STATE OF VERMONT

PUBLIC SERVICE BOARD

Amended Petition of Entergy Nuclear Vermont Yankee, LLC, and Entergy Nuclear Operations, Inc., for amendment of their certificate of public good and other approvals required under 30 V.S.A. § 231(a) for authority to continue after March 21, 2012, operation of the Vermont Yankee Nuclear Power Station, including the storage of spent nuclear fuel	)	Docket No. 7862

<u>SUMMARY OF PREFILED TESTIMONY OF DR. RICHARD K. LESTER</u>

Dr. Lester's testimony addresses the decision facing the Board concerning whether to approve the continued operation of the VY Station and provides perspective on the important role of nuclear power in meeting electricity demand economically. Dr. Lester discusses alternative courses of action, including greater reliance on alternative fuels and generating technologies as well as reductions in electricity use; he addresses the feasibility, benefits, risks and costs of these alternatives in relation to the continued operation of the VY Station. Dr. Lester's testimony focuses extensively on the role of nuclear power in addressing the problem of global climate change and, specifically, its role in avoiding the release of greenhouse gases that might otherwise result from the combustion of fossil fuels. Dr. Lester concludes that continued operation of the VY Station can serve as a bridge to a sustainable, low-carbon future for the state's electric-power sector.

Dr. Lester sponsors the following exhibits:

Exhibit EN-RKL-1	*Unlocking Energy Innovation: A Framework for Action* (February 2012), MIT Industrial Performance Center
Exhibit EN-RKL-2	*The Future of Nuclear Power*, Massachusetts Institute of Technology (2003) (Executive Summary excerpt)
Exhibit EN-RKL-3	*The Future of Coal*, Massachusetts Institute of Technology (2007) (Executive Summary excerpt)
Exhibit EN-RKL-4	*The Future of the Nuclear Fuel Cycle*, Massachusetts Institute of Technology (2011) (Executive Summary excerpt)
Exhibit EN-RKL-5	Richard Lester resume

As explained in more detail in Entergy VY's Motion For A Declaratory Ruling Prescribing Scope Of Proceeding, filed on June 21, 2012, the Board's reliance on certain factors that may be considered under Sections 231(a) (which governs Entergy VY's amended petition) and 248(b) (which may be consulted only by analogy) is preempted or precluded by federal law, and therefore any discussion by Dr. Lester of those factors is in the alternative to Entergy VY's primary position that the factors are preempted or precluded from the Board's consideration. Entergy expressly preserves its right to argue that those factors are preempted or precluded in connection with its June 21 motion and at other points in this proceeding and, if necessary, on appeal.

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PREFILED TESTIMONY OF DR. RICHARD K. LESTER

Q1. State your name.

A1. Richard K. Lester.

Q2. What is your position and by whom are you employed?

A2. I am the Japan Steel Industry Professor and Head of the Department of Nuclear Science and Engineering at the Massachusetts Institute of Technology. I am also the founding director and faculty co-chair of the MIT Industrial Performance Center (IPC). I have been retained by Entergy Nuclear Vermont Yankee, LLC, and Entergy Nuclear Operations, Inc. (to which I refer in my testimony collectively as "Entergy VY"), to address the benefits, risks and costs of nuclear power and alternatives to nuclear power and to provide my perspective on the important role of nuclear power in the context of global climate change.

Q3. What are your qualifications to sponsor the testimony you intend to sponsor?

A3. As Head of the Nuclear Science and Engineering Department, I work with my faculty colleagues to help educate the next generation of technical leaders of the nuclear enterprise and to plan and conduct research on energy and non-energy applications of nuclear science and technology. As the founding director and faculty co-chair of the MIT Industrial Performance Center, I am responsible for the Center's research activities, which are designed to help leaders in business, labor, government and academia better understand important trends in industrial innovation and global competition and to develop effective public policies and business strategies to deal with them.

My own teaching and research focus on industrial innovation and the management of technology, with an emphasis on the energy and manufacturing sectors. I recently served as director of the *Energy Innovation Project*, a study of the U.S. energy innovation system carried out at the IPC by an interdisciplinary team of researchers from MIT and several other U.S. universities. This project focused on how to meet the demands for innovation associated with an accelerated transition to a low-carbon energy infrastructure in order to avoid the worst consequences of climate change while maintaining the reliability and affordability of energy on which our society depends. A summary of this project is provided in Exhibit EN-RKL-1. I was also a member of the study teams that produced two recent MIT reports, *The Future of Nuclear Power* and *The Future of Coal*; the executive summaries of these reports are Exhibits EN-RKL-2 and EN-RKL-3 to my testimony. Recently, my MIT colleagues produced a follow-up to *The Future of Nuclear*

Power report entitled *The Future of the Nuclear Fuel Cycle*, the executive summary of this report is Exhibit EN-RKL-4 to my testimony.

I am author or co-author of several books on nuclear and alternative energy systems, technological innovation and industrial competitiveness including, most recently, *Unlocking Energy Innovation: How America Can Build a Low-Cost, Low-Carbon Energy System,* which I co-authored with David M. Hart. Another recent book, *Making Technology Work: Applications in Energy and the Environment*, which I co-authored with John M. Deutch, presents fifteen cases of technology applications in the energy and environment sectors, including solar, wind, fuel-cell, nuclear, coal-combustion and emission-control technologies.

Exhibit EN-RKL-5 is a copy of my resume.

Q4. What is the scope of the testimony you intend to present?

A4. Decisions on how best to meet customer demand for electricity must take account of the full range of economic, environmental, health, safety and security factors[1] associated with electricity supply and use. Many of these factors are local in nature, while others are regional, national or global in scope. Also, because of the long operating lifetime of electricity-supply facilities and the still longer lifetime of some of their impacts, the

[1] I understand from counsel that considerations of nuclear safety are exclusively the province of the Nuclear Regulatory Commission and other branches of the Federal Government. Accordingly, I have truncated my discussion of these issues in this prefiled testimony.

consequences of these decisions will be felt for several decades or more. Thus, decision-makers must balance the costs, risks and benefits of alternative courses of action over multiple spatial and time scales.

In light of the Board's upcoming decision on whether to approve the continued operation of the Vermont Yankee Nuclear Power Station (to which I refer as the "VY Station" or "Vermont Yankee"), the purpose of my testimony is to provide perspective on the important role of nuclear power in meeting electricity demand economically while addressing environmental, health, safety and security concerns.

