THE LONG HAUL: MANAGING THE ENERGY TRANSITION TO LIMIT CLIMATE CHANGE

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This workshop was held from August 11-13 2008, at Dunsmuir Lodge, Victoria BC, sponsored by the University of Victoria and its Centre for Global Studies, the US National Science Foundation, the University of Michigan's School of Natural Resources and Environment, and the Climate Decision-Making Center of Carnegie-Mellon University. The workshop convened roughly 30 experts from diverse disciplines, to examine how to achieve the huge, multi-decade transformation of world energy systems that will be needed to limit risks of climate change. The workshop had three objectives:

- Identify and integrate current knowledge relevant to this problem from diverse fields.
- Identify insights current knowledge offers for near-term public and private decisions.
- Sharpen questions for research and analysis, to improve guidance for future decisions.

This report synthesizes the workshop's discussions to highlight the most important and promising insights, themes, and questions that were raised. It aims to be a first step in a program of subsequent collaborative research and analysis to follow from the workshop.

Workshop Introduction and Objectives

Climate change has seen a huge rise in attention and concern in the past few years, as debate in many countries has shifted from whether the issue is serious enough to warrant a response, to what that response should be. Most debate, however, has concerned the two endpoints of a response: first steps, and long-term climate-stabilization targets. This workshop targeted the less examined space between these questions: how to move from feasible near-term actions toward reasonably prudent long-term targets.

The scale of transformation needed to manage climate change is huge. By present judgments, avoiding severe risks appears to require limiting warming to about 2 degrees C, which requires holding greenhouse gases to about 450 parts per million (ppm) of CO_2-equivalent, which requires cutting emissions of these gases 50 to 80 per cent by mid-century. Depending how soon developing and emerging economies join in global cuts, this may require rich countries to cut 80 percent or more by mid-century – a massive shift of energy systems toward climate-safe energy sources and technologies, which must be achieved while also preserving prosperity and reliable, affordable access to energy.

A transformation of this scale cannot happen in a single stroke. Rather, we must consider the entire pathway that leads from initial actions to eventual climate stabilization. This is necessary in the first place because the required changes are too big to achieve in a few years, but will take decades of sustained attention and effort. Early steps must thus be assessed not just for what they achieve immediately, but for how they promote or

obstruct the larger steps needed later. We must also consider the transformation pathway and process because of uncertainty. We know emissions must decline a lot, but do not know exactly how much or how soon. The figures above are current estimates, based on judgments and assumptions that will change. Nor do we now know the specifics of how to get there – either what technologies will best achieve the required shift, or what policies will best motivate the required changes in technology and behavior. Yet we cannot delay action in hope of resolving these uncertainties: because of inertia in the climate and energy systems, such delay would give up any chance of making the required changes in time. Rather, we must navigate the required transition under uncertainty. This demands coupling our decades of sustained attention and effort with decades of sustained experimentation, learning, and adaptation – an enormous and novel challenge.

But is it really necessary to think explicitly about the transition pathway and process? Two views of the climate-energy issue would say it is not, for different reasons. The first view, which we caricature as held by a visionary energy analyst and modeler, we call "Just do it." This view holds that we *do not need* further examination of the transition path and process, because we already have stabilization scenarios giving detailed trajectories of emissions and associated emissions taxes, from the present to various future climate-stabilized states. We can consequently realize the transition to climate stabilization by simply creating an expert analytic body, insulated from politics (modeled perhaps on independent central banks), giving them a trajectory of emissions or carbon-tax levels, and empowering them to pursue it. The second view, which we caricature as held a seasoned old political hand, we call "Muddling through." It holds that thinking explicitly about the transition path and process is *futile*. Imagining you can bind the future to any long-term plan, let alone some subtle process of "adaptive management," is academic, impractical, and vain. All decisions are short-term. The most we can do to influence future decisions is put the issue on their agendas, through periodic mandates to review treaties, laws, or regulations, perhaps with input from expert advisory bodies. This was the approach of the Montreal Ozone Protocol, the most successful international environmental treaty to date. Seeking more control over future action than this is futile.

These views are intentionally extreme. Both offer useful challenge and provocation, but neither is satisfactory. The first assumes an extreme ability to lock in control over future policy today. Moreover, by assuming we know enough today to fix the path of future emissions or carbon prices, it ignores the uncertainties that are responsible for the large variations among current stabilization scenarios. Putting these uncertainties back in and considering what to do with them means thinking about the transition: what path should emissions or policies follow, what information should be used in deciding this path over time, and how should authority over these decisions be divided between expert and political bodies, present and future. The second view seems unsatisfactory because it exaggerates the impotence of today's decision-makers. Long-standing practice shows that current decision-makers can, and legitimately may, influence future choices by creating laws, institutions, and constitutions that sustain principles to endure through varying future conditions. On the climate-energy issue, our imperfect but real knowledge of long-term dynamics confers some responsibility to structure and influence future choices, beyond merely placing the issue periodically on their agenda. Moreover, if we

expect our successors to have less capability to manage the issue than we have – e.g., if opportunities to avoid climate change that would greatly harm future generations are lost by inaction or ineffective action today, or if political capacity to cooperate and solve global problems is at risk of declining – then our responsibility may be even greater.

