LESSONS FROM THE SHALE REVOLUTION

Transcript of the Proceedings
January 28-30, 2015
Sausalito, California

NOTE: The text contained herein is an abridged transcript of the six sessions that comprised Breakthrough's Lessons from the Shale Revolution Conference, held January 28-30 in Sausalito, California. The format of each panel was short presentations by two to three speakers, followed by roundtable discussion and questions. Presentations, comments and exchanges among participants have been lightly edited for readability.

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David Northrop worked in various staff and management positions in materials science and energy at Sandia National Laboratories from 1964 to 1998. He is responsible for Sandia's first fossil energy program created in 1974. Subsequently, he developed and managed many R&D programs that matched the broad capabilities of a DOE national laboratory to the needs of the US petroleum industry.

Alessandro Nuvolari is associate professor of economic history at Sant'Anna School of Advanced Studies in Pisa. His research is focused on the role of technical change in the process of modern economic growth. He is published in major academic journals, such as Economic History Review, Explorations in Economic History, and Technology & Culture.

Peter Pearson directs the Low Carbon Research Institute of Wales, Cardiff University, and was previously Director of the Imperial College London Centre for Energy Policy & Technology. His research focuses on past and prospective long run energy and infrastructure transitions and their policy implications. He has been an Economic Adviser to the World Bank Inspection Panel and twice Chair of the British Institute of Energy Economics.

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Matthew Stepp is Executive Director of the Center for Clean Energy Innovation, a nonpartisan policy think tank dedicated to advancing innovation-based solutions to climate change. Matthew recently led a bipartisan effort to reform the US National Lab system, increase funding for key clean tech programs like ARPA-E, as well as re-think global climate negotiations.

Dan Steward is a consulting geologist with Republic Energy Operating in Dallas, Texas and INEOS. Over his 48-year career in the oil and gas industry, he has worked with Ames Oil & Gas, Dresser Magcobar, Shell Oil Company, and Mitchell Energy. During the period 1981 to 2001, he was a member of Mitchell's Barnett Shale team. In 2014, he began working with INEOS in their efforts to evaluate organic shale potential in the United Kingdom.

Peter Teague is Senior Advisor at Breakthrough Institute. Previously he was senior vice president for Research and Strategy at the Nathan Cummings Foundation in New York. A former business litigator and Peace Corps volunteer, he has also served as senior environmental policy advisor to Congressman Leon Panetta, Senate candidate Diane Feinstein, and Senator Barbara Boxer.

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Norm Warpinski is a Halliburton Fellow at Pinnacle – A Halliburton Service in Houston, Texas, where he works on the development of new tools and analyses for hydraulic fracture mapping, reservoir monitoring, hydraulic fracture design and analysis, and integrated monitoring solutions for reservoir development. He joined Pinnacle in 2005 after working as a Senior Scientist at Sandia National Laboratories from 1977 to 2005.

Jim Watson is Research Director of the UK Energy Research Centre and Professor of Energy Policy at the University of Sussex. He has 20 years of research experience on climate change, energy and innovation policies. He frequently advises governments in the UK and abroad, and has been a specialist adviser to three UK Parliamentary select committees. His international experience includes ten years of collaborative research on energy in China. He is a Council Member of the British Institute for Energy Economics, and a member of the social science expert panel for the UK government's energy and environmental ministries.

Index of Acronyms

Advanced Computational Technology Initiative (ACTI)

Atomic Energy Commission (AEC)

Chesapeake Energy Corporation (Chesapeake)

Department of Energy (DOE)

Devon Energy (Devon)

Eastern Shale Gas Program (ESGP)

Energy Information Administration (EIA)

Energy Research and Development Administration (ERDA)

Federal Energy Regulatory Commission (FERC)

Gas Research Institute (GRI)

General Electric (GE)

massive hydraulic fracking (MHF)

Mitchell Energy & Development Corporation (Mitchell)

Multiwell Experiment (MWX)

National Energy Technology Laboratory (NETL)

National Gas Pipeline Company of American (NGPL)

National Research Corporation (NRC)

polycrystalline diamond compact (PDC)

Sandia National Laboratories (SNL)

Society of Petroleum Engineers (SPE)

Unconventional Gas Research Program (UGRP)

Union Pacific Resources (UPR)

US Geological Survey (USGS)

Western Gas Sands Project (WGSP)

Session 1: Q&A with the Founders of the Shale Revolution

Part I

Dave Northrop

In my remarks this morning, I'd like to present what I consider to be a tipping point at the beginning of the shale revolution and give two early examples of activities that resulted from it. But first …

In the good old days, whenever we would draft a proposal to Alex Crawley, or anyone else, we always had to show the impact the proposed work would have — typically with a final milestone that stated: "Transfer to Industry" or "Technology Complete." And that milestone had to be just 3 to 4 years in the future. Any longer, the proposal would never have had a chance of being funded. Little did we know then that our timeframe would actually be decades, because here we are today 30 to 40 years later!

I feel strongly that there was an early "tipping point" in the shale revolution, one that occurred as a result of the first Arab Oil Embargo in the early 1970s. That tipping point is the entry of the US national laboratories into the energy arena.

For you with enough grey hairs, recall what the climate was in those days of the 50s, 60s, and early 70s: a highly competitive Cold War was underway with nuclear weapons as the deterrent. In fact there were no national laboratories per se. Lawrence Livermore, Los Alamos, and Sandia existed as the nation's weapons laboratories under the direction of the Atomic Energy Commission. And these labs were charged with the development, testing, manufacture and stockpiling of the nation's nuclear weapons. This charter required the highest level of technical competency and capabilities — arguably more than the then-completed Apollo Program that had sent men to the moon. Complex weapon systems were developed that had to be deployed under various conditions (even accidental ones) or stockpiled, perhaps for decades, with 100% certainty of not detonating — then at some unknown number of years in the future detonating with 100% reliability, as designed, at the right time and place! To do that required a variety of cutting-edge technologies and capabilities — ones that had been developed by these laboratories over the two-plus decades since WWII.