The decision on whether to allow the VY Station to continue to operate after 2012 must also consider several alternative courses of action, including greater reliance on alternative fuels and generating technologies as well as reductions in electricity use. My testimony will therefore address the feasibility, benefits, risks and costs of these alternatives in relation to continued operation of the VY Station.

A major issue bearing on the Board's decision is the role of nuclear power in addressing the problem of global climate change—specifically, its role in avoiding the release of greenhouse gases (or "GHGs") that might otherwise result from the combustion of fossil fuels—and my testimony will focus on this issue. Today fossil-fuel combustion in electricity-generation facilities is the largest contributor, both nationally and globally, to the emissions of the most important greenhouse gas, carbon dioxide (CO_2), and the risk of climate change will be one of the strongest influences on the evolution of the nation's electric-power infrastructure over the coming decades.

Q5. Why is it important to consider carbon dioxide in connection with evaluating Entergy VY's request that the Board authorize continued operation of the VY Station?

A5. The electric-power industry in the United States is responsible for the release of roughly 2.3 billion metric tons (or "tonnes") per year of CO_2, or about 40% of total U.S. CO_2 emissions. As I will discuss in more detail, coal-fired power plants are the source of most of these emissions.

The most important non-fossil source of electric power today is the nation's fleet of 104 commercial nuclear-power reactors operating in 31 states. These reactors generate about 19% of the nation's electricity, and if they were replaced by coal-fired power plants, an additional 695 million tonnes of CO_2 would be released each year. If the nuclear plants were instead replaced by natural-gas-fired plants, an additional 302 million tonnes of CO_2 would be released per year.[2]

The global picture is similar: nuclear power is the world's most important non-fossil power source, with some 435 nuclear-power plants located in 31 countries generating about 16% of the world's electricity. The continued operation of these plants and the

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[2] In these calculations, an average capacity factor of 90% was assumed for the nuclear plants. Other assumptions about plant performance, including heat rates, were taken from Table A-5.A.4 of the MIT *The Future of Nuclear Power* report.

construction of new ones—some 62 new nuclear reactors are currently under construction around the world—is thus one of the principal options for reducing CO_2 emissions in the future. Indeed, and as I will discuss in more detail later, successfully meeting the challenge of global climate change almost certainly will not be possible without a viable nuclear-power option over the next few decades.

Much of my testimony will draw on the four MIT studies I previously mentioned.

Q6. Why is it important for the Board to consider greenhouse-gas emissions and global climate change in the context of determining whether the VY Station should continue to operate after 2012?

A6. The need to respond to the problem of global climate change may well be the most challenging case of technological decision-making under uncertainty that our society has ever had to face: the risk is of a high order and potentially irreversible; the underlying scientific issues are extraordinarily complex and imperfectly understood; the socio-economic and ecological consequences are in many ways even more complex and uncertain; and preventive action, if it is to be effective, will require an unprecedented degree of international cooperation. Decisions about what course of action to pursue should be informed by the best available scientific evidence concerning:

- the mechanisms—natural and anthropogenic—of greenhouse-gas build-up in the atmosphere and, based on this understanding, predictions of how the atmospheric concentration of greenhouse gases will change over time;

- how different levels and rates of atmospheric greenhouse-gas build-up will affect the global climate;
- how climate change will affect physical, social, economic and ecological systems at multiple spatial scales, from the global to the regional, with potential consequences including:
  - significant sea-level rise;
  - increased frequency and severity of extreme weather events;
  - modification of disease vectors;
  - disruption of water supplies;
  - ecosystem transformation, with implications for habitat;
  - population dislocations and migration; and
  - economic risks to agriculture and coastal property.

Over the past 20 years, since the U.S. ratified the United Nations Framework Convention on Climate Change in 1992, a range of regulatory and other policies and voluntary initiatives designed to reduce GHG emissions have been proposed and in some cases adopted by the Federal government. States and cities across the country have also adopted measures to reduce GHG emissions. Actions taken by the State of Vermont include its decision to become a member of the Regional Greenhouse Gas Initiative, a cooperative effort by Northeastern and mid-Atlantic states to establish a regional cap-and-trade program covering CO_2 emissions from power plants. Most recently, the state's Comprehensive Energy Plan, published in 2011, sets the goal of reducing Vermont's contribution to global climate change.

Q7. How certain is the scientific community about the contribution of greenhouse-gas emissions, including carbon dioxide, to global climate change?

A7. Although difficult scientific questions must still be resolved and major areas of uncertainty remain, important advances in understanding have occurred over the past two decades. This progress has been tracked in the series of reports published at regular intervals by the Intergovernmental Panel on Climate Change (or "IPCC"), which represents the closest approximation to a general consensus within the engaged scientific community. In its most recent reports, published in 2007, the IPCC concluded that: (1) the average global temperature has increased more rapidly over the past half century (by roughly 0.6° C) than at any other time during the past two millennia; (2) this warming has coincided with a 35% increase in the atmospheric concentration of greenhouse gases (mainly CO_2) over pre-industrial levels; (3) this increase in GHG concentrations is mainly attributable to anthropogenic causes; (4) most of the warming is very likely due to the increase in anthropogenic GHG concentrations; and (5) the human influence has likely also extended to other aspects of climate, including observed sea-level increases, changes in wind patterns and increases in temperature extremes. The IPCC further concluded that continued emissions of GHG at or above current rates would very likely induce warming and other climate changes larger than those experienced during the previous century.

More recently, in 2010 the U.S. National Research Council (or "Council") similarly concluded that the climate is changing and that the change is caused principally by human activities, particularly the combustion of fossil fuels. According to the Council's Panel on Advancing the Science of Climate Change, "[t]here are still some uncertainties, and there always will be in understanding a complex system like Earth's climate. Nevertheless, there is a strong, credible body of evidence, based on multiple lines of research, documenting that climate is changing and that these changes are in large part caused by human activities. While much remains to be learned, the core phenomenon, scientific questions, and hypotheses have been examined thoroughly and have stood firm in the face of serious scientific debate and careful evaluation of alternative explanations."[3] The panel noted the observations of several scientific groups that the Earth's average surface temperature in the first decade of the 21st century was 1.4°F (0.8°C) warmer than in the first decade of the 20th century, with most of the warming occurring over the last three decades. It further concluded that most of the warming over the last several decades has been caused by human activities resulting in the release of CO_2 and other GHGs into the atmosphere.