To reject these extremes is to accept the need for explicit forethought on the pathway and process to navigate the transition. Fine, but what should we do? The problem can usefully be parsed into two separate questions – one on "pathway", whose character is technical and analytical, the other on "process," whose character is political, institutional, and legal. The first question follows the "Just do it" caricature in putting complete power in an expert body, but highlights problems of uncertainty and information that the caricature evaded. Suppose this expert body is granted complete authority to vary the level of an emissions cap, price, or other policies over time. In effect, they have a steering wheel to control the path through the transition. How should they use it – i.e., how hard should they steer immediately and how should they vary the stringency of policy over time? And crucially, what observations should they use in making and updating these decisions as the transition proceeds? The second question then examines the legal, institutional, and political issues that the first question set aside. Given that no one has such a steering wheel, what ways to influence long-term decisions and societal trends are actually available, how and how well do they work, and what costs and risks do they carry? In particular, what tools are available to manage the tension between the dual aims we have for future decision-makers: binding them to the long-term goal of shifting to climate-safe energy at low cost, while also empowering them to adjust specific decisions in pursuit of this goal, based on knowledge they will have but we do not?

The workshop was organized in three sections. The first provided a series of briefings, on the energy-climate issue and on other issues that may offer insights or analogies for the energy-climate transition. The second examined the question, "Suppose you had a steering wheel." From recent work in energy-economic and integrated-assessment modeling, it asked what we know about preferred transition paths for emissions and policy stringency, what information would help develop and adapt these, and how the need for future adaptation influences near-term decisions on policy and regulation. The third section examined the question, "What controls do we actually have?" It asked what legal, regulatory, and institutional means are available to motivate and guide the transition, how well they work, with what costs or potential pitfalls.

The workshop focused mainly on the emissions mitigation and energy side of the climate issue, without presuming that this is the whole problem. A portfolio of responses is needed, of course – including measures to adapt to climate impacts, because we are already experiencing climate change, committed to more, and unlikely to stop further changes anytime soon. But mitigation is essential to slow and eventually stop climate change, despite the changes we are already committed to, because the stakes in the size and rate of further changes – which we still have the opportunity to avoid – remain high. All the same questions about managing adaptively under uncertainty and learning must be posed for impacts, adaptation, and vulnerability – and for potential linkages between mitigation and adaptation – but these were not the central focus of this workshop.

Briefing Sessions: Highlights and key Questions

This section summarizes key points from briefings by David Keith, Dan Lashof, Daniel Halberstam, Al Carnesale, Ged Davis, and Buzz Holling, and discussion that followed. It is not comprehensive, but notes points of particular interest or challenge.

- Cutting emissions to limit climate change is predominantly a technological problem of changing how we obtain and use energy, likely to be solvable at manageable cost. Specific knowledge of technical options to cut emissions varies widely across sectors, however. For electrical generation, a clear set of options is available to deploy now, and further development of some mix of these can generate a smooth path to full decarbonization. For other sectors, especially transport, multiple technical options have been identified but which ones will be commercially successful and socially advantageous remains highly uncertain, mainly due to strong network effects.

- There is still a wide range of uncertainty over how bad climate change will be, compounded by uncertainties for major impacts such as loss of continental ice sheets (Greenland and Antarctica). Standard projections of ~ 2 to 4 degrees warming this century have tails on both sides, the high one extending out to severe changes. Although knowledge of climate science has advanced greatly in recent decades, these key uncertainties have not declined – indeed, some have increased – and they are unlikely to resolve soon enough to allow responses to depend on their resolution. Remaining uncertainties in technologies and costs of emission reduction are also unlikely to go down, but for different reasons: probing these further requires real actions to motivate and develop the technologies, to trigger learning by doing.

- In any response to climate change, multiple decisions will be made in parallel, with time-scales extending from immediate operational issues, through intermediate-scale investment and technology development decisions, through attempts to manage century-scale risks. Uncertainties, coupled with high inertia in the energy and climate systems, mean that these decisions are likely to exhibit strong path-dependence, with significant risks of early choices locking in inferior policy or technological solutions.

- Policies already include some provision for adaptation over time, e.g., the FCCC's requirement for periodic review of commitments, to which the Kyoto Protocol was the first adaptive response. Many cap-and-trade proposals provide adaptability by granting permit-holders flexibility in when they make cuts, banking savings when mitigation costs are low and borrowing against future emissions when they are high.

- Several recent policy proposals have defined emission time-paths through 2050. Although these will need adjustment as we gain experience and learn more, stating a long-term default path is valuable, as it provides a baseline for future adjustments that will influence expectations and thus long-term investment and decision planning.

- Some recent proposals defined stronger adaptive mechanisms. For example, a US Senate proposal (SA 4833) required 3-year updates in which the NAS presents

revised emission budgets to hold warming to 2C and the President proposes measures to meet these budgets. Legislation implementing the President's measures would then move with expedited procedures to floor votes in both the Houses and Senate.

