Keen, 2021: 1168; Pindyck, 2013: 860; Stern, 2016) for informing policymakers about pathways for emissions reductions have pointed to the way uncertainties have been modeled therein; namely, as a probability distribution, thus disregarding the Knightian distinction between uncertainty and risk (Saltelli et al., 2015: 83). This is telling, especially in respect to the historical trajectory of the discourse of risk management that we have traced so far, because it neatly demonstrates the enduring presence of a whole intellectual genealogy of colonizing the future by restricting our horizon of expectations to a representation of probabilities.

Using an expression coined by Taleb (2007: 309), one might say that the sociotechnical imaginary of negative emissions suffers from a historically entrenched tendency to relate to the future that is particularly likely to fall victim to "the ludic fallacy." Paraphrasing Taleb, the ludic fallacy refers to an erroneous ontological equivalence between the unstructured randomness of nature and the structured randomness of games, such that one may come to believe that the unforeseen may be anticipated by extrapolating from variations in statistics based on past observations, and that one may therefore "[…] bas[e] studies of chance on the narrow world of games and dice," and then model real-life situations accordingly. While systems of probabilistic reasoning enable the surveying and mapping out of possible futures, this is to caution that they are useful as instruments to leverage risk for financial gain only if the future remains in relative continuity with the past (Knight, 1964: 313; Stirling, 2007: 309–311). Furthermore, unforeseen contingencies will register as significant only insofar as they do not entirely disrupt the modeled climate–economy system. But as should be evident by now, the failure to separate uncertainty from risk is especially vicious when we are talking about Black Swans the size of global climatic tipping points. Once we are led to update our priors due to some sudden change in the dynamics of the climate system, we may already face a catastrophic run-away scenario from which there is no going back. Although an incremental improvement to our understanding of the global climate system's response to anthropogenic GHG emissions provides us with more accurate odds upon which to wager on the optimal price for valuing the SCC, the point is that when we are concerned precisely with a *changing* climate, the conditions for which these odds have been calculated may suddenly no longer apply.

Since the prudentialism of settled out categories in risk modes that rely upon statistical probabilities are likely to underestimate the emergence of statistically significant events, these two worlds—of statistical probabilities on the one hand, and emergent possibilities on the other—are difficult to hold together (Amoore, 2011). For this reason alone, we would seemingly do well to heed Amoore's (2013: 67) proposed distinction between *risk probabilities* and *risk possibilities*. But as Amoore maintains, and which I believe is further confirmed by the case of integrated assessment modeling, the poverty of probability in anticipating radically different futures does not therefore signal the limit point of risk calculus. On the contrary, it is precisely because strict probability tends to occlude the improbable that speculation and inference have been introduced into such calculative efforts. "The contemporary form of risk calculus," Amoore writes, "works hard to keep *both* in view – the insufficient probabilities that continue to supply elements of the underlying risk data, *and* their inferential counterparts of associated possibilities. It is precisely this work that is the work of the derivative" (Amoore, 2013: 75, my italics). This may help explain why—despite recurrent references to a whole slew of parametric and structural uncertainties to which IAMs are subject, both from integrated assessment modelers themselves as well as from their critics—reflections on the epistemic limits of integrated assessment modeling have generally failed to consolidate into support for a precautionary attitude to emissions reductions. Quite to the contrary, it seems rather have introduced additional risk-seeking behavior. Faced with uncertainty about what is known concerning the risks of global warming, prudence has not become a matter of acting effectively to remedy the source of injury. Instead, our computational machinery of foresight has been employed as a means of rationalizing not only the delay of action (Low and Boettcher, 2020) but even the voluntary exposure to chances of harm, merely because it is implied that there resides in this chance the possibility of profitability.

Once we put the sociotechnical imaginary of negative emissions in the context of its attendant discourse of risk management, with its intellectual roots in the conceptual transformation of limits into opportunities, this kind of ludic rationalization begins to look far less surprising. In fact, "[...] a willingness to balance relative costs and benefits," Winner (1986: 145) has noted, "is inherent in the very adoption of the concept of 'risk' to describe one's situation." Adopting risk assessment as a legitimate activity is to define the field of discourse in a way that helps shape the appearance of the problem, along with the methodological quagmires that are entailed in addressing it "properly": Rigorous standards of scientific certainty are emphasized to demonstrate how little is known about relationships of cause and effect; methods of cost-benefit analyses are brought onboard to fill out the balance sheets of possible futures; and statistical probability is employed to indicate that the "rational choice" available is the one that maximizes utility in the face of deep uncertainty (Winner, 1986: 149–150). As "risk" names an anticipated advantage associated with the internality of threat to mitigation, there is thus an implicit value judgment at work whenever this kind of terminology is used in any area of assessment and policy discussion, connected to the presupposition that the source of possible injury is also a source of potential benefits. Viewed against the time horizon of risk, it is the adaptability to act upon the riskiness of possible futures—by turning crises into new investment opportunities as they emerge and unfold—which will appear as the reasonable response toward the demands it puts upon us in the present.

