Link Foundation 2008-2010 Energy Fellowship Report

Vanessa Schweizer, PhD

Department of Engineering and Public Policy, Carnegie Mellon University

Advisor: M. Granger Morgan, University and Lord Chair Professor of Engineering, Department Head and Professor, Department of Engineering and Public Policy

Introduction

I completed my PhD in Engineering and Public Policy at Carnegie Mellon University in May of 2010. My dissertation, entitled *Developing Useful Long-term Energy Projections in the Face of Climate Change*, seeks to identify methods that may calibrate expert judgments for anticipating long-term outcomes for energy demand and related greenhouse gas emissions that may not be obvious.

The motivation for this research is to move beyond the false dichotomy that currently exists in traditional scenario analysis regarding questions of likelihood. Scenario exercises that aim to explore multiple visions of the future insist that judgments about the likelihood of each alternative should not be assigned and that all alternatives are equally possible or plausible (Bradfield et al., 2005; Carter et al., 2007). On the other hand, forecasts, which have served as "statements for which the highest confidence is claimed," (Parson et al., 2006) are more often wrong than right. For instance, past long-term energy demand forecasts for the US were overestimates nearly 75% higher than actual demand on average (Smil, 2005, p. 141). Such errors occur due to a well-documented cognitive heuristic called overconfidence, which refers to the tendency to discount the tails of a distribution of possibilities while making judgments under uncertainty (Dawes, 1988; Morgan and Keith, 2008; Oppenheimer et al., 2008).

More useful thinking about long-term energy projections is important to improve, as the problem of climate change demands a radical shift in societal energy supply and utilization. The Intergovernmental Panel on Climate Change (IPCC) reports that increased atmospheric CO_2 concentrations have been due to fossil fuel use (IPCC, 2007). Estimates for necessary reductions in worldwide greenhouse gas emissions are as high as 80% below year 2000 levels by 2050 (Rive et al., 2007). Because of time lags inherent in energy capital investment decisions, the political process, and climate systems, thinking about potential impacts 20 – 100 years from

now is necessary for making energy policy decisions today. Although long-term energy projections discussed above were gross overestimates, should similar errors in judgment *underestimate* long-term energy demand going forward, there could be serious consequences in different regions of a warming world such as increased water stress; decreased agricultural productivity; increased damage from floods and storms; and increased morbidity and mortality from malnutrition, heat waves, floods, and droughts (IPCC, 2007).

Since the worst impacts of a changing climate could be severe, decision makers have sought guidance on how much adaptation should be planned for, how aggressively mitigation should be pursued, and how much it might cost to undertake these initiatives. To assess costs and benefits, decision theory requires that probabilities be assigned to alternative outcomes (Shlyakter et al., 1994; Schneider, 2002). However, as discussed above, traditional scenario analysis is not well equipped to provide useful probabilities, and even for forecasts that aim to capture the best guesses of experts, overconfidence remains a significant problem. Thus the first step in developing useful probabilistic energy projections is to calibrate expert judgments for overconfidence as much as possible. The central objectives of this research are

- To systematically assess for overconfidence energy-related emissions scenarios that currently guide discussions about climate policy, and
- To compare to traditional approaches long-term energy projections developed with techniques that calibrate expert judgments under uncertainty.

Results

Two major techniques for calibrating judgments under uncertainty were utilized in my research: (1) disaggregation and (2) the use of reasons and disconfirming information (Morgan and Henrion, 1990). Disaggregation is the process of decomposing some question of interest into more basic parts, performing

judgments on the components, and then reassembling the component judgments to determine the implications of those judgments on the larger question as a whole. Alternatively, the use of reasons and disconfirming information refers to asking assessors for reasons to justify their judgments and/or for disconfirming reasons that their judgments might be wrong. I applied these techniques in two case studies. First, I used a disaggregation technique to systematically assess the internal consistency of scenarios and storylines prepared by the IPCC for their *Special Report on Emissions Scenarios* (SRES). Second, I applied the use of reasons and disconfirming information to a bounding analysis of US electricity demand in 2050.