- Institutional change can shape long-term social and political change, as shown by constitutional projects such as the movement to political integration in Europe. First steps that create institutions can advance principles, vindicate rights, and create spaces for interaction in which political preferences and values are changed. Small early changes can thus lead to bigger ones that were initially unattainable, which pass out of the control of their founders. These are normal and legitimate approaches to manage problems on which the future details of desired solutions are unknown. Lessons for a climate regime include: 1) Exploit diverse preferences, by crafting early rules and institutions that different actors support for diverse reasons. 2) Some decisions, even consequential ones, can legitimately be delegated to expert-based processes. 3) Early institutional decisions can build and empower political coalitions, including trans-national ones, e.g., by granting individual standing or rights of action.

- Successful avoidance of nuclear war during the Cold War illustrates the possibility of designing institutions that promote cooperative solutions to global problems in two ways: by changing the incentives of national policy-makers; and by taking some decisions partly out of political hands – e.g., by requiring delays or establishing advisory processes that must rule on specific questions before action is taken.

- Attempts at adaptive management of ecosystems and renewable resources suggest several parallels to managing the energy-climate transition. The dynamic behavior of complex systems, whether ecological or socio-political, exhibits separate domains of stability demarcated by boundaries. Consequently, systems' response to small and large disturbances can differ sharply, if the large one moves the system to a different stability region. We typically have observed little of the space, so the full range of system behavior is unknown and our conjectures about it subject to large errors and surprises. Heavy system exploitation tends to shrink the relevant stability region, so complex managed systems often follow Schumpeterian cycles, with periods of growth and accumulation followed by sudden breaks, in which resources are released and recombined in novel ways. Although such breaks are to be expected, their timing and characteristics defy predictability. Potential lessons for managing climate change include: 1) Do not count on predictability to allow smooth planning projections; accept the inevitability of surprise. 2) Transformative breaks are times of great stress and conflict, but also allow emergence of novelty and creativity. An effective response requires developing resilience, the capacity to bring good outcomes out of surprise and discontinuity. 3) Hints to help develop resilience include broadening imagination to recognize types of surprises that might come (even though they cannot be fully anticipated), through scenario exercises or similar methods; developing adjustment plans to help "panic intelligently" when breaks happen, knowing that they will; and launching experiments and networks to build social capacity that may be available to draw on when breaks occur, and in their aftermath.

Suppose you had a steering wheel – Conditions for policy adaptation under uncertainty: Highlights and key questions

This section identifies highlights from presentations by Jae Edmonds, Mort Webster, Gary Yohe, Larry Goulder, Austin Nichols, Rob Lempert, and Mark Jaccard, plus discussion that followed. It notes points of particular interest and challenge, without attempting to be comprehensive or to impose consistency on the discussion.

- Integrated assessment models have provided multiple scenarios of atmospheric stabilization at alternative levels, including trajectories of emissions and associated marginal costs, under specified assumptions about baseline growth, energy resources, technologies, and costs. These do not answer all key questions about the transition pathway, process, or strategy, but do hold several powerful insights.

- A non-zero emissions price is essential to make a transition to climate stabilization: a zero price gives a baseline emissions scenario, and no baseline scenario stabilizes the climate. The emissions price must rise over time, to deploy progressively more costly climate-safe technologies as emissions decline.[1] The prospect of rising emissions prices will bring technologies to market before they become profitable with constant prices, as investors anticipate conditions over the full lifetime of their investments.

- Uncertainties about specific technologies' future acceptability, performance, and cost are largest after mid-century, but investors' expectations of these future uncertainties move cost uncertainty back toward the present. Scenarios consequently show differences in near-term costs much larger than actual near-term uncertainty, as investors move early into higher-cost technologies in anticipation of future price movements. In practice, letting near-term market actors gamble over such different expectations of future price movements is likely to be socially advantageous.

- The more narrowly emissions prices are applied, the more the difficulty and cost of meeting any reduction target. This applies to sectoral limits, e.g., if emission prices cover only large final emitters or only electrical generation; to regional limits, e.g., if developing countries join late or not at all; and, crucially to omitting land-use related emissions, which are increasingly important under strict stabilization targets.

- In choosing between emissions taxes and cap-and-trade systems as instruments to generate the required emissions price, many researchers now favor taxes while nearly all policies being enacted are opting for the latter. The main reason researchers are favoring taxes is that they allow the intensity of the incentive – the emissions price – to be explicitly controlled and smoothly increased over time. This contrasts with the high short-term volatility of emissions prices seen in cap-and-trade systems, which has weakened incentives for long-term investments. Emission taxes can also more

[1] Prices need not rise without limit. If there is a backstop technology, or strong learning-by-doing in a few dominant technologies, prices may eventually decline. So also, as in the MERGE results, once stabilization is achieved and policies are just doing maintenance. These points limit but do not reverse the general point.

readily be applied upstream in the energy system, where carbon-based energy first enters the economy, so they can achieve broader coverage of emissions across the economy. In addition, tax-based systems are judged likely to be simpler and more transparent, and consequently less subject to gaming. These perceived advantages of taxes may be illusory, however, because they reflect a comparison between fully developed tradable-permit systems, with all the complexities and compromises that were necessary to secure their enactment, with idealized, theoretical tax systems. The apparent advantages of stable incentives, simplicity, and transparency may therefore fade as emission-tax systems also accrete special deals, compromises, and exemptions in moving toward enactment.