What the derivative introduces, then, is merely the addition of a speculative dimension to risk calculus' already entrenched practices of securitability. In fact, the very concept of a derivative has long been considered to have the same kind of "[...] strangely imaginary or virtual character" (Arnoldi, 2004: 23) as NETs (Carton, 2020), underscoring the potential asymmetry between expectations and reality. As it is in the nature of the derivative to allow for exposure to the risk-reward characteristic of underlying assets without even having to possess them (MacKenzie, 2009), then by treating NETs as financial securities, speculation upon their possible implementation may take place without any of them being actualized on any meaningful scale (Markusson et al., 2017: 3–4, 7). Such a speculative dimension assures that this imaginary is more than an impotent delusion too, transforming it into a vehicle for economic and political consequences. It is, for instance, what allows for the investment bank Barclays, through the acquisition of the carbon trader Tricorona, to capitalize on its pre-2012 carbon offset portfolio of 43.7 million tonnes—which itself is only a drop in the sea of the contemporary $144 billion global carbon emissions economy (Paterson and Stripple, 2012: 563–564). Coupled with Carton's (2019: 762) observation that "[…] the main mechanism by which negative emissions operate is through the temporal deferral of mitigation action," we may surmise that one of the most significant consequences of this sociotechnical imaginary has been its successful enrollment of GHG emissions into yet another debt obligation—one which may thereby be profitably speculated upon on a derivatives market (Cooper, 2011: 177).

So, whenever negative emissions are enrolled through means of cost-benefit analyses, such reasoning ought to raise the question of what kind of subjectivity is implied when risk-seeking behavior is justified in the name of utility maximization, and whom it is that stands to gain from it (Lövbrand et al., 2015). Because the subjective-probabilistic approach of integrated assessment modeling highlights the fact that the discourse of risk management that underlies the sociotechnical imaginary of negative emissions involves a hefty degree of judgment on the part of integrated assessment modelers to constitute a population against which risk can become calculable by actively selecting and dividing the risk in question (Beck, 1992: 26; Ewald, 1991: 203). As pointed out by Ewald (1991: 1999), "[…] nothing is a risk in itself; there is no risk in reality. But on the other hand, anything *can* be a risk; it all depends on how one analyzes the danger, considers the event." The futurologist Lempert et al. (2004: 6) have argued along similar lines, pointing to the fact that "[…] *assess-risk-of-policy* is more subjective then *predict-then-act* because it forces analysts […] to explicitly decide, through their choice of strategy, the futures to which they remain vulnerable." When it comes to the global climate, however, we must add to Lempert et al.'s observation that integrated assessment modelers do not merely make the futures to which they themselves remain vulnerable, but rather to which *we*, as inhabitants of the Earth, are all exposed.

To be rendered subject to risk management is thus to be subjectivized in a particular manner (Adam and Van Loon, 2005; O'Malley, 2010). Insurance against risk functions exclusively against the backdrop of an average sociological individuality derived from the abstracted mutuality of a population as a whole (Adam and Van Loon, 2005; O'Malley, 2010): There is by definition no such thing as individual risk (Ewald, 1991: 202–204). Its very designation, then, indicates that not everyone is subject to the same degree of risk. In the case of the sociotechnical imaginary of negative emissions, it is arguably against the backdrop of the abstracted figure of *homo economicus* that any such asymmetries in the distribution of risk are tacitly accepted as collateral damage (Ackerman et al., 2009: 300; Martin, 2007: 137–138; McCollum et al., 2018: 664–666). For it is only on a systemic level and on a global scale that the risk associated with climate change may provide degrees of economic opportunity. Figured inversely to those who stand to lose on this global insurance scheme, it is only those who already have a considerable amount of capital to invest that may profit from it. This is amply evident not only in the case of the commodification of cap-and-trade systems by means of derivatives (Cooper, 2011: 175), but also in the fact that fossil-fuel giants like Shell have been among the keenest to see us collectively gamble on the future arrival of NETs (Carton, 2019: 759–761, 2020). In this manner, actors, whether they be individuals or large corporations, can intentionally manufacture risk, appropriate benefit from these risks, and still disproportionately avoid the consequences of the same risks to profit on an overall cost-benefit balance even as it leaves the least advantaged worse off (Curran, 2018b). Should this process of risk arbitrage be allowed to operate on a global level through the sociotechnical imaginary of negative emission, then I believe we have grounds for being seriously concerned that such manufacture of risk may induce large-scale moral hazard (Anderson and Peters, 2016: 183; Lenzi, 2018: 2–3; McLaren et al., 2016: 67–69; Shue, 2017; EASAC, 2018: iv).