The first study, which is regarding the IPCC SRES scenarios, is in preparation for submission to *Climatic Change* under the title, "Using Cross-Impact Balance Analysis to Improve Future Emissions Scenarios." For the latest Assessment Reports of the IPCC, the SRES scenarios have played a crucial role underpinning conclusions about projected radiative forcing and associated impacts (Moss et al., 2010). Despite their presentation in reports as different long-term descriptions for the future that are equally plausible (Nakicenovic et al., 2000), I used cross-impact balance analysis (Weimer-Jehle, 2006) to find that the SRES scenarios had varying levels of internal consistency. This means that some of the scenarios did a better job of characterizing self-reinforcing (or long-term) trends, while others instead described unstable, or transition, scenarios. This suggests that the SRES scenarios are *not* equally plausible descriptions of long-term trends.

Perhaps more importantly, I also found that

- Changes to disaggregated judgments that intensify the influence of globally-oriented environmental policy to promote low carbon- and energy-intensive energy systems substantially enhance the internal consistency of SRES IPCC A1T scenarios, which represent futures with the lowest CO_2 emissions, and
- Highly carbon-intensive futures with emissions profiles that may exceed those discussed in the SRES were perfectly internally consistent and remained highly robust to changes in disaggregated judgments.

In general, these findings suggest that it would be highly desirable to include systematic, disaggregated explorations of the complete qualitative scenario space rather than to rely on intuitive methods for scenario building alone. It would also be an improvement to include energy and emissions policies as explicit analytical parameters.

The second study, which bounded US electricity demand in 2050, is in preparation for submission to *Energy Policy*. I focused on electricity because CO_2 emissions from this sector in the US currently rival that of transportation (Morgan et al. 2005; US EPA, 2008). Additionally, electrification of the US light duty vehicle fleet may be pursued as a mitigation strategy (Samaras, 2008) thereby substantially increasing CO_2 emissions from electricity generation. Following the recommendation to build as full a set as possible of developments that could influence the future value of electricity demand (Morgan and Keith, 2008), I carefully considered and documented reasons why technological change and long-term economic growth could conceivably result in very high or very low demand by 2050.

For the high case, I considered a future where serious climate impacts in the US, such as much higher summer temperatures (WCRP CMIP3, 2010) and sustained water stress (Barnett et al., 2008), become imminent by 2050, thereby inspiring widespread energy carrier switching in transportation and building heating from fossil fuels to electricity (EPRI, 2009a). However, efficiency improvements were assumed to remain fixed at the current rate. Such a scenario introduces new electricity demands due to adaptation such as increased air conditioning and widespread desalination of public water supplies in the Western US. Also introduced are new electricity demands as a result of mitigation namely electrification of the light duty vehicle fleet, of building heating, and of some industrial processes. Some general findings for the upper bound of new electricity demands were

- Wide deployment of long-range (90 km) plug-in hybrid electric vehicles (PHEVs) would introduce the largest new demand (about 40% more demand in comparison to a simple historical projection of electricity use based on sustained economic growth and decreasing electricity intensity), and
- The next largest share of new electricity demand would be for increased air conditioning and widespread use of heat pumps (about 10% and 8% more demand respectively).

For the low case, I examined an alternative future where substantial expansion of the end-uses of electricity does not occur, since climate impacts, such as higher summer temperatures and regional water stress, are very mild. For this case, temperature projections were virtually indistinguishable from the 1970 – 2000 normal, resulting in a 1% increase in demand for additional air conditioning. For the lower bound, I also considered that efficiency improvements could be prioritized such that an additional 40% of expected demand could be avoided by 2050 (NAS-NAE-NRC, 2010; EPRI 2009b).

The results of the upper and lower bounds were then compared to the Energy Information Administration's (EIA) 2008 and 2009 *Annual Energy Outlook* reports (US EIA, 2008; US EIA, 2009). Neither of these reports entertain significant technological change by 2030, although PHEVs are anticipated to represent a small niche of the automotive market by that time. In general, the range of EIA's projections for electricity demand were much narrower than those developed through the bounding analysis.

Significance and impact

As a body of work, my studies serve as counterpoint to the view that the most relevant efforts in futures research balance the strengths of narrative and quantitative analysis against each other (Raskin et al., 2005). Instead, my studies point out that relevant research remains on addressing the overconfidence of both narrative and quantitative scenarios, as projections of both types have continued to

gloss over important policy-relevant futures. In general, this has occurred because visions of the future have too closely resembled the trends of today.