- Analyses that specify uncertainty explicitly show the value of near-term hedging. The most general lesson is, do not wait to learn. How big an immediate step is optimal depends on the precise specification of future uncertainties and the timing of their resolution, as well as the nature of future opportunities to adjust the initial decisions and any path-dependencies – but it is not zero. In general, if opportunities for future adjustment are fewer and more difficult, the first step should be larger.

- An adaptive policy must consider the time structure of uncertainties. Some are immediate, some near-term, and some long-term, and some can be resolved by action. For example, one key immediate uncertainty is that many actors do not know their emissions. The imposition of policy can thus produce acute anxiety, hoarding, and price volatility, which quickly resolves and stabilizes. This learning, a rapid form of learning-by-doing, is produced by the imposition – or the imminent expectation – of regulations. Other forms of learning-by-doing will be generated by the R&D and investment response to regulation, but over a longer period.

- An adaptive policy must include provisions to conduct or motivate investments in learning to inform and enable future decisions – both research to better characterize environmental risks and technological opportunities, and R&D to develop climate-safe energy technologies. The acute inadequacy of current energy R&D is both distorting current decisions, and pushing feasible emission-reduction pathways off into the future. For some technologies, short-term policy incentives or R&D subsidies will suffice to motivate the required R&D increases, but this is not the case for more distant and risky technologies. For these, particularly those technologies whose commercial viability will depend on large, sustained future policy changes (e.g., sustained high emissions prices), motivating the required increase in private R&D and investment will require the willingness to impose, or at least to credibly threaten, major regulatory constraints, in addition to public R&D subsidies. Even with such aggressive policies, the transition to a climate-safe energy-technology future will still be characterized by large uncertainties about cost and performance of particular technologies, and the possibility of abrupt and discontinuous transitions.

- The flexibility to adjust policies over time can be realized in various ways. Policy adjustment can be made automatic, by pre-specifying future adjustments in policy and the conditions that would trigger them – provided we know now what those future

changes and triggering conditions should be. Adjustment can be discretionary, left to specified future actors to decide, either after some specified time has elapsed or specified changes occur, or fully at their discretion. Finally, policies can delegate adjustment to regulated entities, letting them shift emissions over time under some overall constraint, even if the policies themselves do not adjust.

- If an adaptive process gives discretion to future policy-makers, they must balance the costs and benefits of two types of error: adjusting too frequently, incurring excessive transaction and adjustment costs, or not adjusting frequently enough and letting policies diverge too far from the optimum given current knowledge. Precise design of the time-profile of future adaptations – their frequency, size, scope, and lead-time – must also balance the dual aims of giving long time-horizons to motivate long-term investments, and limiting retroactive costs on investments that are sunk. This may raise conflicts between private actors' interest in reducing uncertainty over investment returns, and policy-makers' interest in flexibility to respond to future events. There may also be limits on feasible rates of adjustment related to capacity constraints in deploying new investments. (E.g., a major build-up of nuclear power would take decades.)

- The need for future adjustment of policies raises new issues for long-standing debates on the relative advantages of tradable permits, pollution taxes, or other environmental policy instruments. These include potential differences among policy instruments in their ease of future adjustment, as well as related questions of different instruments' potential biases re the direction of future adjustments, transaction costs and risks of error in future adjustments, and differences in the institutional location of authority over future adjustments. Preliminary discussion suggested grandfathered permits would be least flexible, because every change would require re-negotiating a vast number of special deals. Emission taxes would be more flexible, but auctioned permits re-issued frequently might be the most flexible, because holders would feel no endowment in permission to emit for which they had to repeatedly re-bid.

- A novel policy proposal with delegated flexibility would involve issuing a single stock of emissions permits, in an amount equal to the total future emissions budget, which holders may then use at any time. This approach – called "Hotelling permits" by Austin Nichols, who introduced it – would let emitters optimize inter-temporally in deciding how many permits to acquire, hold, and use each period, under the expectation that marginal mitigation costs – and thus the value of permits – would rise. All adaptation would thus be delegated to private markets, except changes in the cumulative emissions constraint. These changes might face rigidities, however, of different forms for tightening and loosening the constraint. Tightening would require buying and retiring permits, politically easy but costly to the treasury; loosening would require issuing new permits, thereby creating opposition from current permit-holders who face losses in the value of their holdings, and weakening motivations for long-term mitigation investment by diminishing the government's credibility.

- An alternative to seeking optimality under either current knowledge or expected future learning would be to make policies robust to major uncertainties. Adaptive and flexible policy is one approach to robustness, but not the only one. Some policy choices may perform acceptably under a wide range of plausible outcomes, even without processes for adaptation. The specifics tend to be case-dependent, as demonstrated by analyses of robust policies in specific impact and adaptation areas, such as water management in California.

What controls do we have – Legal, institutional, and social instruments to bind (or guide) the future: Highlights and key questions

This section identifies highlights from presentations by Gary Marchant, Richard York, Johanna Wolf, John Dernbach, Adam Henry, Marco Janssen, Richard Moss, Juan Moreno-Cruz, and Joule Bergerson, plus discussions that followed. Presentations and discussion asked what instruments we actually have to bind future decision-makers – or, more precisely, to balance the contending interests we have in holding them to the broad aim of reducing emissions, while empowering them to adjust based on new knowledge they have but we do not. The session considered what we know about the effectiveness, legitimacy, costs, and pitfalls and risks of different means to seek such influence. The summary here notes points of particular interest and challenge, without attempting to be comprehensive or to impose consistency on the discussion.