The climate casino revisited, or, on the necessity of refusing the rules of the game

So, what have we learned by examining the temporal structure of negative emissions? Well, at the very least, this sociotechnical imaginary becomes conceivable first when the resonances of a future-oriented space of possibilities generate heat around the economy as a means of rendering uncertain futures securable. The assumption behind the concept of negative emissions is that one may seek out securability precisely as a source of profit from futurity's riskiness (Amoore, 2013: 6). Such is the mutually constitutive relationship between the time horizon of risk and the kind of epistemic techniques and technologies that constrain the future to a function of the discount rate. Consequently, the interpretative approach of this paper has allowed us to cast a light on something novel in the case of the risk management of GHG emissions; namely, that this most "natural" way for humans to relate to the future is first and foremost the cultural product of a contingent set of knowledge producing techniques and technologies in conformity with economic demands for efficiency, productivity, and flexibility, and concerned with the systematic solicitation of chance as potentially profitable investment opportunities through a derivative risk calculus. With its basis in the social practice of a particular relationship to the future—as a treacherous reef of hazard to be profitably explored by vessels of computational models and simulations—we are, as subjects, instructed in the ways of the market and rendered functional for markets through market-like modes of behavior (Lövbrand and Stripple, 2011; Read, 2009: 26–32). By positioning this sociotechnical imaginary against the time horizon of risk, we may thus widen the concern with negative emissions beyond that of its potential opportunities, risks, and trade-offs to instead revive the utopian demand for an entirely different attitude toward the future.

But I would also argue that the case of negative emissions is informative for the sake of deepening a sociological understanding of the modern governance of risk, especially that of environmental risks. For it seems to suggest that although the calculative conjecture connected to NETs is but an example of a futurological inclination inherent to the modern epoch as such, the intensification of this inclination through the sophistication of its attendant epistemic techniques and technologies is inadvertently manufacturing greater and greater degrees of risk. With an ever-widening of the scales upon which we seek to make ourselves attendant to—and insure ourselves against—futurity's riskiness, otherwise rational strategies of minimizing costs and maximizing benefits increasingly resemble a high-stakes gamble (Anderson and Peters, 2016: 183). Indeed, the failure of leveraged investment into the mortgage-backed assets we call NETs (Asayama and Hulme, 2019: 940–942) and the associated bankruptcy of the emissions debtor would result in a dangerous spike in global warming and exceptionally severe losses and damages—both environmentally and economically. As opposed to Ulrich Beck's rather optimistic view of risk as a democratizing phenomenon attuned to the indiscriminative happenstance of social and environmental bads, the case of negative emissions rather contributes to the literature that suggests that such a generalization is at best misleading, and at worst alienating. For not only does it intimate that the ludic rationality discursively inscribed into the sociotechnical imaginary of negative emissions, and the concomitant risk management prescribed by WG3, might be inclined to increase the manufacture of risk over time. It also suggests that risk is not necessarily as ubiquitous as Beck would have it since practices of selection and division implicit in the simulation of climate futures with the help of IAMs are crucial for the *social structuration* of risk (Curran, 2018a: 303).

None of the above ruminations on the discourse of risk management should in any way be understood as a contention against the need for scientifically informed decision-making when it comes to emissions reductions. What we should *not* take the presence of non-epistemic values to mean is that IAMs are therefore unreliable or that integrated assessment modelers manipulate data to suit a political agenda (McLaren, 2018: 219). The influence of non-epistemic considerations on how to deal with uncertain futures merely implies that we cannot, in the context of integrated assessment modeling, distinguish sharply between the realms of value-neutral theory and value-laden practice (Winsberg, 2010: 93–119). It highlights the fact that we need to pay attention to the use of techniques and technologies for the production of knowledge in which non-epistemic values play an ineliminable role; to the kinds of values or practical considerations tied up with their use; and not the least, to the effects that these values have upon the way in which they socialize us as users. My claim is that standards of risk management and utility maximization constitute examples of entrenched values that are products of the intellectual histories with which epistemic technologies such as IAMs are entangled. Though some of these values are non-epistemic, they may still be significant for the kind of knowledge that models produce, and in effect for the kind of relationship toward the future that they establish. The simple point is that models are developed and adapted in historical contexts, and within culturally contingent modes of discourse, which may leave indelible and sometimes inscrutable imprints—which are themselves not of a strictly epistemic value—upon them.

