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Klaus Hasselmann and Economics

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Abstract

Klaus Hasselmann has earned the 2021 Nobel prize in physics for his breakthroughs in analysing the climate system as a complex physical system. Since decades, as a leading climate scientist he is aware of the need for creative cooperation between climate scientists and researchers from other fields, especially economics. To facilitate such cooperation, he has designed a productive research program for economic analysis in view of climate change. Without blurring the differences between economics and physics, the Hasselmann program stresses the complexities of today's economy. This includes the importance of heterogeneous actors and different time scales, of making major uncertainties explicit and bringing researchers and practitioners in close interaction. The program has triggered decades of collaborative research, especially in the network of the Global Climate Forum, that he has founded for this purpose. Research inspired by Hasselmann's innovative ideas has led to a farewell to outdated economic approaches: single-equilibrium models, a single constant discount rate, framing the climate challenge as a kind of prisoner's dilemma and framing it as a problem of scarcity requiring sacrifices from the majority of today's population. Instead of presenting the climate problem as the ultimate apocalyptic narrative, he sees it as a challenge to be mastered. To meet this challenge requires careful research in order to identify underutilisation of human, technical and social capacities that offer the keys to a climate friendly world economy. Climate neutrality may then be achieved by activating these capacities through investment-oriented climate strategies, designed and implemented by different actors both in industrialised and developing countries. The difficulties to bring global greenhouse gas emissions down to net zero are enormous; the Hasselmann program holds promise of significant advances in this endeavour.

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1. Prologue

Long before Klaus Hasselmann has been awarded the Nobel prize in physics for his work on climate change, the American Institute of Physics published a refreshing interview with him (API 2006). Although I know and work with him since more than two decades as a colleague and friend, that interview helped me to get a sense of many aspects of his life and the development of his thought and research. Other sources as well as conversations that I shared over the years with Klaus, his wife Susanne, and with other common acquaintances conveyed impressive images of an adventurous past. It goes back to the darkest years in the history of Germany. Seeing Hamburg in ruins after World War II, a German boy came back from an English garden town, where the war seemed far away. And he didn't give up the curiosity and enthusiasm that would shape his future.

Later on, he didn't and still doesn't share the apocalyptic narratives that are spun around the challenge of climate change. For him, climate dynamics and then its alteration through humankind were first of all research challenges. But increasingly they became a matter of personal responsibility as a scholar. So he decided to engage with the economic issues that clearly have to be taken into account by any attempt to tackle the climate challenge. Also Bill Nordhaus, who won the Nobel prize for his economic research on climate change, was spot on when he chose "Climate change: The Ultimate Challenge for Economics" as the title of his Nobel lecture (Nordhaus 2018a). It is in this spirit that I accepted Hasselmann's proposal to work together at the interface of climate science and economics. As an economist educated by postkeynesians like Joan Robinson and trained on the tools the mathematician von Neumann forged to analyse both social interactions and economic equilibria, I see the ultimate challenge raised for economics by climate change in even sharper terms than Nordhaus. But it is in the same spirit that I accepted, more than twenty years later, Jürgen Kurth's proposal to write the present essay on Hasselmann and economics.

We take off with some biographical elements that I consider useful and in a way essential to understand Hasselmann's approach to economics (2). Against this background, we will look at a key paper that he presented in 1990 at the Kiel Institute for the World Economy. There he outlined the research program that would guide his research on climate related questions of economics (3). Since then, the Hasselmann program has evolved in many ways, as the paper will show. The first three building blocks include: first, a low-dimensional climate model to be used for integrated assessments; second, a minimalist model of the costs of climate change and those of climate policy, with different discounting factors for the two; third, a game-theoretic model of decision processes relevant for global climate policy, framed in terms of a prisoner's dilemma with non-linearities in the payoff structure. These three initial models were conceived from the outset in view of being coupled for integrated assessments (4). Using, refining and modifying these building blocks as well as observing the development of global climate policy led Hasselmann to found the Global (initially: European) Climate Forum (GCF). GCF is an open network bringing together researchers and practitioners to share discoveries and disagreements in a constructive way, and Klaus asked me to chair it. Creating this space for innovative research led to a broader flourishing of his program. An important result has been the reframing of the climate challenge from the widespread fixation on the prisoner's dilemma model to an understanding in terms of stag hunt games. In practical terms this implies a robust strategy of investment-based climate policy (5). Such a strategy requires attention to the different interacting time scales involved in shifting from brown to green capital. They are not only about short term versus long term perspectives, but involve a whole spectrum from the milliseconds of algorithmic trading to the decades of implementing new infrastructures. Mastering the climate challenge requires economics no less than climate science to face problems characterised by unprecedented complexities like those involved in the relation between dangerous climate change and the world economy we live in (6). We conclude with an outlook at how the Hasselmann program may further evolve. A key element will be a fresh understanding of cultural evolution and its application to the economy we live in today and perhaps the one our grandchildren may live in tomorrow (7).

2. Seeds of a Researchers Mind

Economics and thinking about social futures are part of Klaus Hasselmann's family background. Erwin, his father, was an economist who had studied with Max Weber, the legendary author of "Economy and Society" (2019/1922). In those times, economics and sociology were not yet themes of disjunct thought collectives, to use Fleck's (1979/1935) felicitous expression. During his whole life, Erwin Hasselmann considered the cooperative movement essential to overcome the destructive tendencies fostered by capitalism (he wrote his PhD thesis about consumer cooperatives). He also saw the basis of that movement in an attitude of warm-hearted empathy towards one's fellow human beings – an attitude that Klaus Hasselmann clearly inherited.

After the establishment of the Nazi government in Germany, Erwin Hasselmann quickly understood that there was no place for him in his homeland. So he moved from Hamburg to England with his family, including little Klaus at the age of three. In England, the family got precious support from the local Quaker community, while Erwin made a living as a journalist and translator in the international cooperative movement. He intensified these activities after the war, when the family moved back to Hamburg. There, Hasselmann sr. worked as author and manager, still in the context of the cooperative movement. As a result for young Klaus Hasselmann, thinking about the economy and about long-term social futures were not exotic topics he would be confronted with only much later in his life, but obvious aspects of the world he grew up in.

As for physics, Hasselmann was curious early on about how nature works. He liked to do handicraft and read books about nature. Around age of 13, still in England, he bought a crystal detector from a school friend. The fact that with such a device he could listen to radio music, even without plugging it in a socket, intrigued him. So he started studying this puzzling phenomenon on his own, using physics books from the local library. This approach – just looking at an interesting problem on his own – remained a key feature of his research style as a physicist, moving along a trajectory through the fields of fluid dynamics, oceanography, meteorology, and climate research. However, he has become more of a leader than a loner. He would always establish and maintain fruitful relations with other researchers, be they PhD students, collaborators of the Max Planck Institute he directed, or colleagues from other institutions. Part of his style was also a highly selective way of using the literature: "I tend to read very diagonally. But when I find something interesting then I read it very thoroughly. When I read diagonally I try to grasp the basic idea" (API 2006).

3. Designing the Research Program

He practiced the same research style when, as a leading climate scientist and founding director of the Max Planck Institute for meteorology in Hamburg, he got more and more confronted with public debates about climate change. In the eighties, both scientific and public debates about climate change intensified. In Hasselmann's words: "I was often invited to interviews on TV or the radio, and to give talks to the general public on climate. At the end of my talks I was always asked the same question: What should we do? And I would say: Well, I do not really know. I'm a climate scientist, not an economist or politician" (API 2006). The resulting tension created a new challenge for his curiosity and creativity – and so he decided to look at the problem on his own. The first opportunity to engage with the role of the economy in climate change was a workshop held in July 1990 at the Kiel Institute for the World Economy, Germany. The paper he presented there (KH 1990) outlined a program he would keep working on in the following decades.

In the Kiel paper, Hasselmann carefully explains the greenhouse effect, presents the dynamics of anthropogenic greenhouse gas emissions and discusses key simulations of state-of-the-art climate models. The main result is the pivot of the emerging program: "there exists no serious doubt within the scientific community that the predicted global warming is real, that the estimated orders of magnitude of the predicted climate change are reliable and that if no corrective measures are adopted, we may expect within the next 100 years the warmest climate ever experienced in the history of mankind" (KH 1990, p.20). The key question then is to find out what adequate corrective measures are. Hence the need for a research program. Hasselmann didn't even declare it as such, he just started working on it.