- On balance, current regulatory systems appear to be too rigid. They do not anticipate changes, and respond to them only slowly. Even foreseeable changes such as advances in scientific detection capabilities or required regulatory updates often collide with rigidities built into the system (e.g., non-attainment categories in the 1990 Clean Air Act, the Delaney amendment), and revision processes are slow and contentious. Rigidities become more harmful as change accelerates, in such forms as emergent or newly understood environmental problems, or new technology areas (e.g., nanotech, genetic testing, reproductive biology, computer privacy) that pose large, diverse, and ill understood risks.

- Current experience offers few models for how to make regulation more adaptive to scientific and technological change, and none are problem-free. Regulation can be made in incremental "baby steps." These must, however, address the tradeoffs involved in seeking to motivate both near and long-term investments, and the need to avoid lock-in to early inferior solutions, perhaps by combining incremental implementation with large-scale assessment and goal-setting that engage the whole problem. Regulations can require periodic re-evaluations, through sunset provisions, safety valves, or program reviews. In principle, the prospect of future adjustment can facilitate early steps, by reducing the stakes of these first steps for parties on both sides. Experience with such system has been mixed, however, sometimes showing abrupt and costly reversals in both goals and favored technologies within a few years, as in the California LEV Program. Experience also suggests that firm compliance deadlines, while creating strong incentives for performance progress, also generate distortionary effects at the sharp compliance boundary.

- There exists the possibility of constructive positive feedbacks between environmental regulation and private-sector-driven technological innovation, in which regulations motivate the pursuit and dissemination of innovations, and are in turn adapted to respond to the resultant expansion in perceived technological possibilities. This possibility has been demonstrated in the history of the Montreal Protocol on ozone-depleting chemicals, in which regulatory adaptation and innovation were linked through a novel technology assessment process operating under the Protocol's Technology and Economic Assessment Panel (TEAP). An adaptive system to manage climate change would greatly benefit from developing similarly effective means of blending technical assessment processes with responsibilities for action to advance environmental performance and capabilities.

- One must view claims that environmental problems are technical matters remediable by purely technical solutions with skepticism. Despite attempts at broad advance assessment of technologies or innovations, unanticipated effects are common. Technological changes to reduce environmental burdens may show rebound effects through offsetting changes in behavior. Moreover, even purely technological changes are rarely free of distributive consequences, especially when driven intentionally by policies. While well designed policies seek easy political enactment by minimizing transfers, this is not always possible, so any policy change may raise political conflict. The more deeply challenging the environmental problem, the more proposed technological solutions may fall short, so effective response may require moving back through the Kaya identity to change consumption or population trends. In such cases, attempting to resolve environmental issues may be intensely contentious.

- If achieving the climate-energy transition requires large-scale behavior change, we must consider what instruments are likely to be most effective. Evidence for the effect of incentives is strongest for incremental change. If the required changes are systemic – meaning either bigger changes in behavior, or multiple linked changes beyond the control of single actors – it is necessary to examine alternative approaches that consider issues of perceived self-efficacy and empowerment, and that address the links of behavior to identity. Conventional measures typically divide into "structural" (changing policies, incentives, institutions) and "agency" (information, education, norm promulgation) approaches, but intermediate approaches or complementary combinations of these may be needed. Incentive approaches target behavior directly, but we may have to consider relationships between incentives and other motivators, and between changing behavior and changing attitudes.

- Achieving large-scale societal change requires more than broad international policies to motivate identified technological options. An effective strategy must consider the multiple levels of decision-maker involved, including international, national, and sub-national authorities with diverse principles, preferences, and capabilities. Policies and institutional arrangements must be tuned and framed to meet the challenges posed by diverse local contexts. For example, climate change may not be the most salient factor in many relevant decisions, and the "rules in use" governing decisions may

diverge from formal "rules on paper." In these diverse contexts, incentives are only part of the solution, and may obstruct progress if they commodify desired behavior or weaken intrinsic motivations. Adaptation and learning may require distinct experiments and resiliency-building initiatives in these diverse local settings. As results of local experience percolate to the global level, increased ability for leverage and coordinated action may build over time. But there will remain a need for a portfolio of activities at local, regional, and global scale, as well as contingency plans to advance action even when blockages arise, internationally or in particular jurisdictions. These complexities call for novel decision structures and networks, involving more actors with broader diffusion of authority, which can be "accidents waiting to happen" when opportunity or crisis demands.

- In considering climate-change response in these diverse global contexts, we cannot consider mitigation in isolation from climate impacts, adaptation, and vulnerability, which provide the motivation for mitigation and are linked to it in multiple ways. Even more than mitigation, these are "retail" problems – diverse and place-specific – which are already being experienced. Managing impacts requires an adaptive approach, as we don't know what changes we must adapt to or where key vulnerabilities lie. But developing adaptive processes and institutions for climate impacts faces multiple problems: for example, institutions responsible for planning to protect resources from climate change are weak or non-existent, and other threats more immediate than climate change are pervasive. Responses are thus often limited to muddling through with "time-buying" strategies that seek to keep threatened systems alive while we try to slow climate change, learn to protect them more effectively, and prioritize. Pursuing these strategies, or stronger ones, will require: 1) development of guidelines for risk screening, assessment, and prioritization; 2) Community-based, participatory assessments for impacts and adaptation, including context-specific identification of conflicts and tradeoffs; 3) Community-based adaptation strategies, mainstreamed into existing decision-making (which is always about multiple concerns, not just climate); 4) A large increase in resources, which are unlikely to come from private investment; 5) New and expanded networks to connect global and national resources to local needs, and link activities peer-to-peer to share results and methods and synthesize results to influence policy. This approach rejects global uniformity but not global action, since well designed global institutions and treaties can support and facilitate diverse and appropriate local activities.