Neither is this to say that there are no issues of broad-scale social policy in which the concept of risk is useful. Rather, it is only to caution that an uncritical attitude toward the discourse of risk may lead us to cluster an astonishingly large range of health, safety, and other social and environmental problems on a global scale under this one rubric, indirectly justifying an incremental recklessness at the expense of devising other ways of expressing caution and care. While modelers are supposed to make modeling decisions in the context of a policy analysis exercise and then counsel policymakers on how to interpret the knowledge produced, and policymakers to supply modelers with requests as to the kind of scenarios to run through their models and then use the knowledge produced by IAMs to inform their policymaking, the subjective-probabilistic dimension that follows from such an issue-driven organization of knowledge production means that it is never entirely clear where the scientific part of the spectrum ends and the political begins (Geden, 2015: 27–28; Geden and Beck, 2014: 747–748). Of course, modelers must continue to do routine work on technical problems, but the question arises as to the influence of non-epistemic values on how the framework for inquiry is set, with whose awareness of the process, and in whose favor (Ravetz, 1999: 648). For as long as emissions reductions are treated solely as a technical problem of how to render the SCC into a bundle of securitisable assets, we will remain prisoners to the time horizon of risk and led down the one-way road of a no-limit betting structure. Long-term, the solution thus cannot be to play ever more accurately or correctly—although this is certainly crucial in the meantime—but also, alongside pursuing such ludic strategies, to interrogate the limits to a horizon of expectations reliant upon the instrumental exploitation of the future through derivative risk calculus. Examining the temporal structure of negative emissions is a first step to questioning the discursive rules that constitute the time horizon of risk against which "the Climate Casino," as Nordhaus (2013) puts it, has invited us to gamble with the temperature of our future climate(s). It is a first step to utilizing the intellectual tools that modernity has equipped us with to identify, and to change, the very set-up according to which are instructed to place our bets. The possibility of transforming the future has been opened in modernity, but it requires that we do not wholly abandon our critical distance toward the future for the purely technical concern of playing well in the present. On the contrary, such a transformation remains today, an ethical—and possibly even an existential—imperative.

Highlights

- Standards of risk management and utility maximization are examples of non-epistemic values inscribed into IAMs.

- A discourse of risk is central to making sense of the kind of future in relation to which negative emissions, as a sociotechnical imaginary, is constructed.
- The sociotechnical imaginary of negative emissions becomes conceivable first when the future is perceived as a territory that may be profitably colonized.
- Practices of selection and division implicit in the simulation of climate futures with the help of IAMs contribute to the social structuration of risk.

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References

Ackerman F, DeCanio SJ, Howarth RB, et al. (2009) Limitations of integrated assessment models of climate change. *Climatic Change* 95: 297–315.

Adam B and Van Loon J (2005) Repositioning risk: The challenge for social theory. In: Adam B, Beck U and Van Loon J (eds) *The Risk Society and Beyond: Critical Issues for Social Theory*. London: Sage, pp.1–31.

Allen MR, Frame DJ, Huntingford C, et al. (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* 458: 1163–1166.

Amoore L (2011) Data derivatives: On the emergence of a security risk calculus for our times. *Theory, Culture & Society* 28(6): 24–43.

Amoore L (2013) *The Politics of Possibility: Risk and Security Beyond Probability*. Durham: Duke University Press.

Anderson K (2019) The wrong tool for the job. *Nature* 573: 348–349.

Anderson K and Peters G (2016) The trouble with negative emissions: Reliance on negative-emission concepts locks in humankind's carbon addiction. *Science (New York, N.Y.)* 354(6309): 182–183.

Anshelm J and Hansson A (2014) The last chance to save the planet? An analysis of the geoengineering advocacy discourse in the public debate. *Environmental Humanities* 5: 101–123.

Arnoldi J (2004) Derivatives: virtual values and real risks. *Theory, Culture & Society* 21(6): 23–42.

Arrow KJ, Cline WR, Mähler K-G, et al. (1995) Intertemporal equity and discounting. In: Munasinghe M (ed) *Global Climate Change: Economic and Policy Issues – World Bank Environment Paper, No. 12*. Washington, D.C.: The World Bank, pp.1–32.

Asayama S and Hulme M (2019) Engineering climate debt: temperature overshoot and peak-shaving as risky subprime mortgage lending. *Climate Policy* 19(8): 937–946.

Baker T and Simon J (2002) *Embracing Risk: The Changing Culture of Insurance and Responsibility*. Chicago: University of Chicago Press.

Bayes T (1763) An essay towards solving a problem in the doctrine of chances. By the late Rev. Mr Bayes, F. R. S. Communicated by Mr Price, in a letter to John Canton, A. M. F. R. S. *Philosophical Transactions of the Royal Society of London* 53: 370–418.

Beck M and Kewell B (2014) *Risk: A Study of Its Origins, History and Politics*. Singapore: World Scientific Publishing.

Beck M and Krueger T (2016) The epistemic, ethical, and political dimensions of uncertainty in integrated assessment modeling. *WIRES Climate Change* 7: 627–645.

Beck S and Mahony M (2017) The IPCC and the politics of anticipation. *Nature Climate Change* 7: 311–313.

Beck U (1992) *Risk Society: Towards a New Modernity*. London: Sage.

Bernstein PL (1996) The new religion of risk management. *Harvard Business Review* 74(2): 47–51.

Bernstein PL (1998) *Against the Gods: The Remarkable Story of Risk*. London: John Wiley & Sons.