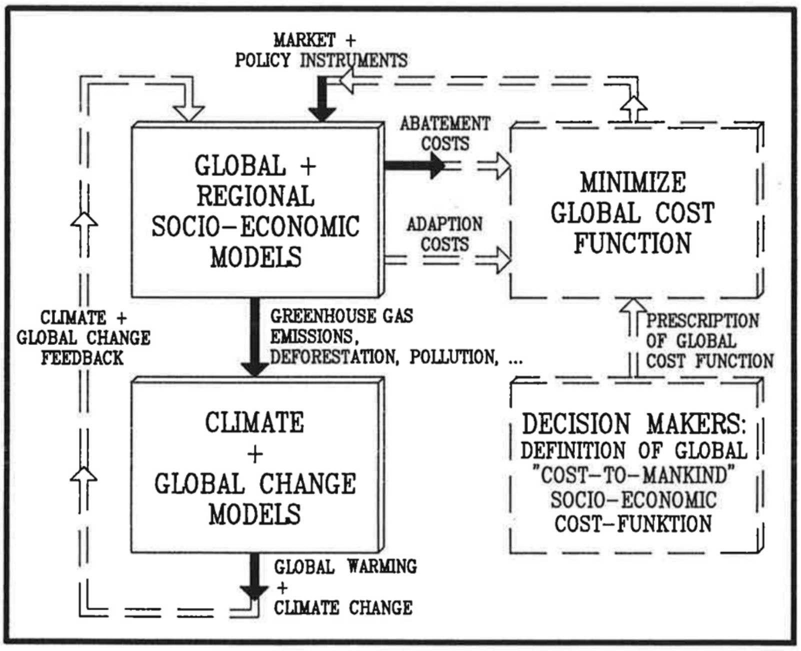

Figure 1: Integration of climate models, economic models and models of decision making process (Hasselmann, 1990, p.1a)

The full lines denote components which have been largely developed. The broken lines indicate missing feedback links or inadequately developed components.

Climate models, to which Hasselmann has made vital contributions, in his view were and still are necessary, but insufficient for this purpose. E.g., it is simply impossible to assess climate impacts without economic and social analysis. Climate models need to be further improved and adapted to new conditions, but most importantly they need to be coupled with suitable economic models.

"This will require a close collaboration between the climate and environment research community and economic analysists" (KH 1990, p.2). Hasselmann worked energetically to foster institutional settings that might enable such cooperation (API 2006). An important step was to help convince the German Federal Ministry for Education and Research to create, together with the government of the state of Brandenburg, the Potsdam Institute for Climate Impact Research (PIK). It was established in 1992. Another important step was for Hasselmann to nudge the University of Hamburg to create a new professorship for environmental economics. It was established in the year 2000.

But his main thrust was to develop suitable economic models himself, and the Kiel paper marks the beginning of this effort. “Economic models [..] need to be extended to include the socioeconomic impacts of climate change” (KH 1990, p. 2). Notice that he did explicitly include social impacts. While this is certainly reasonable, it raises the methodological challenge of identifying possible impacts of climate change like social conflicts (Burke et al. 2015), and the even trickier one of monetising this kind of impacts (Jaeger et al., 2008a). The Hasselmann program and the first steps towards its implementation, however, went further than that. For a start, three points are particularly relevant.

3.1. A spectrum of time scales

In his programmatic 1990 paper, Hasselmann explained and emphasised the impossibility of understanding the climate system in terms of a single time scale (KH 1990, p. 18). He insisted on the necessity of considering a spectrum of time scales not only in view of the climate system, but as well when facing the economy we live in. In economics, it is standard to distinguish between the short and the long term, but for Hasselmann time scales are not about a dichotomy but about a spectrum. This crucial point sheds light on the role of complexity in his thinking about the economy. The Nobel committee for physics awarded the Nobel price to Klaus Hasselmann together with Syukuro Manabe, and with Giorgio Parisi “For Groundbreaking Contributions to Our Understanding of Complex Physical Systems”. Hasselmann saw and still sees the ingenious use of different time scales as essential for understanding complex physical systems like climate, but as equally essential for understanding and improving the interactions of economic dynamics, policy making, and climate change.

3.2. The formation - or lack – of collective will

As figure 1 shows, he considered it essential not only to couple climate and economic models, but to complement these two kinds of models with decision-theoretic models of social processes leading to a collective will. Faced with anthropogenic climate change, different actors may have different views on how to rank costs and benefits of different actions, and even more importantly on what is a cost and a benefit to whom. Without interactions, negotiations, and deliberations among those actors no collective will can emerge, and without collective will at a global scale the climate challenge cannot be met.

3.3. Awareness of uncertainty

In the Kiel paper Hasselmann extensively explained the many uncertainties involved in sophisticated climate predictions and stressed the even bigger uncertainties due to the difficulties of economic models to assess the socio-economic impacts of predicted climate changes. Initially he thought that the methods of stochastic optimisation would be sufficient to tackle those uncertainties. But he never gave in to the illusion that the climate challenge could be successfully addressed by eliminating uncertainty. Quite the opposite, he emphasised the need and possibility to develop adequate methods and strategies to tackle the climate challenge in full awareness of the uncertainties involved. Too often communication between scientists and decision-makers is a one-way street where the latter have no idea of the unsolved problems the former are always struggling with, while scientists are ignorant of the very different but equally hard problems decision-makers are insecure about. This state of affairs is dangerous for society, especially if it aspires to be a democracy. Therefore, a key aspect of the Hasselmann program matters in the face of climate change and also in many other domains: "Policy and model development should be pursued as parallel, interactive, iterative processes" (KH 1990, p.20).

4. First Building Blocks

4.1. On economy-friendly climate models

To work on his program, Hasselmann needed a global climate model suitable for integration with economic models. Around the same time Bill Nordhaus – Nobel laureate 2018 in economics "for integrating climate change into long-run macroeconomic analysis" – was struggling with the same problem: "I needed a few climate equations, certainly less than a dozen, not a dozen thousand. [..] Moreover, I wanted something that was not only simple but acceptable to the climate community" (Nordhaus 2018b). Nordhaus found the solution when, in his words: "I encountered the dazzling scientist-advocate Stephen Schneider, at NCAR, then Stanford. When I told him what I needed, he said that he had just what I needed. It was the Schneider-Thompson model, which was a two-equation climate model" (Nordhaus 2018b; Schneider and Thompson 1981). This enabled Nordhaus to develop the immensely influential DICE family of climate-economy models (Nordhaus 1992).

Hasselmann, being a world class climatologist, solved his corresponding problem by designing his own low-dimensional global climate model together with colleagues from the Hamburg Max Planck (KH et al. 1996, p.6ff). They designed a procedure to approximate with little computational cost future trajectories of the climate system computed with massive computational cost by state-of-the-art nonlinear climate general circulation models (CGCMs). In order to estimate future global mean temperatures, they took a CGCM and performed numerical climate response experiments to produce a table showing the change of the climate system caused in given states of the system by small instantaneous impulses of CO2. Because system changes caused by emission changes are described in the CGCM by a differentiable function, within limits the response can be approximated by a linear relation. They used this fact to construct a computationally parsimonious model that would compute future temperature trajectories resulting from conceivable emissions trajectories. It does so with relatively small computational cost while implicitly taking in consideration the complex mechanisms (e.g. atmosphere-ocean interactions) incorporated in the CGCM. Later on, the resulting model has been further elaborated into a nonlinear impulse response model of the coupled carbon cycle climate system (NICCS) that yields spatially explicit simulations with enhanced inclusion of ocean carbon chemistry and the terrestrial biosphere (Hooss et al. 2001).

The key takeaway from the related experiences of the two Nobel prize laureates is that in order to provide sound economic analyses of climate problems it is necessary and possible to synthesise the insights that can only be achieved by very large climate models into lower dimensional models with meaningful interfaces to appropriate economic models.