The atmospheric concentration of CO_2 currently stands at about 391 parts per million (or "ppm") and is increasing at a rate of about 2 ppm per year.[4] This rate of increase is

[3] National Research Council, *Advancing the Science of Climate Change*, Washington, D.C.: The National Academies Press, 2010, Summary, page 1.

[4] In addition to CO_2, several other gases released into the atmosphere as a result of human activity are capable of absorbing re-radiated solar radiation in the critical wavelength window of 8-12 microns—in other words, of behaving as greenhouse gases. These include methane, nitrous oxide and the chlorofluorocarbons. These different gas molecules differ in their ability to absorb long wavelength radiation. Nitrous oxide, for example, absorbs 270 times more heat per molecule than CO_2. It is conventional to convert the atmospheric concentrations of each of these other GHGs to the equivalent concentration of carbon dioxide. The combined concentration of GHGs is then expressed in terms of ppm of 'carbon equivalent.' The current atmospheric concentration of GHGs is about 430 ppm of carbon equivalent.

accelerating, with the global expansion of fossil-fuel use the main culprit. In 'business as usual' scenarios (*i.e.*, with no additional efforts made to restrict CO_2 emissions), the concentration of carbon dioxide in the atmosphere by 2100 is projected to be roughly triple what it was before the Industrial Revolution began (i.e., about 270 ppm). How the Earth's climate would respond to such an increase cannot be predicted with certainty, but recent estimates indicate that the global average surface temperature can be expected to rise by at least 4°C, and possibly by more than 6°C.[5] The high end of that range is roughly ten times the amount of warming observed so far, and it is similar to the temperature difference between today's climate and the coldest part of the last Ice Age, when ice sheets covered much of North America.

The projected consequences of temperature changes of this magnitude would be severe for both natural ecosystems and human societies. Already there are observable effects of the warming that has occurred in recent decades, such as warming oceans, shrinking sea ice, more powerful storms, and the extinction of vulnerable species. Several more decades of business-as-usual will likely put large coastal populations at greater risk of inundation due to rising sea levels and storms. (About 23% of the human population currently lives within 100 km of the coast and less than 100 meters above sea level.) Changes to the climate will also likely make it more difficult for many people to grow their traditional crops. Public health will likely deteriorate because the range of pathogens will be extended. These burdens will fall most heavily on those least able to

[5] A.P. Sokolov et al, "Probabilistic Forecast for Twenty-First-Century Climate Based on Uncertainties in Emissions (Without Policy) and Climate Parameters." *J. Climate* 22 (2009): 5175-5204.

bear them. The great complexity of the Earth's climate system means that such projections are uncertain, and there is still a chance that the consequences of continuing down the business-as-usual path will turn out to be tolerable. But the weight of scientific evidence points in the other direction. Indeed, recent findings suggest that the most widely accepted projections are underestimates.[6] In this context, a combination of mitigation to reduce greenhouse gas emissions as aggressively as possible and adaptation to protect the most vulnerable human and natural systems is the most sensible course.

Q8. What would be an acceptable upper limit on the atmospheric concentration of GHGs?

A8. Because of the many uncertainties involved, as well as the divergent interests of different stakeholders around the world, there can be no exact answer to the question of what would be an acceptable upper limit on the GHG concentration and global average temperature. As I have already noted, the impacts to be considered include extreme weather events (droughts, floods, storms, heat waves, etc.), sea-level increases threatening coastal populations, declines in agricultural productivity, water shortages and enhanced disease vectors.

Many climate scientists have concluded that the worst risks of climate change might be avoided if the concentration of CO_2 and other GHGs could be stabilized between 450 and

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[6] A.P. Sokolov et al, op.cit. The MIT researchers estimated that the end-of-century temperature increase relative to 1990 for the business-as-usual scenario will lie in the range from 3.81°C to 6.98°C with 90% confidence. Though not strictly comparable, the Intergovernmental Panel on Climate Change, in its 2007 assessment, estimated an increase in the range from 2.4°C to 6.4°C (Intergovernmental Panel on Climate Change, *Fourth Assessment Report.*)

550 ppm of carbon equivalent. At the lower end of this range, the IPCC has estimated that the average global temperature increase would be unlikely to exceed 3°C and would have a 50% probability of remaining below 2°C. At the upper end of the range (roughly twice the pre-industrial GHG concentration of 270 ppm), the temperature increase would have a high likelihood of falling somewhere in the 1.5 to 4.4°C range, a 50% probability of remaining below 3° C and a small but significant probability of exceeding 5° C. Some experts, weighing the risks involved, have concluded that this upper limit marks the outer bound of rational risk-taking. Others advocate a more restrictive limit, arguing that to avoid unacceptably harmful consequences the average temperature increase should not exceed 2° C (This goal has been adopted by the European Union).

Q9. Is it feasible within a reasonable time period to stabilize GHG emissions in the range of 450 to 550 ppm?

A9. Stabilizing the GHG concentration in the 450 to 550 ppm range will be very difficult. The current atmospheric concentration of all GHGs is 430 ppm of carbon equivalent and is increasing at an accelerating rate. If no further preventive action is taken, the lower end of the range will be reached in about 10 years and the upper limit within perhaps 30 to 40 years. Deep cuts in GHG emissions will be necessary if we are to stay within these limits, and the longer we wait to take action, the deeper the required cuts will be. To avoid exceeding the lower bound, the global emission rate would have to peak within a very few years and then decline by several percentage points per year thereafter, and as a practical matter this goal is probably already out of reach. Even for the upper limit of 550 ppm, global emissions would have to peak in 10 to 20 years and then decline at a significant rate. For example, stabilization at the 550-ppm level could be achieved if global emissions peaked in 2020 and then declined at an annual rate of 1 to 2.5% per year. If emissions continued to increase for another decade, however, the necessary post-peak reduction rate would almost double.[7]

In sum, the scientific evidence points to the need for a policy focus on stabilization scenarios in the 450 to 550 ppm range. Above 550 ppm, the chances of avoiding very serious economic, social and ecological impacts appear slight, while scenarios below 450 ppm are probably no longer achievable. Remaining within this range would roughly correspond to an expected average global temperature increase of 2 to 3°C by the end of the century, and perhaps double that in northerly latitudes. If we fail to make the transition to a much lower GHG-emission trajectory during the next 20-30 years, staying within this concentration range will be effectively impossible. In quantitative terms, this will mean reducing the global emission rate by about 50% by 2050.