Boden D (2005) Worlds in action: information, instantaneity, and global futures. In: Adam B, Beck U and Van Loon J (eds) *The Risk Society and Beyond: Critical Issues for Social Theory*. London: Sage, pp.181–195.

Buck HJ (2016) Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change* 139: 155–167.

Bui M, Adjiman CS, Bardow A, et al. (2018) Carbon capture and storage (CCS): The way forward. *Energy & Environmental Science* 11(5): 1062–1176.

Carnap R (1962) *Logical Foundations of Probability*. Chicago: University of Chicago Press.

Carton W (2019) "Fixing" climate change by mortgaging the future: Negative emissions, spatiotemporal fixes, and the political economy of delay. *Antipode* 51(3): 750–769.

Carton W (2020) Carbon unicorns and fossil futures: Whose emission reduction pathways is the IPPC performing? In: Sapinski JP, Buck HJ and Malm A (eds) *Has it Come to This? The Promises and Perils of Geoengineering on the Brink*. New Brunswick: Rutgers University Press, pp.34–49.

Cooper M (2011) Turbulent worlds: Financial markets and environmental crisis. *Theory, Culture & Society* 27(2–3): 167–190.

Crost B and Traeger CP (2013) Optimal climate policy: Uncertainty versus Monte Carlo. *Economic Letters* 120(3): 552–558.

Curran D (2018a) Environmental justice meets risk-class: The relational distribution of environmental bads. *Antipode* 50(2): 298–318.

Curran D (2018b) The organized irresponsibility principle and risk arbitrage. *Critical Criminology* 26: 595–610.

Daston L (1988) *Classical Probability in the Enlightenment*. Princeton: Princeton University Press.

Daston L (1994) Historical epistemology. In: Chandler J, Davidson AI and Harootunian HA (eds) *Questions of Evidence: Proof, Practice and Persuasion Across the Disciplines*. Chicago: University of Chicago Press, pp.282–289.

Devlin K (2011) *The Man of Numbers: Fibonacci's Arithmetic Revolution*. London: Bloomsbury.

Dillon M (2008) Underwriting security. *Security Dialogue* 39(2-3): 309–332.

Edenhofer O and Kowarsch M (2005) Cartography of pathways: A new model for environmental policy assessments. *Environmental Science & Policy* 51: 56–64.

Emmerling J, Drouet L, Van Der Wijst K-I, et al. (2019) The role of the discount rate for emission pathways and negative emissions. *Environmental Research Letters* 14(10): 1–11.

European Academies Science Advisory Council (EASAC) (2018) *Negative Emission Technologies: What Role in Meeting Paris Agreement Targets? – EASAC Policy Report No. 35*. Halle: German National Academy of Sciences Leopoldina.

Ewald F (1991) Insurance and risk. In: Burchell G, Gordon C and Miller P (eds) *The Foucault Effect: Studies in Governmentality*. Chicago: University of Chicago Press, pp.197–210.

Ewald F (1993) Two infinities of risk. In: Massumi B (ed) *The Politics of Everyday Fear*. Minneapolis: University of Minnesota Press, pp.221–228.