4.2. A minimalist economic model

The next step for Hasselmann, therefore, was to identify an economic model suitable to be coupled with his taylor-made climate model. Screening the literature on climate economics as collected by Cline (1992) and Fankhauser (1995), he was irritated by the extent to which assessments of costs and benefits of future emissions differed from each other. The situation was confirmed by the expert poll published by Nordhaus (1994). Given this situation, Hasselmann decided to design an economic model that would not try to produce one more claim about the quantitative amount of costs and benefits of climate change, but rather allow to identify the structural assumptions leading to the most significant differences in assessing those magnitudes. The goal was "to distinguish between relatively robust and more sensitive conclusions of the optimisation analysis and to clarify the role of the characteristic climatic and economic time scales in governing the short- and long-term properties of the optimal emission path" (KH et al. 1996, p.16).

The structure of the model is anchored in a business as usual (BAU) scenario where climate damages may happen, but are ignored in the decisions shaping global CO2 emissions (as is still pretty much the case today). The BAU scenario could be a run of Nordhaus's DICE model with climate damages ignored in the optimisation process, or some other plausible BAU scenario. Without loss of generality, Hasselmann and his colleagues took scenario A in IPCC (1990) as the BAU reference. In this scenario, emissions follow a differentiable trajectory e_A, while abatement costs are set to zero, because the deviation from the BAU abatement costs is what matters for the decision process.

The authors then associate the BAU emissions trajectory e_A with a welfare measure W_A. This might be the value of a Ramsey-Cass style utility functional, taking into account the aggregated utility of both GDP and non-monetary variables like life expectancy. Because they are interested in structural insights rather than premature quantitative estimates, they consider W_A as a given constant for the BAU trajectory, expressed in money equivalents.

If emissions differ from the BAU trajectory e_A, following instead a scenario e, damage costs from climate change, C_d, will differ, too. Moreover, emission reductions come with abatement costs, C_a, so that the two change together. By expressing both kinds of costs in monetary equivalents, KH et al. (1996, p.16) get a welfare functional that they minimise to find an optimal emission trajectory:

$$W(e) = W_A - [C_a(e) + C_d(e)]. \qquad (1)$$

To reduce damage costs, $C_d(e)$, one has to reduce emissions, e, which implies increasing abatement costs, $C_a(e)$. So a balance between the two has to be reached, and both kinds of costs concern interactions with the climate system over different time scales.

At time t, time specific abatement costs, $c_a(e(t))$, depend on the emissions at that moment, i.e. $e(t)$. But abatement takes time: "brown" fixed capital whose use generates CO2 emissions has to be replaced by "green" fixed capital; the faster this shift, the more expensive it will be – even more so if the speed of the shift accelerates. That's why the first and second derivative of $e(t)$ are relevant, too. Because of intertemporal accounting, time t has to be considered explicitly: a time dependent discount factor represents the well-known practice to consider a given expenditure the smaller the further in the future it happens. Last not least, integrating all these variables over time to get the overall cost figures C_a and Cd implies still other, longer time scales (for the explicit shape of functions (2) and (3), see KH et al. 1996, p. 17ff).

$$C_a = \int_{t_o}^{t_h} c_a(e(t), e'(t), e''(t), t)dt \qquad (2)$$

For climate damages, in line with current practice the key variable is assumed to be global mean temperature T. But again, the first derivative is essential, too (here the authors treated the second derivative as negligible). An additional time scale is introduced by the discounting factor, which is set at a significantly smaller level for damage costs than for abatement costs.

$$C_d = \int_{t_o}^{t_h} c_a(T(t), T', t)dt \qquad (3)$$

Coupling the climate model with the economic one is straightforward: the economic model feeds the control function, i.e. the BAU emissions e_A, to the climate model, which feeds back the temperature function to the former, where the two cost functions are computed. The integrated model optimises the control function *e* by minimizing the cost term in (1) with a method of steepest descent (KH et al. 1996, p.19, 35f). Hasselmann called the resulting combined model SIAM, for "Structural Integrated Assessment Model".

4.3. Social dynamics

The sensitivity analyses performed with this coupled climate-economy model confirm the importance and feasibility of integrated assessment models for tackling the challenge of global climate change (Dowlatabadi and Morgan 1993). They also show why attempts to identify a single optimal strategy for tackling climate change are hampered by a whole range of difficulties. First, while discussions about climate change are often focused on the time horizon of the present century and less, the SIAM sensitivity analyses show, that the most severe impacts of human greenhouse gas emissions are to be expected well beyond 2100 (remember that Hasselmann – rightly – includes non-economic losses in impacts). Therefore, the simulations are performed for the range from 1995 to 2200 and also for the range from 1800 to 3000. Understandably, the difficulties to make deterministic forecasts as well as forecasts of probability distributions increase with the time horizon considered. And this holds at least as much for possible costs of emission reductions. Using discount factors based on data about investor behaviour in the present economy then inexorably leads to neglect of long-term risks.

Hasselmann proposed to address this problem by distinguishing between the discount rate for the costs of emission reduction and the discount rate of climate damages, the latter being close to zero, the former closer to estimates of market-based discounting. This led to three critical, but not hostile editorials (including Nordhaus 1997) in the same journal issue where Hasselmann et al. introduced the SIAM approach. Hasselmann (1999a) expanded on the differentiated accounting approach, emphasising the importance of ethical questions when trying to assess benefits and costs ("pros and cons" might be more adequate when talking about ethics): "With regard to the ethical issue of the 'value' of preserving our present climate, or the 'damages' ensuing from a climate change to future generations, it is unavoidable and healthy that there should be discussion and differences of opinion" (Hasselmann 1999a, p.335). This leads to the third modelling effort emphasised in the design of the Hasselmann program (see figure 1 above): the representation of the collective decision processes without which no globally shared overarching goal function can be defined and implemented.

In economics, the standard approach for analysing and modelling collective decision processes is to use one of the many options offered by game theory. In KH & Hasselmann, S. (1996, see also KH 1999b), the SIAM model is used for this kind of analysis. The Hasselmanns start by considering a strictly symmetrical situation where n identical actors decide which emissions $e_{i=1..n}$ they will generate. Let total emissions be $e = \sum_{i=1}^{n} e_i$. The damage costs for all together is just the C_d of the unique actor (aka benevolent planner) in equation (3) above, while the damage cost for each single actor is C_d/n.

At this stage, it is useful to consider the simple two actor situation of figure 2. The benevolent planner would minimise the sum of abatement costs and costs from climate change, realising the minimal total costs of 24 units. Two actors might realise this as the Pareto optimum of the top right square, but from there each one can unilaterally reduce her abatement costs. This causes increased damages, but they are shared by all players, so that if a single player reduces abatement costs it pays off, with the other player paying the price. Of course, this yields the classical prisoner's dilemma story of climate policy where the single Nash equilibrium misses the single Pareto optimum. For an excellent analysis of applications of the prisoner's dilemma model for the climate challenge (and sustainability problems in general) see Carrozzo Magli et al. (2021).