The fall 1973 Arab Oil Embargo created what was perceived as an energy crisis for the nation. Anyone remember the gas lines and nationwide 55 mph speed limit? As a result, the AEC formally asked its three weapons labs to explore how their capabilities might address that crisis. At Sandia, I was involved in several brainstorming sessions where staff from across the lab came up with a wide range of ideas. As a result, various small initiatives in solar, wind, fossil energy, and geothermal would become major, long-term programs not only at Sandia, but also at Livermore and Los Alamos. And over the years, these programs would receive government funding, first from the Energy Research and Development Administration or ERDA, which later became Department of Energy in 1977. Such funding would increase and broaden the capabilities of the labs still further.

This was the tipping point: the charter of these weapons labs had just been broadened to include energy — they had become national laboratories!

My first example is a personal one, and what I call "Value-Added Instrumentation." How did I get involved? At the time my materials group was developing carbon composite materials for ballistic missiles. The idea was to put my group into "reverse." We had been taking methane (natural gas) and turning it into carbon (via chemical vapor deposition). So in reverse, perhaps we should look at the gasification of coal (carbon) to create natural gas (methane) — as a means of exploiting the nation's vast coal resource. Personally, I got interested in the idea of the in situ or underground processing and extraction of energy from fossil fuels. The main idea was to focus on the instrumentation that might be applied to diagnose, understand, and control such extraction processes. And I was to tap the existing instrumentation capabilities that we had developed at Sandia to support nuclear weapons development and testing.

At the time, the Laramie Energy Research Center, then under the Bureau of Mines, was conducting a field test of underground coal gasification in Wyoming. It was a rudimentary, brute-force effort. Two wells were drilled into the coal seam, air was pumped own in one well, the coal ignited so that some of the coal was burned to create heat that, in turn, would gasify the remaining coal, and gas was extracted from the other. All instrumentation was at the surface. No one had any idea what was going on underground. A new manager at Laramie recognized the need to understand what was going on down there and that novel ideas were required.

This led to an invitation for us to come up with our personnel and field test trailers and try different thermal, electrical, and acoustic/seismic methods on their on-going UCG test. (Interestingly, the previous use of the geophone systems used in the test was to monitor enemy troop movements in Vietnam.) Tantalizing data were recorded — sufficient to lead the Bureau to fund Sandia instrumentation efforts on their next field test. However, by the time the funds arrived, both the Bureau's research center and Sandia had been brought under the newly formed ERDA, which really simplified future interactions.

Underground coal gasification has yet to become a proven technology for many reasons. But for the purposes of this talk, our efforts on two large field tests provided value-added information that made Laramie's field tests credible:

- special, hardened thermocouple systems gave thermal profiles of the burn front,
- geophones in observation wells picked up noises associated with the combustion and from rock fall, and
- electrical probes on the surface measured resistivity changes that mapped the movement, direction and rough extent of the process.

Synthesis of all three methods, together with Laramie's surface data, yielded a far better picture of underground coal gasification than had ever been available before. It is clear that Sandia's involvement provided capabilities and resources that would not have developed on their own.

Note from Dave Northrop: A similar story exists for our efforts on Laramie's oil shale program. Though here an additional step is required as the rock must first be fractured to create permeability between the wells. The use of existing Sandia dynamic codes and explosive expertise serves as an additional example of applying weapons-derived capabilities to energy.

My second and last example is Mineback Experiments at the Nevada Test Site. The Nevada Test Site and hydraulic fracturing –– that's an unlikely combination! There's no gas there! But access to the Site and its resources would provide key insight to hydraulic fracturing. (An aside: hydraulic fracturing was the term we always used. We never used the word frack or fracking (especially with a "K") in our work — maybe if we had, the technology might have caught on faster!)

But back then, Ralph Veatch, a fracking expert with Amoco, used to say: "We know everything there is to know about a hydraulic fracture — except how long and high and wide it is, and what factors affect its shape and properties!" To gain insight, we proposed we could use an existing tunnel, first used for nuclear weapons tests, deep under a mesa at NTS. There we drilled a 1500-foot vertical well from the top of the mesa, created a fracture with colored cement, and then mined back through the region to observe and photograph the exposed fracture. The results were stunning and insightful. Imagine a research director at Halliburton, a company that had pioneered hydraulic fracturing and had conducted hundreds of fracks, when he actually observed fractures for the first time in our tunnel! In fact we had hundreds of industry visitors, who were told "a picture may be worth 10,000 words, but a visit to G-Tunnel is worth a 10,000 pictures."

We were able to get DOE funding for 2 to 3 years through Alex's Western Gas Sands Program for a variety of fracturing projects in G-tunnel, most conducted by Norm Warpinski. There's no time to detail them, but except to say that the results simply overturned much conventional wisdom! Key insights included the level of complexity of fractures in the subsurface and the importance of the in situ stress state on the behavior and geometry of the created fractures. All results were thoroughly documented and presented to industry. Information was our ultimate product.

What was Sandia's and DOE's impact here? Being able to leverage vast Nevada Test Site resources including the mine operation, millions in funding, and conducting many, varied, and insightful fracturing tests that industry could not have afforded or conducted on their own.

So, to wrap up, I've presented a "tipping point" (the "unleashing" of the weapons labs) and two early examples resulting from it: value-added instrumentation and the Mineback tests for insights into fracking. I'm sure there will be many more examples resulting from this tipping point given later this morning.

Alex Crawley

Up to 1975, there was no budget for natural gas separate from the petroleum budget. Almost all of the money went to enhanced oil recovery. At Morgantown, well plugging was a problem and the massive hydraulic fracturing test in 1975 was funded. It was a colossal failure, but we learned a lot about surface sensitivity and safety.

We followed up with the Sandstones experiments, such as explosive fracturing tests where we pushed explosives into shale. One time, we created a rocket when the wellhead went 600 feet into the air! Sandia brought their capabilities to tell them how long the fractures were.

In 1976, we dedicated a part of the budget for three unconventional gas projects, the Eastern Gas Shales Project: Morgantown, Western gas sands, and enhanced oil recovery. It was a big project to find out why some shales worked and some didn't.

In the Eastern Gas Shales, 3D seismic was done by hand via point picking. In the Western Gas Sands, we had models, but operators didn't know why plays didn't perform like models.

The national labs showed me their capabilities and I realized that we had a treasure trove of technology to be converted to good use. We developed partnerships with industry and the labs presented their technology to industry. We were formally prohibited from being advised by industry.