Q10. What is the role of developed countries like the United States in reducing GHG emissions?

A10. Considerations of equity demand that wealthy countries accept higher targets for emissions cuts than poor ones. The wealthy countries, with less than 20% of the world's

[7] HM Treasury, *Stern Review on The Economics of Climate Change*, a report to the Prime Minister and the Chancellor of the Exchequer presented by Sir Nicholas Stern, October 30, 2006 (available at http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm).

population, have been responsible for 75% of the atmospheric GHG increment introduced since the pre-industrial era, while as I have already noted poor countries will likely bear the brunt of the impact of global climate change and will certainly feel its effects earlier. Such considerations informed the negotiation of the Kyoto Protocol, under which most of the world's industrialized nations (though not the United States) agreed to limit their emissions, while the developing countries were exempt from emission restrictions. In the more recent round of global climate negotiations, which is focusing on the period after 2012 when the Kyoto Protocol will expire, a different calculus is in effect. It is now widely recognized that even in the hypothetical case that the roughly one billion people who live in wealthy countries were to reduce their emissions to zero, the six billion people living in the rest of the world would still have much to do, since their emissions are growing much more rapidly and in any plausible scenario will account for the bulk of global emissions in the coming decades. (In a transition of more than symbolic significance, China in 2007 replaced the United States as the world's largest emitter of greenhouse gases.) Little has been accomplished in these negotiations so far, but it is clear that the advanced economies, including the United States, will need to commit to deep reductions in order to secure agreement on a global limit on carbon emissions. In 2009 President Obama joined with the leaders of the other G8 nations in pledging to cut emissions at least 80 percent by 2050.

A rationale for such deep cuts has been offered by the British economist Nicholas Stern, who noted that to achieve a global emissions reduction of 50% by 2050 the per-capita emission rate, averaged over the entire global population, would have to decline from its current level of seven metric tons per year of CO_2 equivalent to two to three metric tons per year by mid-century. (This calculation simply reflects the expected rise in the global population to 9 billion by then.) If this average rate were then to become the target for *all* countries, rich and poor alike—a standard that in Stern's view would represent only a 'minimal' view of equity, since it makes no allowance for the fact that the poor countries have contributed relatively little to the GHG build-up thus far—the wealthy countries would have to reduce their per-capita emissions by 80% to 90%.

Since a Congressional effort to enact statutory limits on US emissions failed in 2010, neither Congress nor the Administration has attempted to revisit the issue. In the absence of a federal mandate, many states have been adopting their own measures—including renewable portfolio standards for electricity supply, renewable fuel standards and regional cap-and-trade programs—all of them designed to limit GHG emissions. California's Assembly Bill 32, signed into law in 2006, calls for an 80% reduction in emissions by 2050, and other states have established similar targets.

Also, in 2007, the Supreme Court in *Massachusetts v. Environmental Protection Agency* found that GHGs responsible for climate change, including carbon emissions from power plants and other sources, fit within the definition of an air pollutant under the Clean Air Act. In 2009, the U.S. Environmental Protection Agency ("U.S. EPA") found that carbon emissions and other air pollutants can be reasonably expected to endanger the public health and welfare of current and future generations. In March of this year, the U.S. EPA proposed rules under the authority of the Clean Air Act that would limit carbon dioxide emissions from new power plants.

Q11. Is it realistic for the United States to achieve such deep reductions in GHG emissions by 2050?

A11. The only way for the U.S. to achieve such deep cuts in emissions will be to engineer a transition away from our current heavy dependence on fossil-energy resources. Today fossil fuels account for 85% of the nation's primary energy consumption, and the combustion of fossil fuels is responsible for almost 80% of total U.S. GHG emissions on a carbon-equivalent basis.[8] Because of the long lead-time for turnover of the energy infrastructure, the U.S. will very soon need to begin the shift away from using petroleum for transportation and from using high-carbon fuels for electricity generation towards much greater energy end-use efficiency, much greater reliance on alternative fuels for transportation and low- or zero-carbon power-generation systems.

Q12. What is the role of the electric-power industry in attempting to achieve the GHG reduction that you advocate?

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[8] According to the federal government's latest inventory of GHG emissions, in 2010 the combustion of fossil fuels accounted for 94.4% of the CO_2 and 79% of total GHGs emitted on a carbon-equivalent basis. CO_2 from all sources accounted for 83.6% of total U.S. GHG emissions on a carbon-equivalent basis. The other main contributors were methane (9.8%) and nitrous oxide (4.5%) (see U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010" (April 2012)).

A12. As I have already noted, the single most important source of U.S. CO_2 emissions from fossil-fuel combustion is the electric-power sector, which is responsible for about 42% of the total (the next largest source is the transportation sector, which accounts for another 32%). The de-carbonization of the electric-power sector will thus be crucial to the eventual success of the overall transition.

In 2011 fossil-fuel combustion accounted for 68% of net U.S. electricity generation. The current U.S. generation mix by fuel is shown below (the figures are for 2011 and refer to the share of net kilowatthours generated by each source)[9]:

Fossil fuels:

- Coal: 42%
- Natural gas: 25%
- Petroleum: 0.7%

Non-fossil fuels:

- Nuclear: 19.2%
- Conventional hydro: 7.9%
- Wood: 0.89%
- Other biomass: 0.48%
- Geothermal: 0.4%
- Wind: 2.9%
- Solar: 0.044%

[9]U.S. Energy Information Administration, http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_1.

Q13. What options does the electric-power industry have to reduce GHG emissions?

A13. At least for the next several decades, there are only a few realistic options for reducing CO_2 emissions from electricity generation:

- increasing the use of nuclear power.
- increasing the efficiency of electricity generation and use;
- switching to less carbon-intensive fuels for electricity generation (*e.g.*, from coal to natural gas);
- expanding the use of renewable energy sources such as wind, solar, biomass and geothermal; and
- capturing CO_2 emissions from electric-power plants fueled by fossil resources (especially coal) and permanently sequestering the CO_2.

Q14. How do the new developments involving the production of natural gas from shales affect these options?