Foley AM (2010) Uncertainty in regional climate modelling: A review. *Progress in Physical Geography: Earth and Environment* 34(5): 647–670.
Foucault M (2008) *The Birth of Biopolitics: Lectures at the Collège de France, 1978-1979*, Senellart M (eds) and Burchell G (trans). London: Palgrave Macmillan.
Friedlingstein P, Solomon S, Plattner G-K, et al. (2011) Long-term climate implications of twenty-first century options for carbon dioxide emission mitigation. *Nature Climate Change* 1: 457–461.
Funtowicz SO and Ravetz JR (1992) Three types of risk assessment and the emergence of post-normal science. In: Krimsky S and Golding D (eds) *Social Theories of Risk*. Westport: Praeger, pp.251–274.
Funtowicz SO and Ravetz JR (1993) Science for the post-normal age. *Futures* 25: 739–755.
Fuss S, Candell JG, Peters GP, et al. (2014) Betting on negative emissions. *Nature Climate Change* 4: 850–853.
Geden O (2015) Climate advisers must maintain integrity. *Nature* 521: 27–28.
Geden O and Beck S (2014) Renegotiating the global climate stabilization target. *Nature Climate Change* 4: 747–748.
Giddens A (1991) *Modernity and Self-Identity*. Cambridge: Polity.
Giddens A (1999a) Risk and responsibility. *Modern Law Review* 62(1): 1–10.
Giddens A (1999b) *World Risk Society*. Cambridge: Polity.
Giddens A (2000) *Runaway World: How Globalization is Shaping Our Lives*. New York: Routledge.
Gillingham K, Nordhaus WD, Anthoff D, et al. (2018) Modeling uncertainty in integrated assessment of climate change: A multimodel comparison. *Journal of the Association of Environmental and Resource Economists* 5(4): 791–826.
Gross DJ (1981) Space, time and modern culture. *Telos* 1981: 59–78.
Haas PM (1990) Obtaining international environmental protection through epistemic consensus. *Millennium: Journal of International Studies* 19: 347–363.
Hacking I (2006) *The Emergence of Probability: A Philosophical Study of Early Ideas About Probability, Induction and Statistical Inference*. Cambridge: Cambridge University Press.
Haikola S, Hansson A and Anshelm J (2019a) From polarization to reluctant acceptance: Bioenergy with carbon capture and storage (BECCS) and the post-normalization of the climate debate. *Journal of Integrative Environmental Sciences* 16(1): 45–69.
Haikola S, Hansson A and Fridahl M (2018) Views of BECCS among modelers and policymakers. In: Fridahl M (ed) *Bioenergy with Carbon Capture and Storage: From Global Potentials to Domestic Realities*. Brussels: European Liberal Forum, pp.17–29.
Haikola S, Hansson A and Fridahl M (2019b) Map-makers and navigators of politicised terrain: Expert understandings of epistemological uncertainty in integrated assessment modelling of bioenergy with carbon capture and storage. *Futures* 114: 1–14.
Harvey D (1989) *The Condition of Postmodernity: An Enquiry into the Origins of Cultural Change*. Cambridge: Blackwell.
Harvey D (1990) Between Space and Time: Reflections on the Geographical Imagination. *Annals of the Association of American Geographers* 80(3): 418–434.
Hulme M (2015) Climate and its changes: A cultural appraisal. *GEO: Geography and Environment* 2(1): 1–11.
Hulme M (2017) *Weathered: Cultures of Climate*. Thousand Oaks: Sage.
Huntingford C and Lowe JA (2007) “Overshoot” scenarios and climate change. *Science (New York, N.Y.)* 316(5826): 829.
Huntingford C, Lowe JA, Gohar LK, et al. (2012) The link between a global 2°C warming threshold and emissions in years 2020, 2050 and beyond. *Environmental Research Letters* 7: 1–8.
Intergovernmental Panel on Climate Change (IPCC) (2014) *Climate Change 2014: Mitigation of Climate Change – Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer O, et al. (eds). Cambridge: Cambridge University Press.
Intergovernmental Panel on Climate Change (IPCC) (2018) *Global Warming of 1.5°C*, Masson-Delmotte V, et al. (eds). Geneva: IPCC.

International Energy Agency (IEA) (2016) *Twenty Years of Carbon Capture and Storage: Accelerating Future Deployment*. Paris: IEA.
Jasanoff S (2015) Future imperfect: Science, technology, and the imaginations of modernity. In: Jasanoff S and Kim S-H (eds) *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*. Chicago: University of Chicago Press, pp.1–33.
Jasanoff S (2020) Imagined worlds: The politics of future-making in the twenty-first century. In: Wenger A, Jasper U and Dunn Cavelty M (eds) *The Politics and Science of Prevision: Governing and Probing the Future*. London: Routledge, pp.27–44.
Jewell J (2019) Clarifying the job of IAMs. *Nature* 573: 349.
Keen S (2021) The appallingly bad neoclassical economics of climate change. *Globalizations* 18(7): 1149–1177.
Kelly DL and Kolstad CD (1999) Integrated assessment models for climate change control. In: Folmer H and Tietenberg T (eds) *International Yearbook of Environmental and Resource Economics 1999/2000: A Survey of Current Issues*. Cheltenham: Edward Elgar, pp.171–197.
Knight FH (1964) *Risk, Uncertainty, and Profit*. New York: Sentry Press.
Koelbl BS, Van Den Broek MA, Faaji APC, et al. (2014) Uncertainty in carbon capture and storage (CCS) deployment projections: A cross-model comparison exercise. *Climatic Change* 123: 461–476.
Koselleck R (2004) *Futures Past: On the Semantics of Historical Time*, Tribe K (trans). New York: Columbia University Press.
Le Goff J (1980) *Time, Work, and Culture in the Middle Ages*, Goldhammer A (trans). Chicago: University of Chicago Press.
Lempert RJ, Groves DG, Popper SW, et al. (2006) A general, analytic method for generating robust strategies and narrative scenarios. *Management Science* 52(4): 514–528.
Lempert RJ, Nakicenovic N, Sarewitz D, et al. (2004) Characterizing climate-change uncertainties for decision-makers – an editorial essay. *Climatic Change* 65: 1–9.
Lempert RJ, Schlesinger ME and Bankes SC (1996) When we don't know the costs or the benefits: Adaptive strategies for abating climate change. *Climatic Change* 33: 235–274.
Lenzi D (2018) The ethics of negative emissions. *Global Sustainability* 1(7): 1–8.
Low S and Boettcher M (2020) Delaying decarbonization: climate governmentalities and sociotechnical strategies from Paris to Copenhagen. *Earth System Governance* 5: 1–12.
Lövbrand E (2004) Bridging political expectations and scientific limitations in climate risk management: on the uncertain effects of international carbon sink politics. *Climatic Change* 67: 449–460.
Lövbrand E, Beck S, Chilvers J, et al. (2015) Who speaks for the future of Earth? How critical social science can extend the conversation on the anthropocene. *Global Environmental Change* 32: 211–218.
Lövbrand E and Stripple J (2011) Making climate change governable: Accounting for carbon as sinks, credits, and personal budgets. *Critical Policy Studies* 5(2): 187–200.
Lyotard J-F (1984) *The Postmodern Condition: A Report on Knowledge*, Bennington G and Massumi B (trans). Minneapolis: University of Minnesota Press.
Lysandrou P (2016) The colonization of the future: An alternative view of financialization and its portents. *Journal of Post Keynesian Economics* 39(4): 444–472.
MacKenzie D (2009) *Material Markets: How Economic Agents Are Constructed*. Oxford: Oxford University Press.
Maier CS (1987) The politics of time: Changing paradigms of collective time and private time in the modern era. In: Maier CS (ed) *Changing Boundaries of the Political: Essays on the Evolving Balance Between the State and Society, Public and Private in Europe*. Cambridge: Cambridge University Press, pp.151–175.
Mander S, Anderson K, Larkin A, et al. (2017) The role of bio-energy with carbon capture and storage in meeting the climate mitigation challenge: A whole system perspective. *Energy Procedia* 114: 6036–6043.
Markusson N, Dahl Gjefsen M, Stephens JC, et al. (2017) The political economy of technical fixes: The (mis) alignment of clean fossil and political regimes. *Energy Research & Social Science* 23: 1–10.
Martin R (2007) *An Empire of Indifference: American War and the Financial Logic of Risk Management*. Durham: Duke University Press.