Before 1996, most of the funds pared from the petroleum budget were used as follows: Morgantown's went for assisting independent producers with plugging abandoned wells; Bartlesville's went to fund one person to follow the AEC work in Gasbuggy. There were two contracts out of the 1995 Petroleum budget that went for natural gas experiments. A MHF in the lenticular sandstone formation, using the third well that had been drilled in the Gasbuggy project but never used. The test failed to produce gas as designed. We did get good data from a Sandia mapping experiment using the change in surface electro-potential as the fracture was being produced. The second contract was a hydraulic fracture/explosive combination project in the Devonian Shale. It was to demonstrate both safety and a new technology for enhance recovery. This test was a failure in both respects. The packer leaked and the wellhead became a rocket going a few hundred feet into the air. The 1996 budget had a line item for Unconventional Gas Recovery (UGR). It was divided into three subprograms, Eastern Gas Shales Project (EGSP), Western Gas Sands Project, and Advanced PetroleumTechnology (APT).

The EGSP work focused on understanding the production from the Devonian shale. Work on correlating vaults with production to determine whether there was a relationship that could be extrapolated to find other productive shale areas. This work was hampered by the cost of 3D seismic, which at that early date required significant manual effort, and the use of satellite photography for determining faults was iffy.

The WGSP focused on MHF, with a series of field test where results were spotty. Those in the deep lenticular sandstone reservoirs produced at first but production played down rapidly, leaving many questions, such as: Were we seeing boundary conditions, or was the water saturation greater than the logs were showing, or was the in situ stress to great for the proppants to hold the fractures open? These questions were answered with the Multiwell Project (MWX) in later years. The APT program was where the National Lab research was funded (fracture mapping, mine back, mini-hydraulic fractures, etc).

Bob Hanold

We transitioned from testing nuclear weapons to research in geothermal energy and fossil energy projects. We were tasked by ERDA to develop a manmade geothermal energy system that required drilling a three-kilometer deep well into hot granitic rock and conducting a large hydraulic fracture. The fracture was mapped with a 3-axis geophone package in an adjacent well. Based on the seismic mapping of the fracture system, the adjacent well was sidetracked to intersect the fracture and a downhole circulation loop was established. We were able to circulate hot pressurized water to the surface for either direct use or as flashed-steam for electrical power generation.

Records obtained from the geophones established the existence of detectable microseismic events uniquely associated with the hydraulic fracture. Signals from the microseismic events contained sufficient information to determine the location of the events. Los Alamos believed this experiment had proven the validity of the microseismic fracture mapping technique. These results were published in the Second Annual ERDA Enhanced Oil and Gas Recovery Symposium in 1976. Although Los Alamos continued its research on geothermal energy systems, microseismic fracture mapping was clearly a technology that had broader applications to fossil energy.

Richard Newell: Why was the Eastern Gas Shale Project in Morgantown? What benefit was gained from Eastern project?

Crawley: We fought with Senator Byrd and lost, so we had to set it up there. Porosity was thought to be not good enough. We were forced into funding the shale program. The technology came from the national labs and not the program itself. Then we gained an understanding of the diversity of geology. We found out there was much more gas than the porosity indicated

Dan Steward: We discovered open natural fractures in Freedonia and Appalachia. We discovered organic rich shales. We started to get handle on how much gas there was.

Crawley: The usual concern is that politicians override bureaucrats and scientists. But in this case, the expert knowledge said it's not really worth doing anyway, and Byrd insisted, for his own reasons. Also, private companies were always interested in costs in someone else's budget.

Don Kash: Major oil companies had no interest in shale. The big computer models that structured the policy debate in the 1970s tended to focus on future technologies. There was near consensus that it was a waste to spend money on oil and gas, shale was uneconomic (gas was cheap). Political interference serendipitously created great results.

Crawley: On price, municipalities wanted gas to be regulated. Then cross-state gas was regulated, and cost 42 cents per MCF. In the mid-70s, there was no incentive. In 1984, there was pipeline deregulation, and in 1993 there was total deregulation.

William Burnett: Byrd was interested in money going to Virginia.

Steward: We were interested in the source rock and how gas was trapped. We didn't know the beginning about source rock at the time. Shell Oil Company was not interested. We did the MHF in 1978. Hot limestone had a lot of gas, but we could not get it to yield.

Mitchell believed in research, dedicating time and money to it. Independents did not have much time and money, but majors were not interested. Government wanted to create and supply the "research arms" for independent producers.

Mitchell drilled the wells, and the government via DOE and GRI paid for the additional frack. We tripled the rate from a well! Most people would have said you don't frack limestone — you acidify it. George decided he needed to be in this niche. There was a lot of resistance from peers. He asked his staff to create plans to frack by Monday or he would have new staff by Tuesday.

Norm Warpinski: Yes, there were other private companies involved in 1978, '79, '80 — Mobil, Exxon, Amoco, Shell, majors also used MHF to frack. But they felt "I'm spending my money, didn't need to tell others about it." Information was kept proprietary. GRI was mostly funded by the pipeline levy, so information had to get out. The Oil and Gas Journal publicized Mitchell frack jobs –– there was a feeling in the industry that everyone kept re-inventing the wheel. We needed patient capital and a long term commitment from DOE.

Steward: There was a guy who wanted to flow-chart research but it wouldn't have worked. Mitchell's Woodlands project took money.

Kash: The government has more to do than just being a funder – it also serves as a customer for new technology, following the DOD model in electronics and Texas Instruments and Minuteman. Jim Schlesinger was devastated he didn't become Secretary of Defense but was told Secretary of Energy would also be impactful.

Burnett: There was no government commitment to funding natural gas. The natural gas budget was $35 million out of $800 million in 1980. In 1982, it was $9 million. Gas wasn't the highest priority. In fact, Mitchell provided the patient capital, while government prioritized coal gasification and liquefaction.

Northrop: There was a lot of money in the 1970s, but Reagan cut it as Congress went through its budget cycle.

Frank Geels: Sounds like there was a lot of trial and error involved. Was Mitchell a first mover? Was Mitchell hedging or committed? When did Mitchell switch over to shale gas?

Steward: Mitchell was impressed by the first test. Then he started looking at Wilcox stones. He did not look at Barnett yet. He tested the geology, met resistance, but insisted on the tests. People left the company because of these tests, calling them wasteful. The Barnett was not seen as a "saving hope" but as an opportunity. Commercial operations only had 10 years left and George said we need replacement for supply to meet contractual obligations to provide gas to Chicago in 1982. Mitchell wondered if north Texas gas would be the answer to his needs. Mitchell believed in gas and believed he didn't do enough to unlock gas.