A14. The supply outlook for natural gas has shifted dramatically in recent years as new horizontal drilling techniques and hydraulic fracturing technologies have enabled a large expansion in shale gas production, from negligible levels a decade ago to about 25% percent of total domestic dry gas production today. This relatively low-cost new source of gas has also helped to bring about a sharp reduction in natural-gas spot prices, from $8 per thousand cubic feet at the well-head in 2008 to a little over $2 today. Prices are expected to rise again as demand picks up further, and concerns over the local environmental impacts of hydraulic fracturing will constrain production in some locations. Nevertheless, the U.S. Energy Information Administration now estimates that shale gas accounts for one-third of all technically-recoverable U.S. natural gas resources and could account for nearly half of all domestic gas production by 2035. These developments have already had a significant impact on U.S. CO_2 emissions, as electricity generation in coal plants has been rapidly displaced by low-cost electricity from gas-fired power plants, with associated reductions of 50% or more in CO_2 emissions per kilowatt hour. In the first three months of 2012, coal accounted for 36% of total U.S. electricity generation, down from 44% in the equivalent period of 2011, and 47% a year earlier. Conversely, the share of natural gas-fired generation rose from 20.7% in the first quarter of 2011 to 28.6% in the first three months of this year.[10] This swing from coal to natural gas has led to a reduction in CO_2 emissions from the power sector of roughly 200 million tons on an annualized basis in just one year. The short-run impact on GHG emissions is thus highly beneficial. The longer-term impact is less clear, however, and could be unhelpful over the longer term if it deters investment in even lower-carbon alternatives. Even in the hypothetical case of complete displacement of coal by gas in the electric-power sector, large amounts of CO_2 would still be emitted, and the U.S. could not meet its GHG reduction goals. Thus, shale gas has the potential to be a useful bridge to a low-carbon economy. But ultimately America will need even lower-carbon fuels than natural gas if energy is to be available on the scale that Americans have come to expect. As the recent MIT study on the future of natural gas concluded, 'though it is frequently touted as a 'bridge' to the future, continuing effort is needed to prepare for that future, lest the gift

[10] U.S. Energy Information Administration, http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_1.

of greater domestic gas resources turns out to be a bridge with no landing point on the far bank".[11]

Q15. What has been the role to date of the nuclear-power industry in reducing GHG emissions?

A15. As I have previously testified, the current fleet of 104 U.S. commercial nuclear-power plants plays a major role in reducing GHG emissions from the electric-power sector. To illustrate, if the nuclear plants were replaced by coal and natural-gas generation in proportion to their current contributions to U.S. electricity production (*i.e.*, 42% and 25%, respectively), the U.S. would emit an additional 623 million tonnes per year of CO_2. In other words, the effect would be to increase the CO_2 emissions from the U.S. electric-power sector by about 27.5% and CO_2 emissions from all U.S. sources by about 11%. This is nearly seven times larger than the contribution to reduced emissions provided today by solar and wind, and almost twice as large as the contribution from all other low-carbon sources combined (including conventional hydro.)

Moreover, even though no new nuclear-power plants have been built for many years, the contribution of nuclear power to the avoidance of carbon emissions has continued to grow, as operational improvements have helped increase the output of the nuclear power plant fleet. Between the early 1990s and the present, for example, the fleet-average capacity factor rose from 70% to 90%, in effect creating more than 20,000 megawatts of

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[11] MIT Energy Initiative, *The Future of Natural Gas: An Interdisciplinary MIT Study*, 2011, available at http://web.mit.edu/mitei/research/studies/index.shtml, p. 69.

new generating capacity with near-zero carbon emissions and thus relieving the pressure to build thousands of megawatts of new, fossil-fueled capacity. In parallel, about five thousand megawatts of additional nuclear capacity have been created through capacity uprating programs at most of the nation's nuclear-power reactors.

Q16. Is it true that nuclear power causes GHG emissions?

A16. Even so-called 'carbon-free' sources of electricity like nuclear, wind, and solar are responsible for some GHG emissions if ancillary industrial activities are also considered along with the generation of electricity itself and if we take into account releases of other greenhouse gases like methane, nitrous oxide and the chlorofluorocarbons as well as CO_2.

For example, in the case of nuclear-power generation, it is necessary to consider emissions from associated nuclear-fuel-cycle operations such as the extraction, processing and enrichment of uranium and the disposal of nuclear waste. Similarly, in the case of renewable-power systems, it is necessary to consider related industrial operations such as the production of photovoltaic panels and the manufacture and construction of wind turbines.

Careful lifecycle analyses of these power systems, taking into account all relevant material and energy flows and using as a common basis the production of one unit of electricity, have shown that nuclear, solar and wind power are responsible for at most a few percent of the GHG emissions from fossil-fired power plants. According to one such study, the full-lifecycle GHG emissions from nuclear power, including related nuclear-fuel-cycle activities, amounts to less than 55 grams of CO_2-equivalent per kilowatt-hour of electricity. About half of these emissions are attributable to the uranium-enrichment stage of the nuclear-fuel cycle, which for U.S. nuclear power plants is now mostly carried out at the energy-intensive, gaseous-diffusion facility at Paducah, Kentucky.

Two new enrichment plants employing the much less energy-intensive, gas-centrifuge technology are currently under construction in Piketon, Ohio and Lea County, New Mexico, and the Paducah facility will soon be replaced by these new, more energy-efficient plants. At that point, it is estimated that the total GHG emissions from nuclear power will decline to about 12 grams of CO_2-equivalent per kilowatt-hour. This is only about 1 percent of the CO_2 emissions from conventional, pulverized-coal plants, which range from 830 to 930 grams per kilowatt-hour (where these latter figures do not include the emissions from ancillary activities such as mining, coal transportation, etc.). The estimated lifecycle GHG emissions from nuclear power are even lower than those from the current generation of solar-photovoltaic electricity systems, which range from 17-49 grams CO_2-equivalent per kilowatt hour (though these, too, are trending down owing to continuing improvements in PV-module manufacturing efficiency and electrical-conversion efficiency).[12]

[12] The lifecycle emissions data for nuclear and solar PV are reported in V. M. Fthenakis and H. C. Kim, "Greenhouse gas emissions from solar-electric and nuclear power: A lifecycle study", *Energy Policy 35* (2007), 2549-2557. The coal-plant data were obtained from the MIT *Future of Coal* report.