From the first study, the systematic, disaggregrated approach of cross-impact balance analysis (CIBA) shows potential for calibrating qualitative expert judgments for complex systems. In the second study, the careful treatment of game-changing technological developments resulted in bounds for future US electricity demand that were much broader than those considered by recent releases of the *Annual Energy Outlook*. For policy problems with temporal dimensions spanning long timeframes, effort needs to be made to integrate conceivable developments that could alter the suite of policy options that would be considered desirable in the near term.

From a scholarly perspective, this research demonstrates how to address the first barrier to developing probabilistic energy projections, which is calibrating assessors for overconfidence. It also uncovered the usefulness of treating policy and technology change parameters explicitly in projections. Interestingly, the CIBA study also presents speculative knowledge (Selin, 2006) that anticipated the recent observations of global emissions that had been tracking the highest rates considered by the IPCC (Pielke Jr. et al., 2008; Raupach et al., 2007; Price et al., 2006).

From a human impact perspective, this research could be most valuable for making recommendations to policy makers. In the past, integrating probability judgments in forecasting and scenarios has been resisted primarily because of the complexity of social and technological change (Grübler and Nakicenovic, 2001). Even without probabilities assigned as of yet to scenarios, the disaggregated approach of CIBA could clarify what scientists understand about interrelationships among the socioeconomic drivers of increased greenhouse gas emissions. Such information could help decision makers understand the linkages between social policies (e.g. technology, development, or agricultural policy) and climate change. Additionally, this research on calibration could guide decision makers through assessments of their own when they must consider their own judgments of the likelihood of different tradeoffs (Groves and Lempert, 2007).

Future work

Bearing in mind that the motivation for this research is ultimately to introduce likelihood judgments for scenarios, and that current work has uncovered insights useful for only the first step, there are a number of paths for research going forward. First, the disaggregated elicitation of judgments with CIBA is benefited by the use of influence diagrams, which are part of a rich discipline of decision analysis on their own (Howard and Matheson, 1984). Conceptually, there are also similarities between influence diagrams and Bayesian networks (Jensen and Nielsen, 2007). Future research could build upon either of these linkages to introduce disaggregated conditional probabilistic judgments, which might be synthesized to determine probabilistic judgments for complete scenarios.

Finally, it should be noted that the findings of my dissertation were quite timely, as the IPCC is in the midst of developing new emissions scenarios for its Fifth Assessment Report. How storyline scenarios should be developed to ensure consistency across Working Groups remains a challenge. In this regard, CIBA could be a useful approach for building interdisciplinary narrative scenarios, and some experiments may be launched soon with the integrated assessment modeling group at the National Center for Atmospheric Research (NCAR, 2010). Additionally, the development of very long term (over 100-year long) stylized socioeconomic scenarios would benefit from parsimonious analytical approaches such as bounding analysis combined with probabilistic model switching, which relies on expert judgments of confidence in model assumptions to differentially weigh outputs of models run over long time frames (Casman et al., 1999). The development of very long term, stylized scenarios was discussed during the 2007 IPCC expert meeting toward the development of new climate scenarios (Moss et al., 2008).

References

Barnett, T.P., Pierce, D.W., Hildalgo, H.G., Bonfils, C., Santer, B.D., Das, T., Bala, G., Wood, A.W., Nozawa, T., Mirin, A.A., Cayan, D.R. & Dettinger, M.D. (2008) Human-Induced Changes in the Hydrology of the Western United States. *Science,* 319**,** 1080-1083.

Bradfield, R., Wright, G., Burt, G., Cairns, G. & Van Der Heijden, K. (2005) The origins and evolution of scenario techniques in long range business planning. *Futures,* 37**,** 795-812.

Carter, T.R., Jones, R.N., Lu, X., Bhadwal, S., Conde, C., Mearns, L.O., O'Neill, B.C., Rounsevell, M.D.A. & Zurek, M.B. (2007) New assessment methods and the characterisation of future conditions. IN Parry, M.L., Canziani, O.F., Palutikof, J.P., Van Der Linden, P.J. & Hanson, C.E. (Eds.) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK, Cambridge University Press.

Casman, E.A., Morgan, G.M. & Dowlatabadi, H. (1999) Mixed Levels of Uncertainty in Complex Policy Models. *Risk Analysis,* 19**,** 33-42.

Dawes, R.M. (1988) *Rational Choice in an Uncertain World*, Philadelphia, Harcourt Brace College Publishers.