Alessandro Nuvolari: Which type of knowledge was shared or not?

Steward: When Mitchell started in the Barnett, 90 percent thought they were wasting money. They were not encouraged to share information. A lot of news coverage sounded like "Mitchell does it again." Mitchell ordered that we would not have news releases on the Barnett to avoid speculation and jumpers and promoters, when they did not have acreage yet. The spot price of gas changed, and then Mitchell started to distribute information because he didn't want people messing up the Barnett. Carter banned gas-fired power to save gas for home heating. This removed a market for gas and resulted in more coal and nuclear.

Initially, drillers didn't care about underground imaging to understand horizontal stresses or fracture directions because there was no risk of overlapping at that point. Research needed to discover what was going on to further develop the resource. Surface resistivity sensing and tiltmeters (based on earthquake detection technology) helped resolve the challenge of sensing and underground detection. The people who were most interested in figuring out what was going underground were in the government.

Part II

William Burnett

The Gas Research Institute (GRI) was founded by natural gas industry pipeline and utility executives in 1976. The Federal Power Commission (later FERC) issued regulations allowing the interstate pipelines to collect a surcharge on all natural gas. By the end of the '80s, we were managing a budget of $180 million per year. Gas supply received about 1/3 of our budget. Unconventional natural gas was funded at about $30 million per year. Our priorities were on coal-seam methane, tight gas sands, and Devonian shales. Our priorities were set using a cost-benefit method that incorporated analytical and judgemental inputs.

In 1980, we signed a Participation Agreement with DOE where we agreed to plan our supply research jointly with DOE. Thus, we were aware of everything they were doing and they were aware of our research. Many of our projects were cofounded with DOE.

Our research priorities were on well stimulation/fracturing, downhole instrumentation, seismic monitoring of fractures, and basin specific studies of the resource base. Our staged field experiments were performed to gather detailed technical data on tight sands fractures. Also in the '80s we started our efforts on fracture modelling that ultimately led to the software program called Frac-Pro.

Gas producers were very involved in advising us and in cofounding our field experiments. We were particularly involved with the independent producers since the majors were less interested in domestic unconventional gas resources.

GRI laid out requirements for R&D 1) R&D must be coordinated with all other R&D going on in your field, 2) must show cost-benefit of every project that you do and must be positive for ratepayers. In 1976, AGA was formed and came together with INGAA and NARUC to approve an organization to manage these requirements (GRI). The first activity that they took over was the coal gasification project. DOE funded 2/3 of the project. Our first five-year plan was approved in 1978; it had almost no R&D on natural gas supply. From 1980 plan, GRI did cost-benefit analysis of natural gas, including cost-benefit on unconventional natural gas – coal-seam gas, Devonian shale, tight gas and started moving money from coal gasification to natural gas supply. GRI had particular interest in Devonian shale. Columbia Gas was drilling in Ohio and Pennsylvania, looking for gas close to customs, but weren't getting enough.

The Natural Gas Policy Act of 1978 didn't have much to do with GRI, but changed the view of gas, began deregulation of oil and gas price, began wellhead decontrol, and included incentive pricing for tight sands. From 1976 to1980 lots of people didn't buy the idea that we were running out of natural gas. From 1980 onward, Section 29 tax credit came in, it was the beginning of wellhead deregulation. Pipeline deregulation never happened – prices set by regulation. In 1989, there was the wellhead control act to get rid of government control on wellhead prices, and in 1992, pipelines switched from all service to just being transporters (common carriers) – any user connected could access a pipeline. It created more problems than it tried to solve, pipelines had long-term take or pay contracts with producers – customers could buy their own gas from produces.

GRI was growing rapidly by 1980, funding $200 million/year of R&D, half in gas supply, half in coal gasification. We were working closely with producers, and producers joined the organization directly in 1988, one such producer was George Mitchell. There was a big difference between major producers and independent producers, with 20,000 independent producers and 15 integrated major producers, majors felt like they could take care of themselves and were more interested in Gulf of Mexico and foreign sources.

In the 1990s, there were changes in industry, producers were coming in because they felt any charge added on was being paid by producers so we brought them onto the GRI board. They also believed the price was set in marketplace, not truly the case because set by regulators.

Throughout its existence, GRI collaborated very closely with DOE. In 1980, GRI signed participation agreement with DOE with a requirement to coordinate R&D. a driving factor of participation agreement – jointly plan programs with DOE. The entire unconventional gas program was coordinated with DOE and we knew everything about what each other was doing. Lots of cofounding, both put money into same contract, and about 75 percent of our work done was jointly funded between DOE and GRI. In unconventional gas, DOE had $30 million in 1980 to GRI's 6 million in the '80s, but GRI's share grew rapidly. By '90s, DOE only $10 million to GRI $25 million.

Ted Nordhaus: Were you working with producers during this period?

William Burnett: Yes, we were required to have 30 project advisors, one in each area. Despite looking at unconventional gas in the 80s, GRI's first priority was coal-seam gas, which was seen as "low-hanging fruit". GRI did a lot of work with USGS and with Colorado School of Mines and the University of Texas to properly assess basin reserves. In terms of extraction techniques and following the failure of explosives, GRI tried propellants that burned slower and didn't explode, but that still didn't work out. We did a lot of resource assessment work, in

1988, DOE put out a project on shale and tight gas sands resource. Fracture work wasn't being done in shales, it was being done in tight sands formation and remember each basin is different.

This research ended up in atlases that DOE and GRI co-published. These atlases covered hundreds of basins (mid-continental, Rocky Mountains, Gulf Coast, and the last one in mid-90s was Appalachian).

Norm Warpinski: With the Multi-Well Experiment, we decided we cannot do experiments separately; we have to fully come together and characterize tight sands and fracturing. In 1983, this was the first oil and gas fracturing. 1983 was also first year of microseismic mapping for oil and gas (vs. geothermal). It was the whole nine yards of science to understand what was going on. This was very important data to move forward. Towards end of '80s, one-third of natural gas supply was coming from tight sands. Most of us thought future of natural gas was tight sands.