- Several key challenges to adaptive decision-making arise from the long inter-temporal distribution of efforts and burdens, which has strategic and political dimensions as well as the more frequently identified ethical ones. Near-term decision-makers can err in two directions, either over or under-stating the need, effectiveness, and legitimacy of their taking strong actions, on their own and to constrain future actors. Moreover, either of these errors may be confounded with self-serving biases. At present, the more common error appears to be under-stating current capabilities, consistent with the desire to avoid near-term burdens. But both errors are possible, because current decision-makers cannot fully anticipate either future capabilities (e.g., technologies, wealth, or institutional capacity) or future

preferences – all of which may be endogenous to policy choices, at least over time-scales of decades or longer. Such endogeneity of the bases for future decisions appears to increase the responsibility of current decision-makers.

- Managing climate and energy issues over multiple linked short to long time-scales requires advances in foresight tools such as scenarios or other methods to raise the salience of long time-horizons and uncertainties. The value of such methods does not lie in predicting the long-term, which is not predictable,[2] but in using long-term trends and challenges to continually re-frame short-term issues. Nor does their value lie in projecting conventional, linear futures, but principally in structured exploration of potential abrupt changes and surprises.

- The prospect of geoengineering poses several acute challenges for long-term management of climate change. With geoengineering options appearing increasingly effective and cheap, simple analyses suggest doing it to whatever technical or political limit is imposed exogenously. But considering that the cheapest geoengineering options (albedo modification) offset only some of the environmental harms of greenhouse gases (climate change, but not ocean acidification), and uncertainties about effective implementation and political acceptability of geoengineering, raises concerns about moral hazard. The prospect of a distant, cheap fix may divert attention from available near-term mitigation options and so compel reliance on effective implementation of geoengineering, despite its uncertainties. Yet geoengineering can provide a backstop against unexpectedly severe rates of climate change or failure of mitigation efforts, as well as increasing flexibility in the timing of mitigation. Under these conditions, the preferred near-term approach is to reject the false dichotomy of rejecting geoengineering completely vs. supporting a huge program, but instead to develop options, do small-scale experiments, and assess risks so the option remains available and is better characterized.

Concluding Discussion: Current Knowledge and Consensus Judgments

On the broad topic of the role of uncertainty, learning, and adaptation in managing the transition to a climate-safe energy system, the workshop sought to articulate and synthesize major points of current knowledge, identify resultant practical insights for near-term decisions, and identify priority questions for further research and analysis, to put us in a better position to give decision-useful insights or guidance in two years or ten. Several points emerged relative to each of these aims, with a substantial and surprising (not total) degree of agreement, given the diverse group of participants. This section summarizes these major points of agreement.

- Substantial uncertainties exist on climate change concerning both risk and response. Certain key uncertainties are not diminishing and are not likely to soon – for distinct but equally strong reasons in areas of atmospheric science, various impact domains,

[2] Ged Davis referred to a "heuristic rule of one-seventh" in the time-horizon of scenarios: the useful life of a scenario exercise is of order one-seventh the time it looks forward.

and the cost and performance of climate-safe technologies. But despite these uncertainties – indeed, in many respects because of them – the case for substantial near-term efforts and expenditures to manage the problem is compelling. Factors supporting this conclusion include the non-trivial risk of extreme impacts in the upper tail of the distribution, specific instances of serious impacts even in the middle of the distribution, and the likelihood that serious early mitigation initiatives will both better characterize, and on balance reduce, the costs of the transition. It has been widely noted, but remains true, that this situation poses hard communication challenges, as opponents of action characterize uncertainties as warrants for delay and decision processes give priority to claims of certainty, even spurious ones.

- Although this workshop focused on mitigation, climate change response must combine action, assessment, and research on both mitigation and adaptation, as well as research, assessment and preliminary small-scale experimentation with geoengineering as a reserve against bad luck or failure of mitigation efforts.

- Of these broad response types, mitigation is the highest priority for immediate action, because of the long time-constants of both the energy and climate systems. We know that emissions must be sharply reduced by late this century, even as there remains substantial uncertainty about precisely how much and how soon. The broad set of technologies to be pursued for early progress toward this goal is also evident for some sectors, notably including electrical generation. For other sectors, including transport, preferred directions of technology development are substantially uncertain: several plausible large-scale options are recognized, but which mix of these or others not yet identified will be preferable is not evident, and there are significant risks of lock-in to inferior options. As reduction targets grow stricter, more activities, emissions, sectors, and technologies – including land-use and other non-point sources – will have to be brought under the emissions price or equivalent policies.