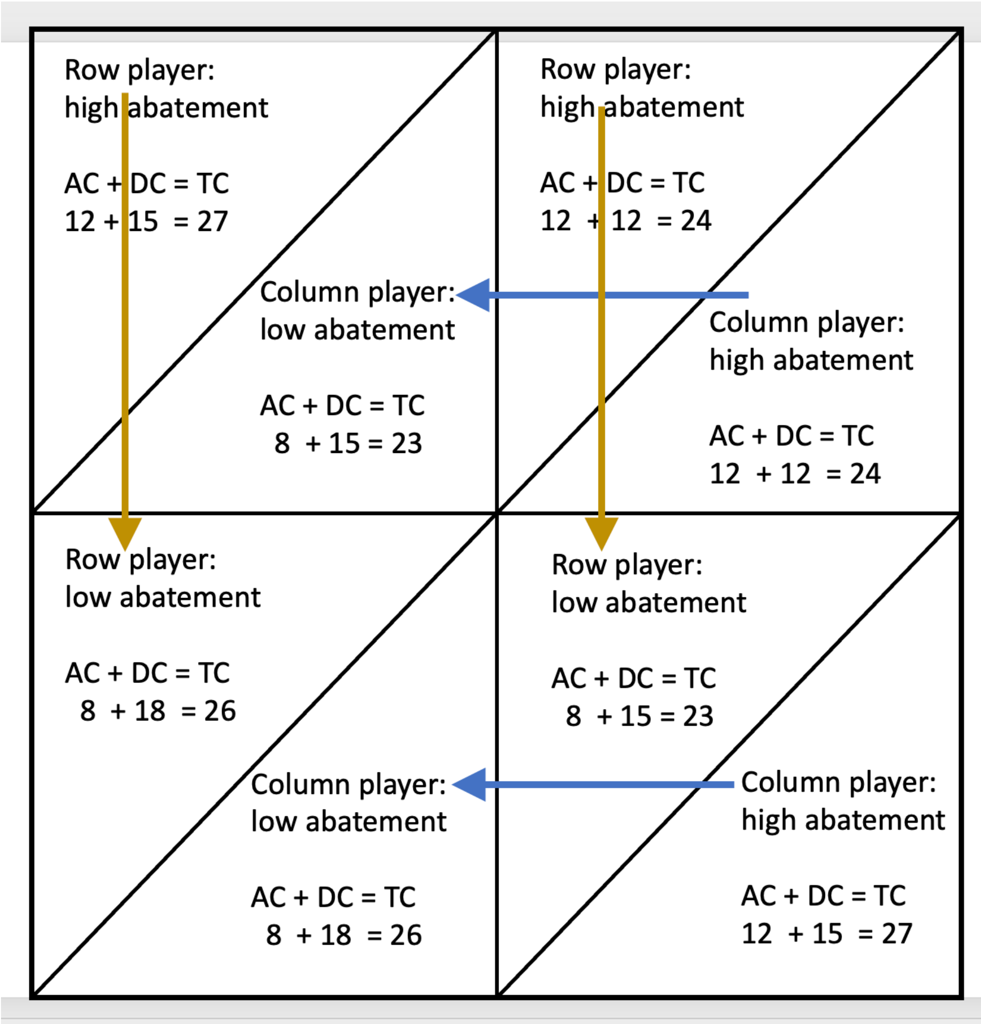

Figure 2: The prisoner's dilemma view of climate change
AC: Abatement costs, DC: Damage costs, TC: Total costs

But as Klaus and Susanne Hasselmann show, here the Nash equilibrium is not a situation where nobody is willing to incur any abatement costs. Looking at figure 2, imagine that beyond high and low abatement strategies each player has a zero abatement strategy available, whereby she produces 36 units of climate damages. If both choose that strategy, with 36 units of total costs, they are even worse off than in the Nash equilibrium in the bottom left square. And if only one, say the row player, avoids all abatement costs, it is still to the advantage of the column player to spend eight units on abatement: then the two players together generate 36+18=54 units of damage costs, of which both have to carry 27. With total costs at 8+27=35, the column player has still lower costs than the not very smart free rider, who makes everybody worse off, including herself.

Could this mean that even if the EU would be all alone in reaching the goal of its European Green Deal, namely climate neutrality by 2050, this would still be to Europe's advantage? Even in the very simple SIAM model structure this depends on specific parameters. With those used in the paper we are discussing here, it seems that a club of less than ten players could gain from investing in abatement on their own. That a single actor could pull off a similar feat is unlikely for many reasons, but given the difficulties of achieving a binding agreement among hundred and more actors, analysing the possibility of so-called climate clubs is definitely highly relevant (see also Nordhaus, 2015).

After investigating the case of symmetrical actors connected only by climate damages, the Hasselmanns extend the analysis to a variety of other cases: a single actor taking the lead in abatement; a multitude of actors connected by climate damages but also by trade; heterogeneous actors who differ in their assessment of the costs of emissions abatement and of climate damages, in particular the strong case of fossil fuel producers vs. the users of those fuels.

Two main results deserve attention. First, while a comprehensive international agreement on climate policy is highly desirable, it would make no sense for all actors to wait whether and when a truly effective agreement of that kind will emerge. At the time of writing, the Paris Climate Agreement is a historical step towards such an agreement. Still, whether and when this will be a truly effective agreement is an open question. Clearly, many actors do pretty much nothing to avoid dangerous interference with the climate system. Still, other actors are doing more than what the standard image of the climate challenge as a global prisoner's dilemma suggests. And beyond national governments there are and will be many other kinds of actors who can make a difference for the better regarding climate change.

The second result concerns the relation between economic and social modelling. The relevant interactions between actors faced with climate change are not restricted to the fact that emissions by one actor have impacts on other ones, nor to economic trade relations. The "present analysis clearly needs to be extended to include negotiations between actors in order to bridge the gap between purely cooperative and purely non-cooperative optimisation strategies" (KH & Hasselmann, S. 1996, p.413). And these negotiations are not restricted to offers, threats etc., they also involve deliberations about what are each one's interests, what are reasonable estimates of costs, benefits, risks, and how the trust necessary for collective action can be generated.

5. Reframing the Climate Challenge

5.1. A platform for a new research style

It was the recognition that deliberations are essential for effective climate action that led Hasselmann to plant the seed for a new kind of scientific organisation. He saw an urgent need to transform the science-society interface in view of climate change (and actually other global problems). Science had been able to describe and understand many features of climate dynamics and how human interference with these dynamics causes global risks. Moreover, science – often in synergy with environmental movements, NGOs, and various media – had generated concern about climate change in large and influential parts of world society. The entry into force of the UN Framework Convention on Climate Change in 1993 and the adoption of the Kyoto protocol in 1997 are tangible results of this growing concern. However, those events did not reverse, not even slow down the growth of CO2 concentrations in the atmosphere (at the time of writing, it is too early to assess the long-term effect of the Paris climate accord, adopted in 2015, on the concentration of CO2 and other greenhouse gases in the atmosphere).

Hasselmann saw this situation, thought about it and reached the conclusion that it would be useful to have an organisation bringing researchers and practitioners together to share discoveries, experiences, and disagreements in a constructive way. The researchers should include climate scientists, economists, and more; the practitioners should come from government, business, and NGOs. The goal was not simply to improve the transfer of research findings to society, but to enable the scientific community to do research that would be in a different kind of resonance with society. So he set up the statutes for an association whose members would be research institutions, businesses, NGOs, and individual members: the Global (then: European) Climate Forum (GCF). Thanks to his many acquaintances, he convinced enough organisations and individuals from across Europe to set up the association under German law at a meeting in Brussels.

At that time, I had just moved from a double appointment at the Swiss Federal Institute of Technology and the Technical University of Darmstadt, Germany, to PIK, the Potsdam Institute for Climate Impact Research (that Hasselmann had helped establish several years earlier) in tandem with Potsdam University. Hasselmann asked me to chair GCF, so that I would do the heavy lifting while he would shape things from the background as vice-chair. I hesitated, but the brilliant founding director of PIK, John Schellnhuber, nudged me in the right direction. Since then, working on climate and economics with Hasselmann in the setting of GCF has been an incredibly fruitful experience of joint research for which I am deeply grateful.

One reason for Hasselmann's confidence in possibilities of constructive exchange between people with very different backgrounds and beliefs was his familiarity with Bayesian methods (KH 1998). Respecting different subjective priors seemed natural to him, and the fact that people could revise their priorities so that they would converge to a consensus view, gave a template of joint learning. Later on, Hasselmann and other researchers from the GCF network would apply this pattern of convergent learning in a technical way to the attribution of climate risks like heat waves (Jaeger et al. 2008b). Against this background, in the GCF network a practice of stakeholder dialogues has developed (Kasemir et al. 2003, Welp et al. 2006, Mielke et al. 2016), a practice that was later refined in long-term cooperation with Arizona State University into the Decision Theatre method, where stakeholder dialogues are combined with interactive computer models method (Wolf et al., 2021a).

5.2. From the prisoner´s dilemma to the stag hunt

In the GCF network, the modelling perspective that Hasselmann had opened up with his 1990 program on climate and economics became a vibrant activity. An important impulse came from Ottmar Edenhofer, whom I had brought to PIK as a Postdoc because he had been one of my most gifted PhD-students ever. At PIK, he was one of two coordinators of a modelling comparison project focused on induced technological change (Edenhofer et al. 2006). As a result, both induced (by policy) and endogenous (to economic dynamics) technological change became important elements in the further development of the program laid out by Hasselmann in 1990.