We did weeks and weeks of testing; 60 test results of fractures; extensive logging; five years of testing and stimulation. We had an industry advisory panel and they gave us guidance on what they were doing and what they needed to know and we went different directions with their buy-in. Field research laboratory is what we called it.

Companies like Exxon and Shell were doing a lot of work they weren't publishing or telling us about. So we had a general understanding, but at the level of science, we didn't know what they knew. Mitchell knew about the Multiwell Experiment and some of our fracking people had studied results.

Dan Steward: I had not. Mitchell Energy had Steve, a frack specialist, who was appointed to know what was happening with these experiments.

Frank Geels: Aren't financial tools innovation killers?[1] Why was this was an important criteria at GRI? To show that money was well spent as public relations exercise? Or, to make up data and go along with it? Make a nice chart and be done with it. We know that financial tools are not always useful for radical innovation, so how did this play out?

Burnett: As for work that could lead to radical innovation, we set aside 10 percent of budget that had no requirement for cost-benefit justification. You're exactly right – we took a lot of credit in having a better project appraisal methodology. It was 70 percent judgmental and 30 percent analytical at the beginning; at the end it was probably 90 percent analytical because we were driven there by regulators and economists. We had our own supply and demand model; we didn't need to do that, because EIA could have done that. The last one was in 1990; how much shale do you think it showed for year 2015?

Your point is well taken; with my scientific background I agree with you; on the other hand, you can't just turn loose $200 million. You've got to find a way to justify the spending, especially with lots of constituents, and we needed a way to stand up to that. Early methodological appraisal was so bad we threw it away because we realized it was worthless in Congress.

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[1] Christensen, C.M., Kaufman, S.P., and Shih, W.C., 2008, Innovation killers: How financial tools destroy our capacity to do new things, Harvard Business Review, 86(1), 98-105

Jim Watson: So you have methodology to get approval by FERC; how much sway did FERC have in what you funded and the mix of funding? How did that dovetail with what DOE was funding? Was there tension in different agendas?

Burnett: FERC had no say. The commission had three people whose jobs were dependent on GRI's existence and made sure regulations were complied with. Every year we got new regulations (13 with our first approval). We had to prepare maybe 100 reports at the end of each year, proving what we did; project results, cofounding, coordination with other agencies, etc. We hired good project managers, and we didn't dictate what our project managers did, though they were burdened with all our reviews and regulations. Every project we had was discussed with industry, and then we selected and managed the contractor. This information was passed along as much by contractors, the people working on it, and everyone carried it forward. We widely distributed the reports that were required on each project.

Richard Newell: Cost-benefit analysis is very useful to structure thinking and force rigorous data collection. Without that you're left to the wind. It's not as much about the final Net Present Value number as it is about demanding an analytic process.

Burnett: Long-term stuff was not highly quantified.

Jesse Jenkins: Cost-benefit is a poor metric a priori; were there ex-post analyses of projects?

Burnett: With every successful project that resulted in a commercial product or process, we had to track it, and we reported back on application and use of findings and how many were sold. We were called out often to show how our work had value. Conditions of contracts and licenses required manufacturers to report on sales.

David Mowery: I was on NRC panel that looked at this. Our report was titled "Was It Worth It?" We invented and popularized the idea of an "option value" of knowledge by these projects. Option value: this information became valuable in a different set of circumstances down the road. It's difficult to deploy in prospective sense, because of the difficulty of forecasting, but extremely important in strengthening options. A few of the remaining private firms that support long-term research use this kind of language. It's difficult to translate metaphor to financial market. This is fundamental uncertainty, a useful argument to retain in these types of programs.

Ted Nordhaus: Which of firms tended to use Natural Gas Act pricing? What was the prospective value of one instrument vs. others, like the tax credit?

Dan Steward: Mitchell had a contract where we were getting a high price, but because of different gas categories – new, old, stripper, deep, tight – we had to come up with a basket of wells that would be equivalent or higher than contract price. We had to have mixture of gases to get that price. We were already getting the price, but we had to jump through hoops to put wells in there to justify that price.

Zhongmin Wang: The deregulation act came in the late 1970s, so prices were higher. Given that, firms naturally chose tax credit.

Michael Shellenberger: Where was horizontal drilling at this point in '80s?

Alex Crawley: We did one in Devonian and it was ten times as expensive. It got much more production, but not enough for the cost. The technology was not there at that point.

Steward: At Austin Chalk they were drilling to cross open natural fractures, but used acid. But it turned out uneconomical.

Jane Long: Horizontal drill crossing or bisecting vertical wells helped them increase productivity, but horizontal was not taken into account as benefit.

William Janeway: Research is a mission-driven program rather than one evaluated as costs-benefits. One of the issues with energy is the back and forth between mission-driven policy on the hand, and on the other hand, conventional correction to market failure that ought to be subjected to CBA tests like everything else.

Don Kash: Slant drilling from platforms in Gulf of Mexico became common as production moved into deep water and some of those slant-drilled wells almost became horizontal. Did that experience feed into what happened onshore with Mitchell?

Steward: That was done by majors who didn't share. When Mitchell got involved in horizontals, it was through GRI. We got involved in '91 with GRI and DOE and that was our first venture.

Part III

Norm Warpinski

Geology is complicated and complexity was driving drilling and mapping activity. We needed to understand the diagnostics. The M-site experiment was driven by GRI. The idea was, let's do the science to understand if we can monitor fractures and put it together with models. It was at a Multiwell Experiment site to validate and understand fractures. Could we get fracture length? That's what microseismic imaging answers. Could we get fracture height? It's important also from an environmental standpoint. This was the basis of work done later to understand shale.

What happens with Barnett? The first attempts to monitor fractures in the Barnett was with Mitchell. We got data of microseisms and we didn't know what to do with it. We thought the tests were failures. This data looked nothing like what was in the tight sands…we found out later on when we developed more sophisticated instruments that the Barnett was really complicated. We monitored lots of waterfracs and the fractures were not simple. Barnett shale stimulation results shows with microseismic data proves wide-scale complexity. It was an incredibly fascinating area of R&D –– extremely wide spectrum of behavior and mechanisms.

We finished M-site in 1996 and were asked how to build systems with reliability. It took until the 2000s. GRI had originally links between Mitchell. The focus was not on Mitchell relationship but let's build service companies that can actually use these tools and have a service industry.