Q17. What role can the electric-power industry in Vermont play in reducing GHG emissions?

A17. In any particular location, the electricity-generation mix typically differs from the national average I described previously, and the opportunities for de-carbonization therefore also differ. In Vermont, nuclear power dominates the electric-power-supply system to a degree unmatched in any other state. The VY Station accounts for 72% of electricity generated in-state, with hydroelectric plants responsible for another 20% and most of the remainder coming from biomass. (In terms of the role of nuclear power, Vermont is in first place by a large margin. New Jersey, Connecticut, and South Carolina share second place, with about 50% of generated electricity provided by their nuclear-power plants.) Vermont is also one of only two states in the country with no coal-fired power plants. These facts explain why Vermont today ranks lowest of all states in terms of emissions of CO_2, sulfur dioxide, and nitrogen oxides from its electric-power sector.

The dominant role of the VY Station means that a decision not to authorize the plant's continued operation beyond 2012 would have far-reaching implications for the state's electricity-supply system. Since this system is so closely integrated with the regional electricity-supply infrastructure, however, it makes sense to consider alternatives both inside and outside the state.[13] So the basic alternatives to continuing to operate Vermont Yankee are to build new generating capacity of some kind in Vermont, or elsewhere in

[13] An indication of the extent of electricity-supply system integration is that of Vermont's total electricity supply of 9.1 million megawatt hours in 2010, 2.46 million megawatt hours, or 27%, was imported from Canada, while 2.99 million megawatt hours, or 33%, was exported to neighboring states (EIA State Electricity Profiles, Vermont, http://www.eia.gov/electricity/state/vermont/).

the region or outside the region, or to reduce electricity consumption in Vermont. I will consider these possibilities.

Q18. Begin with demand-side options.

A18. The long-term trend towards reduced energy and electricity intensity in the U.S. economy (i.e., reductions in the amount of energy and electricity used per unit of economic output) has been one of the most important factors constraining the growth of U.S. GHG emissions. These reductions have been partly the result of improvements in the efficiency of energy use. At the national level, the key indicator for the electric-power industry—the amount of electricity consumed per unit of economic output—has been declining for decades, and between 2000 and 2010 this indicator continued to decline at an average rate of about 0.6% per year. Over the same period, Vermont's electricity intensity declined at more than twice the national average rate (*i.e.*, 1.43%/yr vs. 0.61%/yr), and electricity consumption per unit of economic output in Vermont today stands at just 85% of the national average. However, the contribution of these trends to electricity savings was offset by the economic growth that occurred in the state. Even though growth only averaged a relatively anemic 1.37% per year between 2000 and 2010, the additional economic activity was sufficient to hold electricity consumption roughly constant in the state over this period. (At the national level, economic growth was slightly stronger—1.56%/year versus 1.37%/year in Vermont—and the rate of reduction in electricity intensity was, as I have noted, smaller; as a result, national consumption of electricity increased by about 10% over the decade.)

The potential for further improvements in the efficiency of electricity use in the residential, commercial and industrial sectors is undoubtedly large. Some of these improvements will be associated with the deployment of smart grid technologies; others with new building design innovations and existing building retrofits; and still others with behavioral changes. Many of these improvements are likely to be economically attractive at current energy prices; that is, the investment required to exploit them will generate a positive return even without subsidy. An even greater focus on end-use efficiency will therefore provide both economic and environmental benefits and should be strongly encouraged. But even in the most aggressive efficiency scenarios, the impact on GHG emissions will be modest. Assume, for example, that the electricity intensity of the Vermont economy were to decline over the next 10 years at a rate of 2% per year (i.e., 50% faster than over the last decade, and three times faster than the national average over the same period). If economic growth in Vermont over the next ten years were to continue at the same rate as during the last decade—not a goal that would excite much enthusiasm—electricity use in the state would shrink. Still, by 2022 it would be just 6% lower than it is today (a reduction equivalent to about 7.5% of the current output of the VY Station.) A continuation of these trends through the year 2032 would mean a reduction in demand equivalent to about 14.2% of the current output of the VY Station by then. With a stronger (though still relatively modest) economic growth rate of 2%/year, there would be <u>no</u> net reduction in electricity use in the state. So increased energy efficiency is not on its own an alternative to continuing to operate the VY Station.

In short, while a stronger focus on electricity end-use efficiency is clearly desirable, even if sustained over a 20-year period it will not come close to bringing about a reduction in GHG emissions equivalent to the emissions that the operation of VY is preventing today. By itself, therefore, an aggressive efficiency strategy is not a credible alternative to the continued operation of the Vermont Yankee plant from the perspective of GHG emission reduction.

Q19. Now turn to supply-side options, including nuclear power.

A19. The question is which new electricity-supply options would be credible alternatives to the VY Station. As a practical matter and as I have noted already, the new capacity could be located either in Vermont or elsewhere in the region, or it could be imported into the region from elsewhere, and my discussion of this topic will not specify the location. Of course, from the perspective of GHG emissions the question of location is immaterial in any case. Because of the long residence time of CO_2 in the atmosphere (on the order of a century) and its resulting nearly uniform distribution around the globe, emissions from any location contribute equally to the buildup of the atmospheric concentration and thus to the climate-change risk.

In the short run, a loss of the electricity generated by the VY Station would have to be made up by unused existing generating capacity in the New England region or elsewhere. The Vermont Comprehensive Energy Plan (to which I refer as the "CEP") reports that some of the state's utilities have already contracted for power to replace the VY Station power, but that a gap between contracted supply and demand still exists. At present, natural-gas-fired power plants are the marginal source of supply in the New England region, and it is likely that the shutdown of the VY Station would be accompanied by a significant increase in CO_2 emissions from these plants as their output is increased to help make up the deficit. (Replacing nuclear electricity with gas-fired generation results in a roughly thirty-fold increase in CO_2 emissions per unit of energy output. If all of the lost VY Station generation were made up by natural gas plants, the additional emissions of CO_2 would be equivalent to 30% of the state's total current emissions of CO_2 from all sources.)