Another, fundamental impulse goes back to Kirman's (1992) seminal criticism of the assumption of a representative agent that is taken for granted in much economic analysis. That criticism resonates with the arguments of Janssen and Ostrom (2006), Farmer and Foley (2009), and others who later emphasised the need and opportunity of agent-based models (Mandel et al. 2010, Wolf et al. 2013a, Wolf et al. 2013b). Among other things, this is relevant to the issue of discounting that led to the exchange between Hasselmann et al. (1997), Nordhaus (1997) and

Hasselmann (1999a): in a multi-actor world it is misleading both empirically and normatively to postulate a uniform discounting factor, constant over as many generations as you like.

Both impulses were taken up by Hasselmann with the "multi-actor dynamic integrated assessment model (MADIAM) of induced technological change and sustainable economic growth" (Hasselmann et al. 2004). The model was presented in Weber et al. (2005), and further elaborated in the following years (KH & Kovalevsky 2013, Kovalevsky & KH 2014). As mentioned above, in the Kiel paper (KH 1990), Hasselmann argued that "Policy and model development should be pursued as parallel, interactive, iterative processes" (KH 1990, p.20). When ten years later he designed GCF, he expanded the practical complement of modelling, that he first saw mainly in public policy, to the practices of businesses, NGOs, and other actors as well. Within the GCF network, the result has been a broad range of models evolving through interactions with practitioners. This is particularly evident in the use of the DIVA (Dynamic Interactive Vulnerability Assessment) model to improve adaptation of coastal zones to sea level rise. DIVA was initiated by Jochen Hinkel and shepherded by him through a series of EU projects (see Hinkel et al. 2013, Hinkel et al. 2019, Amores et al. 2021), involving various forms of stakeholder interaction – e.g. shared modelling exercises about flood risks in pacific island states.

Already in the Kiel paper (KH 1990), Hasselmann had identified a key challenge for the program he was developing in the tension between on the one hand the long-time scale relevant for (monetary and even more serious non-monetary) damages from climate change and on the other hand the short-time scale on which effective action with a long-term perspective has to be started, if those damages are to be reduced or avoided. This led him to advocate for two different discount factors for those two dynamics, and (in KH & Hasselmann, S. 1996) to emphasise the free rider problem, typical for prisoner's dilemma situations (Hardin, G. 1968, Carrozzo Magli et al. 2021). But in contrast to standard presentations of a prisoner's dilemma, instead of just two discrete strategies he considered a continuum of strategies. von Neumann and Morgenstern (1947) did so, too, but they considered a continuum of strategies as a convex combination of pure strategies where payoffs would be the analogous convex combination of the payoffs of those pure strategies. Hasselmann's payoffs, however, are a non-linear function of the convex combination of the extreme strategies under consideration. Therefore, if two extreme strategies are zero abatement of greenhouse gas emissions vs. strict carbon neutrality, free riders may avoid the latter, but the Nash equilibrium is not zero abatement but limited abatement that falls short of carbon neutrality.

Against this background, Hasselmann launched a search for win-win strategies, i.e. climate related actions that limit climate change in the long run while producing positive outcomes already in the short run (KH and Hasselmann, S. 1996, see also KH et al. 2015, Kovalevsky and KH 2016). In the GCF network, that search was performed with increasing intensity (e.g. Wolf et al. 2016, Hinkel et al. 2020). A major breakthrough has been achieved in a study commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety against the background of the global financial crisis and its ramifications in the Eurozone (Jaeger et al. 2011). The study took a multi-purpose economic model used as a standard tool by the EU and adjusted it for the purpose of European climate policy. This implied quantitative modelling of three mechanisms: (1) the impact of public and private investments on economic growth combined with learning by doing; (2) the impact of positive expectations that public investment and related policies can generate on private investment; (3) the impact of accelerating growth on matching processes on the labour market, resulting in mobilisation of underutilised human resources. The outcome is a perspective of investment-based climate policy that takes advantage of the multiple equilibria structure of the actual economy, a policy supported by empirically based computer simulations.

The quantitative estimates of Jaeger et al. (2011) have been updated in the context of the Covid-19 recession and the vision of the European Green Deal by Wolf et al. (2021b). They show the possibility of realising a carbon-neutral EU by 2050 by triggering a wave of private investment through investment-oriented climate policies across the EU countries and the broad range of relevant economic sectors. This would lead to real growth rates clearly above 2%, to unemployment rates below 7% and rates of youth unemployment below 15% even in critical EU states and keep inflation below but close to 2% over the medium term. A key challenge for the European Green Deal then is to shed a misplaced austerity mindset that reinforces counterproductive financial regulations (Jaeger et al. 2021).

These analyses and assessments show that investment-based climate policy offers the possibility of reframing the climate problem from a zero sum game to win-win solutions (Jaeger et al. 2012). While talk of win-win solutions is often used as facile rhetoric for public relation purposes, here we are dealing with a robust strategy based on solid empirical and theoretical work. Using the example of the EU, the empirical work has showed that investment-oriented climate policy offers the possibility to mobilise underutilised human, technological, and institutional resources (Jaeger et al. 2011, Wolf et al. 2021b, Jaeger et al. 2021), thereby improving living standards in the short run while reducing greenhouse gas emissions down to zero in the longer run.

The theoretical work, that has been performed through years of research by Hasselmann, myself and other GCF members clarified that the prisoner's dilemma, useful as it is in a wide range of social situations, is misleading when applied to global climate policy. In a prisoner's dilemma, there is one Nash equilibrium and distinct from it one Pareto optimum. The Pareto optimum requires that all players (in typical expositions as in figure 2 there are just two players) choose the same strategy, which may be called the Pareto strategy. The key property that characterises the prisoner's dilemma is the fact that in the Pareto optimum a player can improve her payoff if she drops the Pareto strategy while other players stick to it.

Now consider the climate challenge. Since the beginning of coal-based industry in the UK, an essential strategy for investors is to invest in "brown" technologies that are geared to fossil fuel use. In most countries and in the world as a whole, those investments don't grow as fast as the economy as a whole because of increasingly more productive energy use. Another strategy, essential from a climate policy point of view, is investing in "green" technologies, geared to renewable energies. These investments need to scale up much faster than the growth rate of the economy as a whole, because they are only helpful for climate policy if they take over large parts of the energy system. As an effect of the different expansion paths of brown and green investment, the latter generates much faster learning by doing effects and will yield higher returns if – and that's the crucial if – green investment is undertaken by a critical number of investors (Mielke and Steudle 2018).

In the simplified example of figure 3, the single Pareto optimum is reached if both investors engage in a green investment boost. If one of the two decides to continue with a strategy of short-term minimalism where she continues to invest in "brown" technologies at the scale of the past decades, however, she will not get an attractive payoff increase as in a prisoner's dilemma but the same payoff as if both choose the minimalist strategy. The Pareto optimum then is a Nash equilibrium, but it is not the only one. The Pareto inferior situation where both players pursue the minimalist strategy is a Nash equilibrium, too, because if a player decides to go for a green investment boost alone, she will fail.