Darrell Wood at USGS said we could use tiltmeters for models. It was Lawrence Livermore that got involved with Pinnacle to build better tiltmeters and they were much better devices.

Ted Nordhaus: Microseismic mapping comes out of the weapons labs and DOD, and some of it was used for monitoring troop movements. Livermore particularly had huge efforts doing seismic monitoring for underground nuclear tests. Where are these capabilities coming from?

Warpinsks: It was a combination. At the Nevada test site they are using tests on nuclear testing; a number of science people were monitoring what the Russians and Chinese were doing.

Northrop: Geophone that monitors troop movement is much more crude than seismic, but its an evolution from it.

Steward: Seismic tools were used to predict mine failures as safety precaution –– that's another aspect.

Nordhaus: Microseismic helped the move to waterfracs? Was there a relationship between enhanced abilities to see what's going on and the linear gel-frack to complicated nonlinear with waterfrac?

Steward: Most of them were used in waterfracs. You have balloon events and we were surprised by it. It validated that waterfracs were happening in all directions. We didn't know what to expect from waterfracs. Nick proposed this and was treated like an idiot, because people that thought that waterfracs weren't needed. UPR was using slick-water frack or waterfracs.

Nick Steinsberger: Riverfracs pumped water from rivers in '50s. UPR was trying to reduce cost, pumping waterfracs into tight sands. Oil and gas business in Fort Worth were small, had lots of acquaintances, and we knew what they were doing. I watched slickwater fracks. They were using microseismics to better understand.

In '96 we did experiments with tiltmeters with Pinnacle, in same well with slickwater and waterfracs, and the two measurements showed two different things. That showed that tiltmeter wasn't giving information that you needed.

Warpinski: UPR got involved with GRI in the Cotton Valley. About 25 companies were involved in a consortium with GRI running what was going on. Dick Zeno left UPR and tried to develop a service industry. They were looking at how experiments with microseimic were feeding back into cost-effectiveness and advantages of slickwater fracks.

Steinsberger: Slickwater fracks were done more independently than microseismic; slickwater was done to reduce cost. Microseismic was used to better understand slickwater fracs. That started happening in 2001 to 2002 with Pinnacle. We did huge study in tight vertical wells.

Warpinski: You can do slickwater without microseismic, but the latter enhances and optimizes process.

Peter Pearson: It sounds like a lot of positive cooperation between industry and government. There were cases where industry knowledge is proprietary. In past experiences, difference between time horizons, etc. Was your process constrained by not having knowledge, and where?

Burnett: When we started our research into natural gas, we were looking into unconventional, resources that were owned by independent producers. UPR helped Mitchell, but they had totally different lands and leases. There's something we need to understand there. As far as information transfer in the supply arena, there was little money, and you had to publish a report when you were done. You could have requested a separate report that included proprietary information and a public copy, but often this wasn't taken advantage of. We worked with many small, independent producers. We paid independent producer organizations (TIPRO, OIPA, IPAMS) to hire technology transfer agents to figure out what's in the reports and what's important to industry since industry guys often didn't read the reports.

Geels: Small players are innovative. I was surprised in the previous session. I would have thought that many of big majors did a lot of fracking technologies and capabilities. But they didn't. The '90s was a story of independents, not big players. Why did they drop out? Strategic decision? Too many CBAs?

Warpinski: With collapse of price in 80s, they dropped their R&D departments. They became tech services. The research guys left, so we no longer had focus from majors. The majors went offshore and to foreign.

Jeremy Carl: Majors originally didn't share information. It's the same with fracking fluid disclosure now, things are being played close to the chest. Have attitudes of majors changed over years?

Fred Julander: The majors reentered the US market for unconventionals with varying degrees of success. Shell came in with several indicated discoveries and with some failures, and then Hague bailed on unconventionals across the country. Exxon has done OK through their acquisition of XTO.

Tom Price: At Chesapeake we didn't share anything. We had thirst for acreage. Our competitive advantage was that we had land. For better part of 15 years, we were most active operator every year in the country. We saw no benefit in sharing. We didn't think GRI had anywhere near the budget much of anything.

Zhongmin Wang: Majors had better opportunities to go offshore. Risk-taking behavior is the key – what's incentive to take risks? Land and mineral rights are the key to why independent take risks. Independents are the billionaires, the huge potential.

Steward: In the UK, that's a big issue – the land and mineral rights. If a landowner feels like he's getting something out of it, than he might be more willing.

Newell: Advances in horizontal and directional drilling and fracturing were being made by majors, but not for unconventional gas. They were experimenting for different purposes, but this trickled over to shale gas and oil. Innovations in one sub-sector are picked up and translated to another and then improved…as Isaac Newton said "If I have seen further it is by standing on the shoulders of giants."

Session 2: The Development of Fracking in Context

Zhongmin Wang

Today I will ask what drove the shale gas revolution? The first and biggest factors in driving the revolution were the efforts of independent gas producers and of DOE, the second was the contribution of oil companies, the third was the influence of pricing, especially high prices in late 1990s and early 2000s. The final thing to recognize is the importance of exogenous factors such as infrastructure and favorable geology.

The contribution and effort of independents was big. DOE was covered in first session, but as for contribution of oil companies, they played a big part in developing horizontal drilling, over 99 percent of horizontal wells in oil in 1990. The oil industry also had large outlays in 3D seismic throughout '90s.

Why did the government have an energy R&D program? If the market can do it, why should government get involved? Because private firms do not have enough incentives. 1) In oil and gas industry, it is hard to make new technology propriety so why invest in R&D? 2) Most US gas firms are small and do not have capacity to do R&D, and 3) oil firms will likely get better returns investing in oil.

Why did Mitchell invest in shale gas? I tried to distinguish between idiosyncratic and non-idiosyncratic factors. On the idiosyncratic side, Mitchell had the need because it had a long-term contract with NGPL and needed to deliver the gas, it also benefited from relatively good geology and had overlapping formations of conventional gas.

General factors that encouraged Mitchell and others were the ESGP work in Devonian shales. Mitchell engineers thought the Barnett could be similar though it later turned out the geology was quite different. The use of private land mineral rights ownership overcomes difficulty of making money from R&D. If you can buy land at cheap price and prove you can extract gas or oil from it economically, then you can make a high return of R&D investment by selling the land with a much-inflated value.