McCollum DL, Wilson C, Bevione M, et al. (2018) Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles. *Nature Energy* 3: 664–673.
McJeon HC, Clarke L, Kyle P, et al. (2011) Technology interactions among low-carbon energy technologies: What can we learn from a large number of scenarios? *Energy Economics* 33: 619–631.
McLaren DP (2018) Whose climate and whose ethics? Conceptions of justice in solar geoengineering modelling. *Energy Research & Social Science* 44: 209–221.
McLaren DP, Parkhill KA, Corner A, et al. (2016) Public conceptions of justice in climate engineering: Evidence from secondary analysis of public deliberation. *Global Environmental Change* 41: 64–73.
Mehta L, Adam HN, Bhatt MR, et al. (2021) Uncertainty from "above": Diverse understandings, politics, and implications. In: Mehta L, Adam HN and Srivastava S (eds) *The Politics of Climate Change and Uncertainty in India*. London: Routledge, pp.27–53.
Mehta L and Srivastava S (2020) Uncertainty in modelling climate change: the possibilities of co-production through knowledge pluralism. In: Scoones I and Stirling A (eds) *The Politics of Uncertainty: Challenges of Transformation*. London: Routledge, pp.99–112.
Merchant C (2016) *Autonomous Nature: Problems of Prediction and Control from Ancient Times to the Scientific Revolution*. London: Routledge.
Miller CA (2004) Climate science and the making of a global political order. In: Jasanoff S (ed) *States of Knowledge: The Co-Production of Science and the Social Order*. London: Routledge, pp.46–66.
Moss RH and Schneider SH (2000) Uncertainties in the IPCC TAR: Recommendations to lead authors for more consistent assessment and reporting. In: Pachauri R, Taniguchi T and Tanaka K (eds) *Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC*. Geneva: World Meteorological Organization, pp.33–51.
Moynihan T (2020a) Existential risk and human extinction: An intellectual history. *Futures* 116: 1–13.
Moynihan T (2020b) *X-Risk: How Humanity Discovered Its Own Extinction*. Falmouth: Urbanomic.
Muratori M, Calvin K, Wise M, et al. (2016) Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters* 11: 1–9.
Muri H (2018) The role of large-scale BECCS in the pursuit of the 1.5°C target: An earth system model perspective. *Environmental Research Letters* 13: 1–9.
Nacol EC (2016) *An Age of Risk: Politics and Economy in Early Modern Britain*. Princeton: Princeton University Press.
Nordhaus WD (2007) A review of the stern review on the economics of climate change. *Journal of Economic Literature* 45(3): 686–702.
Nordhaus WD (2013) *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. Cambridge: Yale University Press.
Nordhaus WD and Popp D (1997) What is the value of scientific knowledge? An application to global warming using the PRICE model. *The Energy Journal* 18(1): 1–45.
O'Malley P (2010) Uncertain subjects: Risks, liberalism, and contract. *Economy and Society* 29(4): 460–484.
Oreskes N, Shrader-Frechette K and Belitz K (1994) Verification, validation, and confirmation of numerical models in the earth sciences. *Science (New York, N.Y.)* 263(5147): 641–646.
Parson EA and Fisher-Vanden K (1997) Integrated assessment models of global climate change. *Annual Review of Energy and the Environment* 22(1): 589–628.
Paterson M and Stripple J (2012) Virtuous carbon. *Environmental Politics* 21(4): 563–582.
Pindyck RS (2013) Climate change policy: What do the models tell us? *Journal of Economic Literature* 51(3): 860–872.
Pindyck RS (2017) The use and misuse of models for climate policy. *Review of Environmental Economics and Policy* 11(1): 100–114.
Ravetz JR (1987) Usable knowledge, usable ignorance: Incomplete science with policy implications. *Science Communication* 9(1): 87–116.
Ravetz JR (1999) What is post-normal science? *Futures* 31: 647–653.
Read J (2009) A genealogy of homo-economicus: Neoliberalism and the production of subjectivity. *Foucault Studies* 6: 25–36.