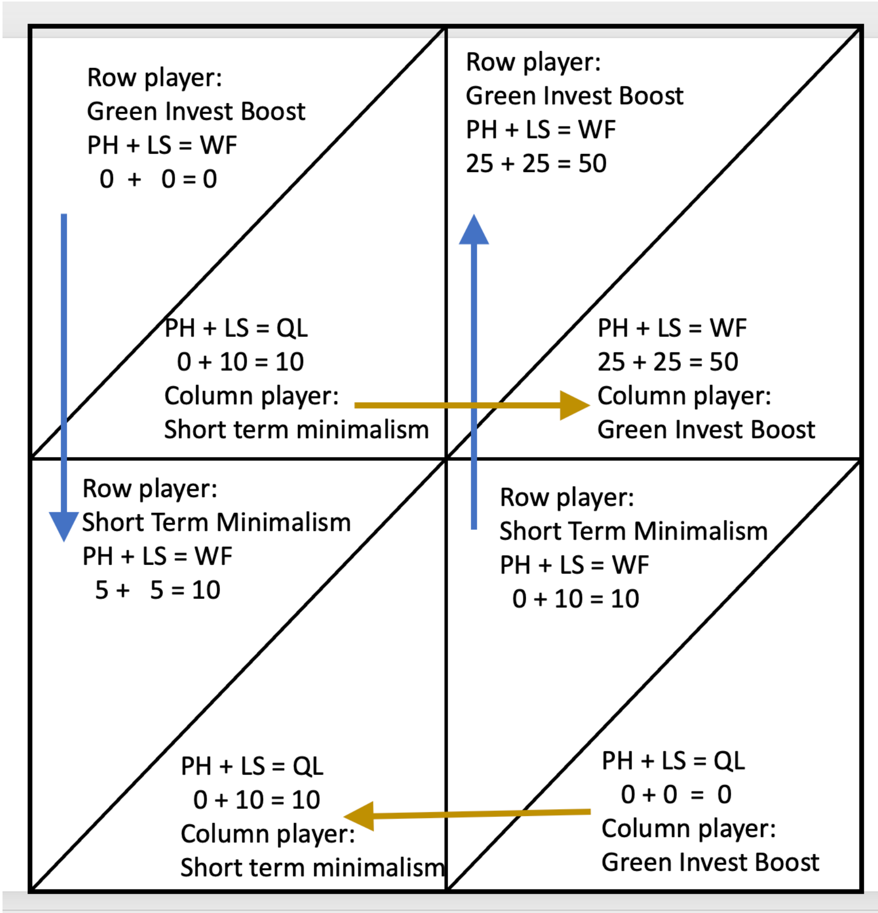

Figure 3: The stag hunt view of the climate challenge
PH: Planetary home, LS: Living standard, QL: Quality of life

This kind of game with two Nash equilibria, one of which is the unique Pareto optimum, is known as a stag hunt. It was introduced by Rousseau more than two centuries ago with the story of hunters that can successfully hunt a stag together, while each of them can catch a hare for themselves as well. Basically, the stag hunt raises a problem of coordination. The stag hunt pattern plays a key role in research about the evolution of social norms (Skyrms 2002), because institutions that establish suitable social norms can solve such coordination problems. It may well be that eventually the climate challenge will be mastered not primarily by international negotiations and agreements, but by an increasing number of investors – including pension funds, governments, and more – coordinating their strategies through social norms favoring a green transition of the world economy.

The emergence of social norms that solve coordination problems was crucial for the research of Elinor Ostrom, who earned the 2009 Nobel prize in economics "for her analysis of economic governance, especially the commons". In that research she has showed that local communities sharing a common pool resource quite often avoid the "tragedy of the commons" (Hardin 1968) by developing rules and institutions that enable them to solve their coordination problem (Ostrom 1990). This is clearly relevant for the climate challenge. This challenge, however, is not a local coordination problem that generations of villagers experienced until they gradually developed new institutions and social norms over a long period of time (Jaeger 2012). Rather, we, the people sharing planet Earth as our home, need to foster the evolution of new institutions and social norms for joint action at a global scale.

Misunderstanding the problem as a prisoner's dilemma jeopardises this necessary process of cultural evolution. The UN clearly is part of the institutional structures needed to tackle the stag hunt for a sustainable and climate friendly world economy, but it will hardly be sufficient. Rather, new rules and institutions that can act in this direction need to emerge, initially perhaps amongst industries, cities, occupational groups, and other organisations at regional and national scales, but ultimately at the global scale. This will be a process of cultural evolution of unprecedented complexity and critical importance for the future of humankind.

The fact that the Nobel prize awarded to Hasselmann and his co-laureates was justified by their "ground-breaking contributions to our understanding of complex physical systems" suggests that the Hasselmann program will be helpful, perhaps indispensable, to tackle the complex network of stag hunts and similar situations that the climate challenge offers and imposes upon us.

6. Climate change and the Economy

6.1. Hasselmann and complex physical systems

The 2021 Nobel prizes in physics were the first ones ever to be awarded for research on complex physical systems. Remarkably, Hasselmann did not even use the notion of complex physical systems while making key contributions to understanding their functioning and relevance for human action. In today's world, the concept of a physical system is rather clear cut: since the days of Galileo, physical systems are described in the language of mathematics, with mathematical language connected by practices of measurement to a domain of discourse including space, time, matter, energy, and more.

However, while the word "complex" has a long history going back at least to ancient Greek "plektós", for twisted, plaited, braided (Gell-Mann 1997, p.2), the notion of a complex physical system is much younger. The first explicit link between science and complexity goes back to the landmark paper by Weaver (1948). Papers referring to complex physical systems started to make a difference in the 1990ies (e.g. Anderson 1995, Gell-Mann 1997). In 1984, Anderson and Gell-Mann were among the founders of the Santa Fe Institute, which would soon become a Mecca of complexity scientists all over the world.

Keeping in mind that ambiguous concepts often are often very fruitful in the sciences as in other domains, it is fair to say that as a technical term "complex physical system" is still quite ambiguous. In practice, this means that „Presently, a bunch of complexity measures exist" (Kurths et al. 1994, p.220) and that "measures of complexity and meaning are essentially contextual, i.e., they cannot be defined universally, without respect to any context" (Kurths et al. 1994, p.232). Gell-Mann (1997, p.2) shares this view: "complexity, however defined, is not entirely an intrinsic property of the entity described; it also depends to some extent on who or what is doing the describing." Therefore, complexity measures for physical systems establish partial orders within certain sets of such systems. In many respects, the turbulent, opaque flow of water quickly leaving a faucet is more complex than the laminar, transparent flow of water slowly falling out of the same faucet. Whether the tea in a cup is simpler or more complex than either of them, however, depends on circumstances and points of view.

In this rather complex conceptual landscape, Gell-Mann distinguishes two kinds of complexity measures; one he calls crude complexity, the other effective complexity (Gell-Mann 1992, p.2f; for a different, if related, typology of such measures see Kurths et al. 1994). Gell-Mann illustrates crude complexity with what is known as algorithmic information content (AIC): the length of the shortest available program that will get a standard universal computer to print out a given binary string of zeros and ones, and then stop. Because any description of a physical system written with a finite alphabet can be encoded as a string of zeroes and ones, one may define the crude complexity of a physical system as identical to the AIC of a binary string encoding what one considers an adequate description of that system.

As a case in point, consider the description of the climate system conveyed by the three lines in figure 4. These lines can be encoded as a single string of zeroes and ones. The points where the black line changes direction represent observation-based data for global mean surface temperature changes, a key aspect of the climate system. These points document the internal variability of the climate system, that Hasselmann (1976) analysed as Brownian motion with negative feedback, triggered by short-term stochastic weather changes (Gupta et al. 2022, p.5ff). This implies that the black line has maximal AIC: the only way to write a program that will print the black line is to incorporate the full list of data points in the program and instruct the computer to print it: the list is algorithmically random and cannot be further compressed like, say, a list of points on an exponential curve.