It's also worth noting that prices clearly played an important role throughout the technology's development: When prices were high, Mitchell drilled substantially, when the prices fell, it reduced its investments accordingly. Other factors to take into account were water availability and good infrastructure (once the gas was extracted, distribution was relatively simple).

John Golden

For a patent law scholar, the shale gas revolution seemed like an intriguing case study. There has been a fair amount of work done on sectors with limited IP such as fashion design or even tattoo artists; these are areas that rely on getting products out there quickly. This case apparently had a similarly humble role for IP but arguably involved a more significant part of US economy.

I was interested also in what were the government policies that worked? And what does this innovation story tell us about what can be done with renewables?

The shale revolution has a whole ecosystem behind it, there was the regulatory and tax relief as we talked about before. Also a dedicated infrastructure and industry with many players, nationals labs, etc. Lots of interesting examples of crosspollination from different sectors such as PDC drills bits from geothermal research.

This isn't a 'no patent' story. There were a lot of patents in this area, Stanolind and Halliburton patented early fracturing processes from the 1940s. From that point on, a great variety of fracturing techniques and components such as gels were patented. In general, the majors seemed to be doing much of the patenting. This may not have been a bad thing, as it helped make their discoveries public.

Major services companies like Halliburton and Schlumberger also patented various horizontal drilling techniques. But why did Mitchell not patent its slickwater fracturing process?

I can posit a few reasons, because Mitchell already had or sought complimentary assets, the mineral and land rights that allowed it to capture substantial returns. Further, the smaller independents did seem to have a culture of sharing.

It is often assumed that method patents are far more difficult to enforce than product ones, this may have been true in this case. The patent might not have the scope necessary to extract an adequate return; maybe it's not worth it on an ex-ante basis.

Lessons: provision of stable, reward mechanisms was a major advantage (in contrast to boom and bust in subsidies for wind and solar). Having a diverse industry with numerous mid-size firms like Mitchell (and including smaller and bigger ones) was an advantage as each brought something different. This was a mixed information environment: you can hold some stuff back, share other things, patent some, and offer others for free.

Shellenberger: Why did Mitchell not patent your innovation?

Steinsberger and Steward: It literally didn't cross our mind.

Steward: Since UPR gave us the technology, had we patented it, I wouldn't have thought much of us. Another thing to note is that many didn't think our waterfracs was valuable. If there is one thing they really teach you in oil and gas engineering is that you don't put fresh water in shale. How wrong they proved to be!

Nordhaus: What about patenting today?

Steinsberger: There are loads of patents in chemical additives but that's about it.

Shellenberger: So is the story, it didn't cross your mind, and you didn't see the value in it? What about the labs?

Warpinski: Sandia wasn't interested in IP; our job was to disperse information as much as possible. Although this did change in time, I think around 1990, the labs started to patent their IP.

Northrop: Yes, national labs are government-owned contractor operator so decided to try and extract some royalty from research later on but certainly not in the early days.

Mowery: What Dave and Norm are talking about are the effects of the Bayh-Dole Act. It took a long time to seep through and change national labs policy. Many talk about its effects on university but it was also designed for national labs.

Warpinski: In 2000, Pinnacle bought all the mapping systems from GRI. And GRI got stock in return.

Shellenberger: The IP?

Warpinksi: Systems engineering is what got sold, microseismic monitoring was public information, published in numerous papers so other companies could and would use it. But Pinnacle got a head start by acquiring GRI's expertise.

Julander: Both fracking fluids and microseismic are in a constant state of flux.

Long: It seems to me that the big impediment to innovation today is trade secrecy. Fracking is losing its public support because the chemicals used to frack are kept secret. Loss of social license because keeping chemical secrets.

Shellenberger: Is this an impediment to innovation?

Warpinski: Well if you get the chemical mix just right, you'll get drillers to buy your mix regardless.

Long: Well it depends, lots of places where fracking is getting banned, in large part because of the lack of transparency. It makes people suspicious and leads to bans. And if there's bans, then obviously that slows down innovation.

Geels: I don't understand why we are so focused on patents, in most sectors, they are not that important, maybe in some sectors like ICT or biochemical they are key but usually not. In most industry surveys, firms often list it as their 3rd or 4th priority.

Nuvolari: Just a clarification. Did Bayh-Dole lead to national labs to do IP? Bayh-Dole was in 1980 and the discussion of the patent system seems to be occurring from the early 1990s.

Warpinski: Don't know but we didn't care in early '80s, only cared around the '90s. In the MWX, we were heavily encouraged to share our information.

Mowery: Each lab is different so can't be sure about Sandia but certainly the case at LVM.

Price: It's worth emphasising that even if everybody was using different chemical ingredients to their fracking fluids, the differences in performance was super minimal. We never saw any differences with a variety of service firms with supposedly different fluids.

Nordhaus: Regulation evolved over time, semi-deregulated in 1980s, completely deregulated in 1990s. Did deregulation help diffusion but hamper innovation? Did you need semi-regulation to motivate Mitchell?

Steward: Mitchell decided to buy out contract NGPL because he could get a cash infusion and Mitchell himself wanted the company to spend it on R&D. He thought the company was getting too comfortable and not trying to get Barnett commercial at industry price (in early '90s), but getting it commercial at NGPL price. George wanted to force the company to get commercial at spot price, to accelerate productivity gains.

Julander: We went from an era when drillers were relegated to price taking from the pipelines. It was very discouraging to exploration and new supplies. When we achieved open access it proved very beneficial to producers because we could negotiate on price with multiple buyers, not just one or two pipes.

Shellenberger: If price deregulation had happened earlier, would have it boosted private R&D?

Steward: Hard to say; one aspect we haven't dealt with is that people in companies weren't moving around past 1986 because industry wasn't doing so well. During late 1980s and early 1990s, it was beneficial that industry wasn't doing to well because people would stay put.

Nordhaus: High prices were at time of diffusion, pretty low when lots of investments were happening?

Steward: That's right. Depressed market benefited Mitchell because people had to stay in same place

Newell: On the price question, there was the period before prices rises, and lots of innovation and period after high prices (last ten years) with lots of innovation, induced through learning-by-doing in the process of commercialization and production. Had natural prices not gone up, would we even be having this conversation?

Steward: No, I doubt it. The period of high prices was really beneficial.