Reith G (2004) Uncertain times: The notion of “risk” and the development of modernity. *Time & Society* 13(2–3): 383–402.
Rogelj J, Luderer G, Pietzcker RC, et al. (2015) Energy system transformations for limiting end of century warming to below 1.5°C. *Nature Climate Change* 5: 519–527.
Rogelj J, McCollum DL, Reisinger A, et al. (2013) Probabilistic cost estimates for climate change mitigation. *Nature* 493: 79–83.
Rotmans J and Van Asselt MBA (2001) Uncertainty in integrated assessment modelling: A labyrinthic path. *Integrated Assessment* 2: 43–55.
Saltelli A, Benini L, Funtowicz SO, et al. (2020) The technique is never neutral: How methodological choices condition the generation of narratives for sustainability. *Environmental Science & Policy* 106: 87–98.
Saltelli A, Stark PB, Becker W, et al. (2015) Climate models as economic guides: Scientific challenge or quixotic quest? *Issues in Science and Technology* 31(3): 79–84.
Schneider SH (1997) Integrated assessment modeling of global climate change: Transparent rational tool for policy-making or opaque screen hiding value-laden assumptions? *Environmental Modeling and Assessment* 2: 229–249.
Shue H (2017) Climate dreaming: Negative emissions, risk transfer, and irreversibility. *Journal of Human Rights and the Environment* 8(2): 631–639.
Stanton EA, Ackerman F and Kartha S (2009) Inside the integrated assessment models: Four issues in climate economics. *Climate and Development* 1(2): 166–184.
Stern N (2016) Current climate models are grossly misleading. *Nature* 530: 407–409.
Stirling A (2007) Risk, precaution, and science: Towards a more constructive policy debate. *EMBO Reports* 8(4): 309–315.
Taleb NN (2007) *The Black Swan: The Impact of the Highly Improbable*. New York: Random House.
Van Bree L and Van Der Sluijs J (2014) Background on uncertainty assessment supporting climate adaptation decision-making. In: Capela Lourenço T (ed) *Adapting to an Uncertain Climate: Lessons from Practice*. Berlin: Springer, pp.17–40.
Van Vuuren DP, Kriegler E, O’Neill BC, et al. (2014) A new scenario framework for climate change research: Scenario matrix architecture. *Climatic Change* 122: 373–386.
Van Vuuren DP, Deetman S, Van Vliet J, et al. (2013) The role of negative CO_2 emissions for reaching 2°C-insights from integrated assessment modelling. *Climatic Change* 118: 15–27.
Van Vuuren DP and Riahi K (2011) The relationship between short-term emissions and long-term concentration targets. *Climatic Change* 104: 793–801.
Vervoort J and Gupta A (2018) Anticipating climate futures in a 1.5°C era: The link between foresight and governance. *Current Opinion in Environmental Sustainability* 31: 104–111.
Viner D and Howarth C (2014) Practitioners’ work and evidence in IPCC reports. *Nature Climate Change* 4: 848–850.
Weber M (1992) *The Protestant Ethic and the Spirit of Capitalism*, Parsons T (trans). London: Routledge.
Weyant J (2014) Integrated assessment of climate change: State of the literature. *Journal of Benefit-Cost Analysis* 5(3): 377–409.
Weyant J (2017) Some contributions of integrated assessment models of global climate change. *Review of Environmental Economics and Policy* 11(1): 115–137.
Wilson C, Kriegler E, Van Vuuren DP, et al. (2017) *Evaluating Process-Based Integrated Assessment Models of Climate Change Mitigation*. Laxenburg: International Institute for Applied Systems Analysis.
Winner L (1986) *The Whale and the Reactor: A Search for Limits in an Age of High Technology*. Chicago: University of Chicago Press.
Winsberg E (2010) *Science in the Age of Computer Simulation*. Chicago: University of Chicago Press.
Workman M, Dooley K, Lomax G, et al. (2020) Decision making in contexts of deep uncertainty – an alternative approach for long-term climate policy. *Environmental Science & Policy* 103: 77–84.