- A substantial consensus is emerging on near-term policy choices required to begin promoting the required transition. An essential element of these policies will be economy-wide, market-based measures that put a price on emissions. A strong consensus was expressed on the following points: 1) that these measures should provide a consistent emissions price, as broadly across the economy as conditions of feasible policy implementation, monitoring, and enforcement allow; 2) that the emissions price must rise over time, from a starting level of order $10 to $30 per ton CO_2; 3) that the emissions price, or the associated emissions constraint if policy is enacted as a cap-and-trade system, must have a default trajectory, pre-announced with enough lead-time and credibility to motivate investment and R&D with time horizons of years to a decade or two. While clearly necessary to promote the transition, these market-based policies may not be sufficient, and may need to be augmented by additional regulatory measures targeting high-impact sectors and technologies, and policies to motivate and support climate-safe energy R&D.

Priority Questions for Research and Analysis

Note that the points of consensus discussed above primarily refer to near-term policy choices, not the pathway or process of subsequent adaptation. On these points, the principal focus of the workshop, participants strongly affirmed their importance but expressed less confidence on specific points of how to proceed. These issues consequently yielded not a set of propositions re how to proceed, but rather a set of high-priority questions for research and analysis. This section presents these questions for research and analysis, clustered into four broad topic areas.

Further analysis of stabilization transition scenarios under uncertainty

- Expand treatment of uncertainty, learning, and adaptive decisions (with specified future information available) in models of stabilization scenarios, in particular by relaxing restrictions imposed on what can be learned and at what time.

- Analyses of adaptive decisions without assuming time-certain future resolution of uncertainties; e.g., uncertainty that resolves at an uncertain time, or persisting, or non-monotonicities such as expanding unknowns or false learning.

- Model explicitly the overlaid structure of different durations of uncertainties, including some resolved immediately upon implementation of policies. For example, the evidence of dropping and stabilizing prices immediately after introduction of cap-and-trade systems suggests that actors' initial uncertainties about their actual emissions are a significant factor in observed price volatility. Is there a corresponding immediate uncertainty associated with initial imposition of an emissions tax, how is it likely to be resolved, and with what consequences? I.e., would imposition of a tax provoke a sudden re-assessment of emissions and mitigation costs and a subsequent stabilization of emissions expectations? And if so, what is the direction and size of likely bias in ex ante estimates?

- Model the effects of constraints or path-dependencies on future decision-making that may limit the potential for future adaptation, to examine the relationship between expected future flexibility and preferred near-term decisions

- Broadly, how can formal models provide more useful guidance to adaptive decision-making over time? Note that better informing adaptive decision-making is not necessarily the same as better representing adaptive decision-making. Rather, potential directions of contribution may include, e.g., more explicit representation of potential learning pathways, including over-confidence and negative learning; or modeling the determinants and consequences of potential over and under-reactivity in decision-making in response to new information.

Further analysis of specific policy instruments, at both national and international levels, focusing on the effects of the need for adaptation on policy choice

- What differences in potential adaptability, biases, and adjustment costs are associated with emissions taxes, tradable permits, and related instruments? In addition, where is authority over future adjustments likely to reside in specific political contexts, with what implications for adaptability, biases, and adjustment costs?

- Formal analyses of tradeoffs in design of adaptive policy between the frequency, size, and character of policy adjustments. These should consider the balance between providing long-term investment and R&D incentives and flexibility to adapt to changed conditions, under realistic specifications of investors' optimization of their portfolio of investment durations. These analyses should consider various forms and combinations of price-based and quantity-based policy instruments, as above.

- Further analyses of novel potential policy instruments that may facilitate advantageous adaptation, in particular including alternative time-structures of regulatory obligations. For example, analyses are needed of the efficiency, credibility, and incentive effects of alternatives to the traditional regulatory structure of fixed compliance deadlines – including the infinite-duration "Hotelling permits," discussed above, and other novel approaches.

Legal, Institutional, and Political Dimensions of Adaptive Management

It was widely recognized that a few basic elements are required for an adaptive decision structure that would balance the competing aims of letting future decisions respond to new knowledge and changed capabilities while holding to underlying goals and principles. These required elements included: 1) Investment in research, monitoring, and assessment likely to yield knowledge advances relevant to future decisions; 2) Expert bodies to monitor relevant knowledge trends, synthesize their implications, and offer some degree of guidance for decisions – which may range from simple identification of options and characterization of their potential consequences, through explicit advice and recommendations, to actual decisions; 3) Policy-making or political bodies with actual authority over decisions, operating under procedures making it difficult to defy or ignore the expert advice. But there was little in the way of specific insights into how to design each of these elements, how to fit them together, or the implications of alternative designs. Several areas of required research and analysis follow.

- The design of expert assessment bodies, including their membership, mandate, leadership, and processes. How can these do better at sustaining both high standards of scientific and technical quality and relevance to decision-making, while avoiding demanding more precision or confidence from assessment methods than they can provide, or allowing political conflicts to obtrude into expert assessment bodies?