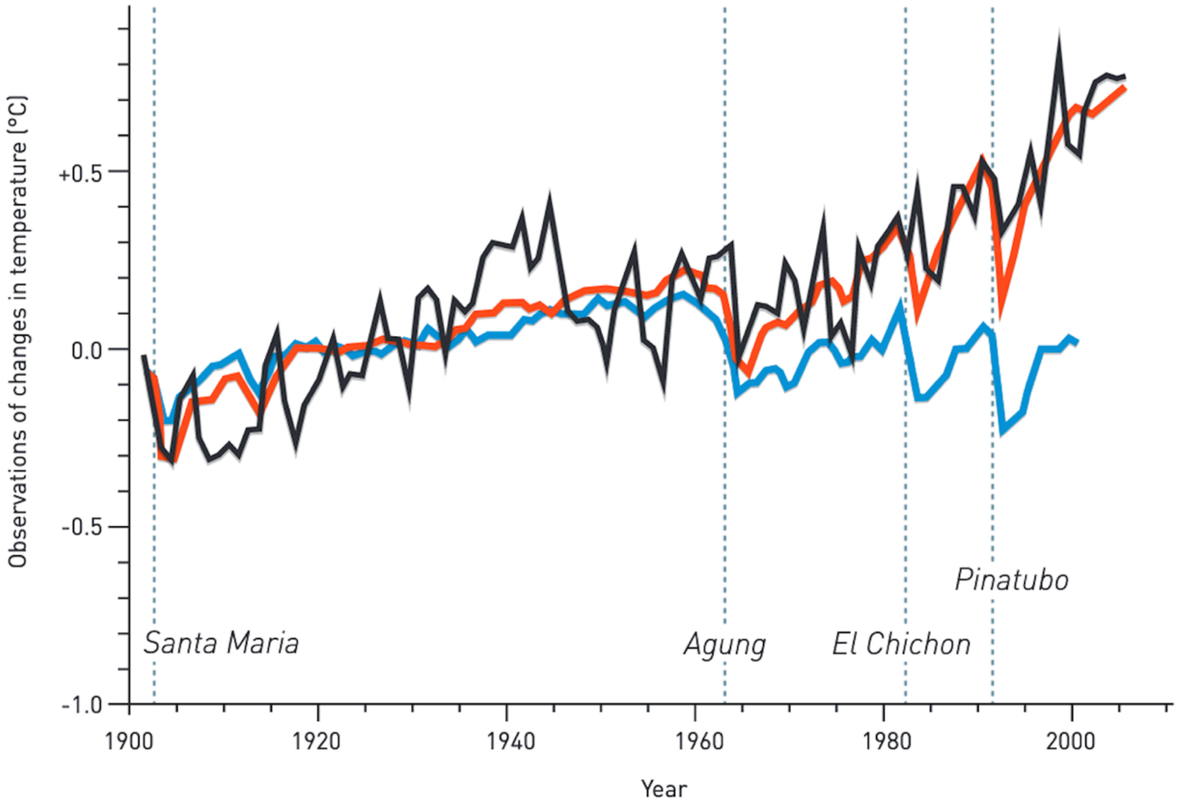

Figure 4: Complexity of the climate system
______: Observations
______: Modelling natural effects (e.g. volcanos)
______: Modelling natural and human sources
Dotted vertical lines: Volcanic eruptions
The graph represents global mean temperature changes (relative to the 1901-1950 average, °C) for the period 1901 – 2005.
Source: Hegerl and Zwiers (2011) via
www.nobelprize.org/uploads/2021/10/fig4_fy_en_21_fingerprints.pdf

Due to negative feedbacks, however, the weather induced randomness of the climate system does not lead to unbounded variance but rather to bounded fluctuations around detectable trends. A quick look at figure 4 allows to distinguish three trends corresponding to different periods: a warming period roughly from 1910 until 1940, then a slight decrease of global mean temperatures until 1975, followed by a period of rather steep warming until 2010 (for a more detailed analysis see Folland et al. 2018, in particular panel A in Fig. 1 and equation 1; for time series over the past 1000 years see Cowley, 2000). These trends are due to regularities of the climate system characterised by different time scales than those of weather induced random climate effects.

This is where Gell-Mann's measure of effective complexity is helpful. Looking at a system displaying both random behaviour and detectable regularities, he looks at the set of regularities relevant for a given observer. In view of figure 4, we may characterise the climate by the following regularities. Given actual global mean surface temperature, its change depends on six directional derivatives with regard to the following inputs:

- past sequencies of short-term weather variables
- past sequencies of medium-term oceanic oscillations
- total incident solar radiation
- aerosol concentration from volcanic eruptions
- greenhouse gas concentrations from human activities
- aerosol concentrations from human activities

Technically speaking, Gell-Mann is not interested in the AIC of the black line in figure 4, nor the one of the blue or red lines, but in the AIC of the whole set of six regularities listed above. Again, how large such a set will be and what will be the regularities included is context dependent.

The first four regularities combined correspond to temperature dynamics from internal variability and from non-anthropogenic forcing (mainly changes in solar radiation and cooling from aerosols due to volcanic eruptions). In figure 4, modelling results for those dynamics are represented by the blue line. It clearly misses the observation-based record after about 1965. Adding the two regularities for human activities gives a much more reasonable fit, as illustrated by the similarity between the black and red line. More recent data and simulations, like those discussed in Folland et al. (2018) allow a more detailed analysis with far-reaching implications – an example being the effect of the clean air act and related measures in the US and Europe on the end of the slowdown period that started around 1940.

However, the take-away points here are more fundamental. First, Hasselmann's (1976) approach separates signal and noise by distinguishing the short time scale of atmospheric events from the longer ones found in other compartments of the climate system, i.e. the oceans, the cryosphere and the land with its ecosystems. Different time scales, combined with spatial patterns, also play a crucial role in the fingerprint approach to detection and attribution of climate change as presented in Hasselmann (1997). The connection between time scales and different components of the climate system invites a complex network approach to climate phenomena that promises new insights – e.g. about tipping points – by complementing numerical modelling methods (Gupta et al. 2022, p.10).

Second, if one is used to look at the climate system as a network with the standard five compartments atmosphere, hydrosphere, cryosphere, lithosphere (the rocky upper layer of our planet) and biosphere – each of which includes its own finer grained networks – it is now time to accept the fact that we, humankind, have become the sixth node. A key argument for this perspective is the "Early Anthropogenic Hypothesis" (Ruddiman et al. 2020) of humankind generating substantial CO2 emissions long before industrialisation even began. In a similar vein, Crutzen (2002) proposed to declare the Anthropocene as a new geological epoch succeeding the Holocene.

Geologists will have to decide about whether they want to introduce such an epoch in their technical vocabulary and if so, what rough date they want to set for its beginning. A complementary perspective may focus on when and how we as members of the human species have become aware of our impact on the global environment we live in. One may call it the beginning of the reflexive Anthropocene (deepening the inquiry on reflexive modernity by Beck et al. 1994). This remarkable transition happened in the second half of the 20th century, with nuclear testing, biodiversity loss, pollution of air, soil and water, climate change, and pandemics being major issues raising concern. Science was a key transformative agent of this transition and will be transformed by it more than most realise (Renn 2020). And Klaus Hasselmann is one of the many scientists who did and do their best in assuming the responsibility researchers are faced with at this historical juncture. It led him to realise that overcoming the climate challenge – one of the core challenges of the reflexive Anthropocene – requires a deeper understanding of the economy we live in than currently available.

6.2. Time scales for a future world economy

The Paris Agreement, ratified by nearly all countries on the planet, declares in § 2 that it "aims to" keep the increase in global average temperature to "well below 2 °C above pre-industrial levels" and to pursue "efforts to limit the temperature increase to 1.5 °C". In § 4 the agreement specifies that each one of the countries that are party to the agreement is supposed to cut down their greenhouse gas emissions to net zero (i.e. including man-made carbon sinks) by 2050. Obviously, to get there a country needs to reach peak emissions well before 2050, and the agreement explicitly states that "Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognising that peaking will take longer for developing country Parties". Finally, all this shall happen "on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty."

There are different ways to justify these ambitious goals (Jaeger and Jaeger 2010), but implementing them is another matter. "A successful climate policy must consist of a dual approach focusing on both short-term targets and long-term goals." This statement made in Science magazine by Hasselmann et al. (2003, p. 1923) emphasises the importance of heterogeneous time scales not only in the climate system, but also in the socio-economic realm. The following rough bands of relevant time scales conveys the complexity of the matter:

- Milliseconds to seconds: high frequency algorithmic trading
- Days: Prices and quantities on flex-price markets (e.g. oil)
- Days to months: stock market investing
- Quarters: quantities on fixed price markets
- Quarters to year: capacity utilisation, prices on fixed-price markets
- 3 years: capacity expansion / reduction
- 10 years: business cycles, implementing infrastructure tested elsewhere
- 30 years: workforce education
  developing new technology
  implementing new technology and infrastructure
  market creation

- 30 years and more: implementing novel infrastructure
  transforming educational systems
  transforming financial systems

Such a spectrum of time scales is hard to reconcile with the fact that so much economic modelling assumes that the system is in equilibrium at any moment in time. Unfortunately, the word equilibrium easily leads to misunderstanding here. In physics, equilibrium typically means a stable fixed point of a dynamical system, i.e. a state that will last unchanged for quite some time and towards which the system will converge if it is not too far away from it. In economics, however, equilibrium in general means a balance of supply and demand on a market or perhaps even a whole system of interdependent markets. Prices and quantitites traded may well be in continuous flux – as long as supply and demand match it is a market equilibrium. And most economic thinking takes it for granted that as long as there is competition and no inappropriate political interference in markets, they will rapidly converge towards a single stable equilibrium. As Saari (1995) explains in a remarkable paper with the title "Mathematical Complexity of Simple Economics", with standard curves of supply and demand this is the exception and not the rule.