EPRI (Electric Power Research Institute) (2009a) *The Potential to Reduce CO2 Emissions by Expanding End-Use Applications of Electricity*. Palo Alto, CA, 1018871.

EPRI (2009b) *Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the U.S. (2010-2030)*. Palo Alto, CA, 1016987.

Groves, D.G., & Lempert, R.J. (2007) A new analytic method for finding policy-relevant scenarios. *Global Environmental Change*, 17, 73–85.

Grübler, A. & Nakicenovic, N. (2001) Identifying dangers in an uncertain climate. *Nature,* 412**,** 15.

Howard R.A. & Matheson J. (1984) *The Principles and Applications of Decision Analysis*, 2nd edn, Menlo Park, CA, Strategic Decisions Group.

IPCC (Intergovernmental Panel on Climate Change) (2007) Bernstein, L., Bosch, P., Canziani, O., Chen, Z., Christ, R., Davidson, O., Hare, W., Huq, S., Karoly, D., Kattsov, V., Kundzewicz, Z., Liu, J., Lohmann, U., Manning, M., Matsuno, T., Menne, B., Metz, B., Mirza, M., Nicholls, N., Nurse, L., Palutikof, J., Parry, M., Qin, D., Ravindranath, N., Reisinger, A., Ren, J., Riahi, K., Rosenzweig, C., Rusticucci, M., Schneider, S., Sokona, Y., Solomon, S., Stott, P., Stouffer, R., Sugiyama, T., Swart, R., Tirpak, D., Vogel, C., Yohe, G., Pachauri, R.K. & Reisinger, A. (Eds.) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Geneva, Author.

Jensen, F.V., & Nielsen, T.D. (2007) *Bayesian Networks and Decision Graphs*, 2nd edn, New York, Springer.

Morgan, G., Apt, J., & Lave, L. (2005) *The U.S. Electric Power Sector and Climate Change Mitigation*. Arlington, Pew Center on Global Climate Change.

Morgan, M.G. & Henrion, M. (1990) "Human Judgment about and with Uncertainty" IN *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*, New York, Cambridge University Press.

Morgan, M.G. & Keith, D.W. (2008) Improving the way we think about projecting future energy use and emissions of carbon dioxide. *Climatic Change,* 90**,** 189-215.

Moss, R., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J., Elgizouli, I., Emori, S., Erda, L., Hibbard, K., Jones, R., Kainuma, M., Kelleher, J., Lamarque, J.F., Manning, M., Matthews, B., Meehl, J., Meyer, L., Mitchell, J., Nakicenovic, N., O'Neill, B., Pichs, R., Riahi, K., Rose, S., Runci, P., Stouffer, R., van Vuuren, D., Weyant, J., Wilbanks, T., van Ypersele, J. P. & Zurek, M. (2008) *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies.* Geneva, Intergovernmental Panel on Climate Change.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P. & Wilbanks, T.J. (2010) The next generation of scenarios for climate change research and assessment. *Nature,* 463**,** 747-756.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenham, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N. & Dadi, Z. (2000) *Special Report on Emissions Scenarios*, New York, Cambridge University Press.

NAS-NAE-NRC (National Academy of Sciences-National Academy of Engineering-National Research Council) (2010) *Real Prospects for Energy Efficiency in the United States*, prepublication copy accessed 11 March 2010, http://books.nap.edu/catalog.php?record_id=12621.

NCAR (National Center for Atmospheric Research) (2010) Integrated Assessment Modeling, accessed 02 September 2010, http://www.isp.ucar.edu/iam/.

Oppenheimer, M., O'Neill, B.C. & Webster, M. (2008) Negative learning. *Climatic Change,* 89**,** 155-172.

Parson, E., Burkett, V., Clarke, L., Edmonds, J., Fisher-Vanden, K., Jacoby, H., Keith, D., Mearns, L., Pitcher, H., Reilly, J., Richels, R., Rosenzweig, C., & Webster, M. (2006) *Global Change Scenarios: Their Development and Use*. Sub-report 2.1B of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, Department of Energy, Office of Biological & Environmental Research.

Pielke Jr., R., Wigley, T. & Green, C. (2008) Dangerous assumptions. *Nature,* 452**,** 531- 532.