- A closely related question is how to design technology assessment processes to motivate and enable both private-sector-driven technological innovation and

adjustment of regulatory policies, and support positive feedbacks between these, drawing on the analogy of the Montreal Protocol TEAP bodies. By analogy to this process, the conditions of success include motivating participation, related R&D, collaboration, and free sharing of information by first-rank experts from multiple sectors including industry; managing the process to limit biased judgments in service of political interests, whether these take the form of material interest in favoring particular firms or technologies, or ideological or other broader interests in either over or under-estimating aggregate prospects for technological progress; and sustaining high technical standards for deliberations on the prospects for particular technologies, to provide credible and useful information to guide adaptation of policy decisions. The key factor in promoting these conditions of success was in finding ways to align the interests of participating firms and individuals with the public interest in advancing environmental protection, suggesting that a key requirement for generalizing the success of this process will be finding ways to achieve such interest alignment in the context of the energy/climate transition.

- Feasible designs for adaptive decision processes, and the implications of alternative designs: Who holds the authority to make future policy adjustments? How much independence, over what scope of authority, is delegated to administrative bodies or hybrid expert/policy processes, as opposed to legislative bodies? What procedures or defaults are used to guide or constrain these decisions – e.g., super-majority decision rules, time-lags built into policy adjustments, or recommendations from expert or expert-hybrid bodies that are enacted by default, unless over-ridden? What enduring principles of adaptive policy-making might beneficially be enacted in constitutional measures, and what are the implications of doing so?

- If we abandon the assumption of smooth, continuous changes in behavior, technologies, and environmental and economic conditions – which support long-term planning and incremental policy change – in favor of the inevitability of disruption and surprise, what concretely can we do about it? If we recognize that predictability is limited, and that the most important events for future decision-making are often the least predictable, what practical steps can we take to facilitate advance preparation of a capability to panic intelligently when surprises happen?

- How can we do useful experiments in adaptive decisions? These appear to require small-scale diverse activities that 1) Push on the system hard enough to generate informative variation in response; 2) Do not build in biases to support the presumptively favored answer; 3) Pursue diverse options long enough to get results, resisting the pressures to corner solutions that come in a world of positive feedbacks, and; 4) can be adopted and sustained politically. We need research into the factors that obstruct these and potential means of surmounting them, including smaller-scale experiments that reveal the obstacles and challenges. (And investigation of these questions needs to recognize that researchers' interest in experimentation to learn how systems work may well go beyond what is socially optimal.)

Broader questions about long-term social change and the climate/energy transition

- ***Limits to leverage and centralized decisions?*** We frequently assume that centralized, high-leverage decisions, exercised by policy-makers and firms responding to the resultant incentives, can suffice to achieve the required long-term societal changes. But what if these assumptions are false, yet the changes are still essential: i.e., the laws that are failing to pass are getting better, but are still failing to pass, or we are enacting seemingly appropriate laws and policies but not seeing the required changes? Beyond the standard invocations of the need for leadership or political will, or when these also fail, for education, what do we do? Societal outcomes are ultimately determined by individual behavior, aggregated through various processes, networks and communication channels. Beyond policies to manipulate incentives, information, and institutional structures, are additional means needed to influence individual and collective behaviors and attitudes – changing hearts and minds – and what might these be? Discussion on these questions suggested priority questions about several possible mechanisms and potential relationships between them. For example, what is the relationship between material incentives and other motivational mechanisms, and between changing behavior and changing attitudes? Under what conditions are these substitutes, under what conditions complements? When behavior change is promoted by externally imposed incentives, does this ease or obstruct attempts to change attitudes that may contribute to further behavioral change? Under what conditions do small, environmentally expressive behaviors (e.g., recycling, changing light bulbs) make larger, more effective behavior change or support for strong policies more likely versus less likely? At present two behavioral theories (identity change and single-action flags), each supported by substantial evidence, give precisely contrary answers about this relationship, suggesting a priority area for further research. More broadly, what is known about how to re-frame issues, find new motivators, empower political constituencies, or propagate new norms to change societal environmental burden if conventional centralized means fail?

- ***The elephant in the room: stepping back through the Kaya identity:*** Discussion largely assumed that the required transformation can be achieved predominantly by technological change, plus modest behavior change from long-term shifts in prices and policies. But how much this is true – as opposed to the transformation also requiring fundamental changes in consumption or population trends – is an open question. If significant restrictions of consumption aspirations or reproductive behavior are required to avoid severe climate change, then sharp conflict over both basic values and societal distribution of wealth and power become much more likely. How can we anticipate the approach of such boundaries of acute conflict, and how (if at all) is it possible to prepare for the possibility while still pursuing more optimistic strategies based on technologies and incentives?

- ***Interaction between fixing climate change and improving society:*** Effective political leadership finds real ways, not just rhetorical flourishes, to turn crises into opportunities. Debate on climate change has not yet embraced this large aim, but instead lies at two poles: declarations from civil society that solving the climate

problem requires advancing social justice, answered by pragmatic calls for narrow, technical responses that avoid broad questions of social justice – in part because climate-change risks are too serious and questions of social justice too hard to dare link them. Few voices have suggested that both sides may be wrong, and considered the third possibility that a global environmental crisis may open up opportunities to make a better world in other ways – as Daniel Halberstam described in Jean Monnet's planning for future European integration even during the London blitz. For climate change, it would do well not just to seek pragmatic and expedient solutions, but also to ask whether such opportunities exist, and how they can be found – or created.

Appendix: Workshop Participants:

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