In the longer run, as demand increases in the region and the existing capacity surplus shrinks, an increasing share of the lost output from the VY Station would have to be provided by new generating capacity. From an economic perspective, the key considerations in selecting from among alternative generating options are capital costs and financing, fuel costs and operations-and-maintenance costs. Of the traditional generating technologies, the projected all-in cost of electricity from new natural-gas plants is today significantly below that of new coal and nuclear plants. In recent years, as the price of natural gas has fallen and the cost of complying with current and prospective new environmental regulations on coal plants has risen, natural gas-fired combined-cycle power plants have been the technology of choice for new baseload capacity in much of the country. The rapid growth in supplies of relatively low-cost shale gas is expected to reinforce the preference for gas-fired generation in many regions for the foreseeable future. The CEP recognizes that large-scale combined cycle gas plants are likely to be built in other parts of New England, while recommending against this in Vermont on the grounds that siting options would be limited by the gas-transmission infrastructure.

Q20. What is the potential for Vermont to consider using coal-fired generating plants instead of natural gas-fired electricity as an alternative to nuclear power, including the VY Station, for the provision of baseload power to the state and region?

A20. A baseload coal plant would dramatically increase Vermont's GHG emission footprint unless it was augmented with CO_2 capture and sequestration (or "CCS") technology. Coal-fired plants also generate other air-borne and water-borne pollutants that degrade the environment locally and regionally and that in some cases may also be detrimental to human health. Important progress has been made over the past two decades in reducing emissions of sulfur oxide (or "SOx"), nitrogen oxide (or "NOx") and particulates from coal plants, and regulations have also now been put in place to reduce mercury emissions. However, the reduction or elimination of CO_2 emissions is still an unresolved problem.

The U.S. EPA's proposed new rules for CO_2 emissions under the Clean Air Act would effectively preclude the construction of new coal-fired capacity without CCS technology. The MIT *The Future of Coal Study* carefully analyzed the status of CCS technology. It concluded that although there are no fundamental technical obstacles, CCS cannot be regarded as a viable option until all of the major components of a CCS system—that is, CO_2 capture, transportation and storage—have been demonstrated at full scale and in an integrated manner. This must include demonstration of the operational feasibility of carbon-capture technology in a commercial power-plant setting as well as demonstration of a properly instrumented CO_2-storage site operating within a comprehensive regulatory framework that includes criteria for site selection, injection, surveillance, certification, closure and the conditions for eventual transfer of liability to the government. The MIT study further concluded that even with adequate funding, the applied research, development and demonstration program that will be required to establish the feasibility of CCS will take on the order of a decade to complete.

Progress on CCS technology since the completion of the MIT assessment has been slow. None of the components of a CCS system has yet been demonstrated individually at scale, let alone in an integrated fashion, and an appropriate regulatory framework has still to be developed. Large investments are required for full-scale CCS demonstrations, and these are difficult to finance given current federal fiscal constraints. Private financing will also be difficult given the projected gap between the cost of CCS-equipped coal-fired power plants, even after maturation of CCS technology, and combined-cycle gas-power plants. In its latest assessment, the Energy Information Administration estimates that the levelized cost of electricity from advanced coal plants with CCS will be more than twice the levelized cost of electricity from advanced combined cycle plants.

In sum, there appear to be no fundamental technical obstacles in the way of eventual CCS implementation. But even assuming adequate funding, the development and demonstration of CCS systems will take a decade or more to complete, and based on present technology cost expectations and fuel price projections it is not likely that CCS-equipped baseload coal-fired power would be competitive with combined-cycle gas-fired generation, even if CCS were also applied to the latter.[14]

Q21. What about renewables instead of natural gas-fired electricity for replacing the VY Station's supply of baseload power for the state and the region?

A21. The application of renewable technologies, especially wind and solar, is expanding rapidly around the world. In addition to having very low lifecycle GHG emissions, wind and solar have the additional advantage of not emitting other atmospheric pollutants such as NOx, SOx, particulates and mercury. One drawback of the power from these sources is that it is supplied only intermittently. This is a particularly challenging problem when, as in the present situation, the capacity to be replaced operates in baseload mode.

The CEP establishes ambitious goals for the deployment of renewable electricity supplies. Today Vermont electricity users obtain about 50% of their electricity from renewable sources, including 30% from Hydro-Quebec and another 11% from in-state hydro. The CEP sets the goal of increasing the share of renewable electricity to at least 75% within the next 20 years and 90% by the year 2050. The expectation is that these

[14] The EIA levelized cost estimates are presented in the *Annual Energy Outlook 2012*. They are specified for plants that would be brought online in 2017 (even though for some of the technologies, including CCS, the lead-time for commercialization means that commercial plants could not actually be brought online by 2017.) Advanced coal technology with CCS is estimated at 14.1 cents/kwh, while advanced combined cycle gas-fired technology with and without CCS is estimated at 9.8 cents/kwh and 6.6 cents/kwh respectively. See http://www.eia.doe.gov/oiaf/aeo/index.html.

supplies will come from a combination of distributed and central station sources, both local and out-of-state. The potential to expand in-state supplies of hydro and biomass is relatively limited, according to the CEP, and the implication of these goals is that reliance on wind and solar will increase considerably.

Q22. How do the costs of renewables compare with the cost of natural gas-fired electricity?

A22. The cost of electricity from wind and, especially, solar is significantly higher than from combined-cycle natural gas plants today. In both cases costs have declined markedly in recent years, and further reductions are expected. However, for new utility-scale plants coming online in 2017, the EIA estimates levelized costs of 9.7 cents/kwh for on-shore wind and 15.7 cents/kwh for solar photovoltaics, compared with 6.6 cents/kwh for advanced combined-cycle plants. Moreover, these estimates do not account for the additional costs of addressing the lower reliability of the non-dispatchable sources.

Q23. What are the reliability implications of depending on intermittent power sources?

A23. In general, when intermittent power sources are added to existing power networks, they must be backed up by other generating units on the system (or, in rarer cases, by storage capacity), and they are therefore credited with a capacity value lower than their rated (or "nameplate") capacity. The extent of capacity discounting depends on the local conditions (*e.g.*, wind-speed distribution, solar insolation), the design features of the technologies themselves, the characteristics of the rest of the network and the characteristics of the load being served. In the past, capacity credits assigned to wind farms have ranged from as little as 13% to more than 30% of the rated wind-turbine capacity. In general, the larger the share of intermittent power on the network, the more challenging the grid-integration issues become, and the lower the credit assigned to the intermittent sources. Currently, dependence on these sources is low enough that it can be managed effectively, but as Vermont and other states in the region increase their sourcing of intermittent power, additional steps will have to be taken to ensure overall reliability of service.