Price, L., de la Rue du Can, S., Sinton, J., Worrell, E., Nan, Z., Sathaye, J. & Levine, M. (2006) *Sectoral Trends in Global Energy Use and Greenhouse Gas Emissions*, accessed 09 April 2008, ies.lbl.gov/iespubs/56144.pdf.

Raskin, P., Monks, F., Ribeiro, T., van Vuuren, D. & Zurek, M. (2005) Global Scenarios in Historical Perspective. IN Carpenter, S.R., Pingali, P.L., Bennett, E.M. & Zurek, M.B. (Eds.) *Ecosystems and Human Well-being: Scenarios, Volume 2.* Washington, Island Press.

Raupach, M.R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J.G., Klepper, G. & Field, C.B. (2007) Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America,* 104**,** 10288-10293.

Rive, N.; Torvanger, A.; Berntsen, T.; Kallbekken, S. (2007) To what extent can a long-term temperature guide near-term climate change commitments? *Climatic Change*, *82,* 373-391.

Samaras, S. (2008) *A life-cycle Approach to Technology, Infrastructure, and Climate Policy Decision Making: Transitioning to plug-in hybrid vehicles and low-carbon electricity*, PhD Thesis, Carnegie Mellon University.

Schneider, S.H. (2002) Can We Estimate the Likelihood of Climatic Changes at 2100? *Climatic Change*, *52,* 441-451.

Selin, C. (2006) Trust and the illusive force of scenarios. *Futures,* 38**,** 1-14.

Shlyakhter, A.I., Kammen, D.M., Broido, C.L. & Wilson, R. (1994) Quantifying the credibility of energy projections from trends in past data: The US energy sector. *Energy Policy*, 22, 119-130.

Smil, V. (2005) *Energy at the Crossroads: Global Perspectives and Uncertainties*, Cambridge, US, MIT Press.

US EIA (Energy Information Administration) (2008) *Annual Energy Outlook 2008 With Projections to 2030.* Washington, DOE/EIA-0383(2008).

US EIA (2009) *Annual Energy Outlook 2009 With Projections to 2030*. Washington, DOE/EIA-0383(2009).

US EPA (Environmental Protection Agency) (2008) *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006*, accessed 09 April 2008, http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

WCRP (World Climate Research Programme) CMIP3 (Coupled Model Intercomparison Project phase 3) (2010) Bias Corrected and Downscaled WCRP CMIP3 Climate Projections, accessed 9 February 2010, http://gdo- dcp.ucllnl.org/downscaled_cmip3_projections/.

Weimer-Jehle, W. (2006) Cross-impact balances: A system-theoretical approach to cross- impact analysis. *Technological Forecasting and Social Change,* 73**,** 334-361.

List of all archival journal papers or scholarly reports, both published and expected to be submitted/published, that have acknowledged or will acknowledge Link Foundation support

THESIS

Schweizer, V. J. (2010) *Developing Useful Long-Term Energy Projections in the Face of Climate Change*, PhD Thesis, Carnegie Mellon University.

WORKING PAPERS

1. Schweizer, V. and Kriegler, E. (2010) Using Cross-Impact Balance Analysis to Improve Future Emissions Scenarios. In preparation for *Climatic Change*.
2. Schweizer, V. and Morgan, M. G. (2010) Bounding US Electricity Demand in 2050. In preparation for *Energy Policy*.
3. Schweizer, V. (2010) Dimensions of Scenario-Based Analysis Relevant for Global Climate Scenarios. In preparation.

Statement regarding discretionary funds
Vanessa Schweizer

Discretionary funds (other than the stipend) were spent on a laptop and related accessories to run software needed for research, conference travel and poster printing, scholarly books/reports need for research, and thesis publishing.

The independent support of the Link Foundation through an Energy Fellowship was extremely beneficial to me. Indeed, I believe that the Energy Fellowship helped me secure the postdoctoral appointment that I now have in the Advanced Study Program at the National Center for Atmospheric Research (NCAR). Were it not for the travel support, I probably would not have submitted an abstract to the 2009 European meeting of the International Association for Energy Economics. It was during that trip to Vienna that I rekindled my connection with a contact at the International Institute for Applied Systems Analysis, who, in turn, put me in touch with my current mentor at NCAR, Brian O'Neill. That crucial conference aside, the travel support of the Energy Fellowship generally inspired me to advance my research and to strive to attend various conferences for my professional development. I am grateful that I was chosen to be a Link Energy Fellow.