The vagaries of oil prices in nearly half a century since the oil crisis of the 1970ies, the interplay of financial and "real markets" in the global financial crisis that started in 2008, and then again in the Covid-19 recession, provide strong arguments to the effect that the spectrum of time scales in the world economy is important and should not be ignored, particularly in view of the time scales (and risks of failure) implied by the Paris Agreement.

Fortunately, competence in dealing with heterogeneous time scales in the economy is growing in the field of complexity economics. With roots like Rosser (1983), Anderson et al. (1988) and Arthur et al. (1997), fresh ideas like Beinhocker (2006), Hidalgo and Hausmann (2009), and new connections to well-matured insights like those analysed by Orlando (2021), it should become possible to help the IPCC to deal with the complex interplay of time scales when dealing with targets like the ones of the Paris Agreement.

The need to take into account different kinds of time scales is a main issue flagged by Hasselmann et al. (2003), especially in view of economic dynamics. Surprisingly perhaps, that paper does not join into the chorus of those who claim and believe that there are only a few years left to avoid apocalyptic climate catastrophes. The argument is rather different: the key challenge is to bring global greenhouse gas emissions down to zero within the 21st century, because the biggest danger is what will happen in the following centuries if we miss the opportunity of the present one. But in order to get to zero emissions within the present century three kinds of investment are needed without further delay: investing in a range of new technologies that may become helpful on the way to zero emissions, investing in infrastructure that will be needed as well, and investing in human skills that will be essential, too.

The basic rule then is to start investing in what one may call different kinds of green capital, and to do so in a way to increase the overall investment share of the economy, thereby creating new jobs, new effective demand, and rising salaries and other incomes. Such green investment will then create the conditions where brown capital stocks like coal power plants can be quietly phased out (a big component of today's capital stock is compatible with brown as well as with emerging green capital). And by fostering learning by doing in a green direction it will accelerate directed technical change (Acemoglu 2002) in the right direction. To capture the transition from an economy whose energy subsystem is shaped by a large array of brown fixed capital towards one where brown capital has become obsolete thanks to green variants, a multisectoral model with depreciating fixed capital is essential. The architecture of von Neumann's seminal model of general economic equilibrium provides the basis for representing the shifting production structure (von Neumann 1945). The possibilities to enlarge and modify von Neumann's basic structure are manifold, e.g. in view of private and public consumption and saving (Morgenstern and Thompson 1967), credit money (Burley 1992), and technical progress (Färe et al. 2020).

The widespread unwillingness to seize the opportunity offered by investment-oriented climate policy is due to the worry that it might be either impossible or dangerous to finance the required investment (especially the public component). This worry is based on the illusion, debunked by Keynes, that investment can only be performed if there is a corresponding amount of savings waiting on some shelf. As Gupta et al. (2022, p.10), referring to Stolbova et al. (2018) put it: "There is also a growing need to not only assess the economic impact of climate change but also to find solutions for the economy that can help to transfer economic losses associated with climate change into opportunities for creating a climate-friendly sustainable economy. This will aid political decisions by providing a better estimation of the uncertainties involved. Including nonlinearities and stochasticities in coupled climate-economy models, and using financial macro-networks to comprehensively evaluate the economic impact of climate policies are promising lines of research in this direction."

Investment oriented climate policy needs careful assessment, monitoring and analysis of slack in capacity utilisation (Petach and Tavani 2019). Work by Post-Keynesian economists has made significant breakthroughs in this direction (Lavoie 2022). It can and should be integrated with research on the technological evolution and economic growth performed in a complexity perspective (Nagy et al. 2013). The slack in the world economy is threefold. First, there is underemployment of hundreds of millions of people; second, underinvestment of trillions of Dollars; third, lack of adequate education for billions of people (Jaeger 2014). Investment- oriented climate policies designed and implemented by different actors both in industrialised and developing countries may be the way to go if the Paris Agreement is to realise the historical achievement it aims for.

7. Outlook

As with any fruitful research program, Hasselmann's initial approach has evolved in important ways since the first sketch in his Kiel paper (KH 1990). What has become increasingly clear is his view of anthropogenic climate change not as a scary slope to the edge of the ultimate abyss, but as a challenge to be mastered with a sense of responsibility informed by a calm mind. This responsibility calls for an improved understanding of the economic system that played a key role in setting the climate system on a new, dangerous trajectory. Nordhaus (2018a) was certainly right when he chose the title for his Nobel lecture: "Climate change: The Ultimate Challenge for Economics" (as a complement see Bowles and Carlin 2021 on "Rethinking Economics").

An important development in the future development of the Hasselmann program will concern evolutionary processes. We have met them in the connection between stag hunt games and social norms (Skyrms 2002, Ostrom 1990). We have met them again when discussing how to model the shift from brown to green capital stocks in the spirit of von Neumann: replacing coal-fired power stations with solar power plants starts with a new technology emerging and then taking over a substantial part of the market - a bit like a new species emerging and then assuming a key role in an ecosystem.

An evolutionary understanding of technological progress will be crucial for a realistic assessment of carbon taxes. Experience shows that carbon taxes induce people to decrease the consumption and use of products whose price is increased by the tax – certainly a desirable effect in the context of climate policy. But experience also shows that carbon taxes are not a key trigger for technological change, nor for large-scale investment in new technologies (Lilliestam et al. 2021; Lilliestam et al. 2022; Jaeger et al. 2011). The reason is that technological change and large-scale investments are saddled with deep uncertainty about future effective demand, an uncertainty that can best be overcome by Keynesian "animal spirits" (KH and Kovalevsky 2013) in combination with public investments that create new effective demand and operate as credible signals for future policies (Jaeger et al. 2011). Carbon taxes are appropriate in situations where the relevant technological options are known and implemented, but when an evolutionary dynamics is needed to generate new technologies and consumption patterns more complex strategies and policies are called for.

Studies of technological change and the dynamics of social norms often run into difficulties because they are not content with the many family resemblances between biological and cultural evolution and look for isomorphisms instead. This has led to a search for cultural equivalents for genes, with memes, routines, skills, etc. as candidates. Often, the search has led to an impasse (for a more promising alternative see Bowles et al. 2021). Recent work on extended evolution in biology can help avoid the impasse (Laubichler and Renn 2015). Of course, genes continue to play an essential role in biological evolution, but they couldn't play that role without molecular regulatory networks that control the expression of genes and without environmental niches that allow for intergenerational heritage of many phenotypic traits. Families, states, professions and many other institutions are stabilised by rule systems ranging from etiquette to constitutions, and from accounting patterns to vocabularies and grammars. And institutions are embedded in human ecological settings ranging from caves to houses, airports, power grids, concert halls and more. Exogenous factors, random events, conscious human choices as well as unintended consequences of the latter then guarantee a non-deterministic evolutionary dynamics leading to the amazing braid of individual stories and collective histories.

To answer the grave question: "Is Net Zero Carbon 2050 possible?" (Deutch 2021), and if so, "under what conditions?", it will be important, perhaps indispensable, to pursue the Hasselmann program all the way to its ramifications in the realm of cultural evolution. This sets the climate challenge in a broader context. If nothing else, then the sequence of a global financial crisis, a worldwide pandemic with massive economic consequences, a war where nuclear power plants and nuclear weapons represent clear and present dangers, and persistent inequality within and between countries suggests that the climate challenge may require institutional changes that at the beginning of the 21st century are hard to envisage.

With this reasoning we raise questions of a kind where researchers can easily get lost in fruitless speculations. To avoid them we heed Hasselmann's insistence on embedding research in iterative exchanges between researchers and stakeholders of different kinds. The Decision Theatre method used and continuously enhanced in cooperation between the Global Climate Forum, Arizona State University and the Freie Universität Berlin (Wolf et al. 2021a) facilitates such exchanges as essential ingredients for research that shall be both technically sweet and socially useful.

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KH *stands for Klaus Hasselmann; a comprehensive list of his publications (mostly with fulltext links) is to be found at* https://mpimet.mpg.de/en/staff/externalmembers/klaus-hasselmann/publications

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