One way to mitigate the problem of local wind intermittency is to take advantage of the asynchronous nature of wind-speed fluctuations by siting wind farms at different locations around the region and connecting them through the transmission grid. Recent studies have shown, however, that even for dispersed interconnected arrays of wind turbines, the overall output power level that could be guaranteed with a reliability comparable to that of a baseload nuclear or coal plant (about 90%) would only be a small percentage of the total rated capacity of the turbines. The actual level would depend on the specific local wind conditions. According to one study of a hypothetical array of 19 interconnected Midwestern wind-farm locations using actual windspeed data for the locations, such an array would provide reliable power (that is, with a reliability of about 90%) at a level of less than 15% of the total rated power of the array. On its own, this strategy would therefore be a prohibitively costly way to provide baseload supplies.

An alternative approach would be to supplement the output of a distributed windfarm array with peaking turbines fueled by, for example, natural gas or diesel. This would add to the cost and would also introduce GHG emissions. Physical limits on the rate at which thermal units can ramp up and down in power to offset wind-power fluctuations would be another important factor to consider in this case.

Q24. What about solar power?

A24. The intermittency issues associated with solar-photovoltaic technology are somewhat different from those of wind, but the basic problem of obtaining high-reliability power supplies from this source is similar.

Grid-scale electricity storage technologies currently under development may eventually provide a solution to the problem of intermittency. However, there are still large uncertainties regarding cost as well other aspects of performance, and the lead-times required for initial commercialization and then large-scale deployment of these new technologies are likely to be considerable.

In sum, the CEP anticipates that a strategy of relying primarily on local and renewable sources will be capable of replacing the baseload electricity currently supplied by the VY Station. While this goal may eventually be achievable, it will require overcoming difficult technical challenges for which solutions are not available today. Moreover, for at least the next decade and possibly for much longer, the cost to electricity users of this approach will almost certainly be significantly higher than the cost of relying instead on natural gas. There is no precedent for completely replacing a large central-station baseload unit, providing power at a constant level with high reliability, with intermittent power sources such as wind or solar. As long as sufficient existing reserves are present on the grid, new wind or solar capacity can be used to offset at least some of the displaced supply. But even then, the cost of this electricity will very likely be significantly higher than the marginal cost of continuing to operate the baseload unit.[15] As deployment of solar and wind resources increases, new backup peaking capacity will have to be built to maintain overall reliability levels on the grid. This will further increase costs and also introduce new sources of GHG emissions.

Q25. Now address the role that nuclear power could play in providing baseload power to Vermont and the region.

A25. As I have previously noted, nuclear power is today the leading contributor on the supply side to the mitigation of carbon-dioxide emissions from the electric-power infrastructure both globally and within the U.S. Compared with fossil-fuel generation, nuclear power also provides other environmental benefits including the avoidance of the so-called 'criteria pollutants' (SOx, NOx and particulates) as well as mercury. Finally, in the particular situation at hand, the expenses incurred in continuing to operate the VY Station will be a small fraction of the all-in cost of supplying electricity from either new

[15] For nuclear plants, these costs are mainly comprised of fuel and operating-and-maintenance costs. Combined operating expenses for the U.S. nuclear-power plant fleet as a whole averaged between 1.6 and 2.4 cents per kilowatt-hour between 2000 and 2010 (U.S. Energy Information Administration, *Electric Power Annual 2010*, released November 2011, Table 8.2, http://205.254.135.7/electricity/annual/pdf/table8.2.pdf).

renewable electricity plants or new coal-fired plants with associated carbon capture and sequestration.

Q26. Entergy VY has asked to continue operation for a 20-year term. During that period, what are the prospects for technological progress or alternative supply-side resources?

A26. All of the supply- and demand-side options I have discussed in my testimony are likely to undergo significant technological or economic advances over the next 20 years.

Though far from certain, it is possible that CCS technology will be ready for application in commercial fossil-fired power plants by the end of this period. Photovoltaic electricity generation costs are likely to continue to decline for some time to come, and there is a good chance that both solar and wind-power technologies will be more competitive with conventional power systems in 20 years than they are today. Technological progress is also likely in grid-scale storage and in the integration of intermittent and decentralized power sources into regional power networks. Next-generation nuclear-power systems now under development, including small modular reactors, may by the end of this period be capable of providing electricity at lower cost and with even better safety performance than today's most advanced commercially-available systems. And major additional gains in energy-use efficiency are highly likely.

In short, in 20 years the menu of cost-effective, environmentally benign demand- and supply-side alternatives to the continued operation of Vermont Yankee is likely to be considerably longer than it is today. It is thus plausible to expect that the retirement of Vermont Yankee at that time—as opposed to today—will be achievable without sacrificing Vermont's commitment to GHG-emission reduction, its ranking as the lowest source of electric-power-related CO_2 emissions in the United States and its adherence to the principle of long-term least-cost integrated electric resource planning.

Q27. Summarize your testimony.

A27. Fossil-fuel combustion in U.S. electricity-generation facilities is the biggest contributor to the nation's carbon-dioxide emissions, and the task of de-carbonizing the electric-power infrastructure to reduce the risk of climate change will be one of the strongest influences on the evolution of the U.S. electricity industry over the coming decades. Nuclear power is today by far the largest supply-side contributor to reducing the power industry's GHG emissions, while improvements in end-use efficiency are the largest contributor on the demand side.

Vermont has both the highest share of in-state generation of nuclear power of any state in the country and one of the nation's most effective energy end-use efficiency strategies. This is in many ways the ideal combination for addressing the challenge of global climate change, and Vermont is unusually well positioned to respond to this challenge with a minimum of economic sacrifice.

A decision to close the VY Station in 2012 would likely incur significant economic penalties and probably also result in considerable increases in the state's GHG emissions, since for the next few years the options to replace the VY Station with low-carbon alternatives will remain very limited. On the other hand, if the decision to close the VY Station is deferred for another 20 years, it is reasonable to expect that a much broader array of economically competitive low- or zero-carbon alternatives will be available at that time. The VY Station can therefore serve as a bridge to a sustainable low-carbon future for the state's electric-power sector.

Q28. Does this conclude your testimony?

A28. Yes.