Julander: Well they dropped in 2008 and we've been fine!

Newell: Yes, but we still had the high prices in the late 1990s and early 2000s, which helped get things going, to bring down production costs, so that those costs are now compatible with lower prices.

Nordhaus: Full deregulation drove diffusion, semi-deregulation helped innovation. To the original point that different conditions were beneficial to different stages in technology, is that right?

Mowery: A criticism that needs to be made is that innovation and diffusion are not different; these are two sides of the same coin. They should only be separated for analytical clarity and as little as possible.

Kash: The shale revolution required the integration of a very large numbers of different components. What George Mitchell did required gluing those components together. Mitchell was willing to pay for repeated efforts to try different mixes of components. There was a broad wave of technological improvement going on, some related to oil, some to all sorts of others technologies, so let's not over-exaggerate the role of regulation in driving innovation.

Price: One of the things that we experienced at Chesapeake was that we had a CEO who was great at raising money, especially through junk bonds. In joint ventures deals, we raised as much as $20 billion from foreign governments international oil companies. So one point I would stress is 'access to capital' as a key component of the tech development. Big difference between 1990s and 1970s in terms of access of capital, it was much easier in the 1990s. There was great teamwork because Chesapeake employees got stock options. As so many companies went public in the 1990s and 2000s. In the 1980s, public debt in the energy arena was about 4% of total publicly traded debt, today's its 17% to 20%. There is so much money washing around. Also all fractures are different, which can explain the limited role of IP.

Julander: In wave one, we applied technology to the shales, in wave one to shale oil, and now we're doing horizontal drilling in original reservoir rocks.

Golden: A common problem of innovation is that people don't often work together well across disciplines. There's been suggestion elsewhere that the US atomic-bomb effort outpaced that of the Germans in part because the US was more successful at getting physicists and engineers to work together. There's been suggestion here that Mitchell succeeded in bridging divisions between geologists and engineers. How did Mitchell do this? At Chesapeake, there was apparently a use of stock options.

Steward: As a geologist, I was held to different standard than engineers. I was considered an artist, engineers were calculator, less room for error. If I messed up on a well, I would still have my job the next day. Can't say the same for Nick.

Janeway: The cohesiveness of keeping the group together for a decade or more was key. In the world of IT, you have to move jobs every two years. Highlights very different nature of innovation in different areas. When financial constraint gets looser, you get the chance to pull engineers out of the big companies and start from scratch in exotic areas.

Kash: Once Mitchell proved profitable production from shale was possible there was a stampede. This is the pattern with most radical innovations. There is a parallel with what occurred after Columbus discovered America. Once you know it can be done lots of people want to get involved.

Kelly Sims Gallagher: Mobilization of capital is big constraint on innovation in general, so Tom and others how did that capital mobilization succeed? There wasn't much in the papers on this, how did they mobilize capital for this, especially in the early days?

Price: I'm a salesman, my CEO was a salesman. Their CEO just convinced people there was going to be uptake in demand. He convinced people there was a tremendous opportunity for enormous return.

Sheridan Lorenz: On Dan's point about collaboration, I wonder if it made a difference that Mitchell himself was both an engineer and geologist.

Burwen: I talked to Vello about Section 29 tax credit, his sense was that it was pretty useful. People were monetizing these tax credits: was it key to providing capital to innovation in 1980s? Did it help industry try more things? Did it play a big role in 'learning by doing'.

Julander: Section 29 drove tight sands, shale gas.

Steward: Section 29 was useful but we didn't have to have it. Just like severance tax abatement in Texas, it was useful but not necessary. George loved to get whatever he could but its contract with NGPL was more important.

Bozmoski: If everyone agreed that we didn't need it, was it a waste of money?

Julander: It was key for tight sands!

Wang: The credit was much higher for Devonian shale and coal gasification. George Mitchell didn't really benefit from it because the benefit was useful.

Steward: Was it a waste of money? In hindsight maybe but how could we possibly know in advance?

Session 3: Fitting Theory to Practice

Richard Newell

I'd like to recall some lessons from a book by myself and Rebecca Henderson — *Accelerating Innovation: Lessons from Multiple Sectors*. We looked at agriculture, chemicals, semiconductors/computers, biotech, etc, to draw out lessons with relevance to energy. We argue that three key things accelerate innovation: 1) Substantial, sustained funding of research/R&D tightly tied to private sector 2)Robust demand 3) Vibrant, competitive private sector

Why do these three things matter in practice? On research/R&D there are spillovers/knowledge failure; there's a value in public funding and institutions getting together because it is hard for individual innovators to capture all the gains. It needs to be tightly connected to the private sector to make sure research is useful and responsive to commercial needs.

Without demand you have no market — innovation must adjust to private market interest needs and feedback from the market.

Finally, you need competition in the private sector. Mitchell was one of thousands of independents — you need competition for motivation. Competition needs to exist in the world of ideas.

This framework fits very well: shale gas is a textbook example of the importance of each of these factors, including market-driven innovation. DOE/GRI was a public mechanism to pool resources and it was hugely important that they worked with private sector. Natural gas prices provided profitability for initially high cost technology. The opportunity to do things at lower cost is also a demand signal. We also see the role of entrepreneurship and competition.

What doesn't fit neatly into these three bins? Richard Nelson would emphasize that fracking was the coming together of many different technologies. The role of building on prior innovations and incremental innovations is also important.

My paper included for this meeting was "A Tale of Two Market Failures." R&D spillover is not a total market failure — it's also a way of rationalizing why there can be a benefit beyond individual private actors. Climate change is the second market failure; the importance of demand in inducing innovation. In the case of shale gas there's a natural private market demand for fuel; in climate, that demand doesn't exist without policy, so we need to create a second market demand there.

Frank Geels

I don't disagree with Richard; his three points are important. But Richard's framework is pretty close to a linear model — fund R&D, demand induction. So there are some problems to flag:

First is the "Valley of Death" problem — how does R&D get to the market? Richard did allude to linking R&D to industry. We see various mechanisms for this — GRI, learning by doing, the importance of failure, and the importance of risk-taking.

The role of a strong government not mentioned explicitly. I've done a dozen historical case studies of technological transitions — not just in funding R&D, but in creating markets, regulating, bringing actors together, creating institutions.

In the United States, there's a question of why should the government do anything at all — this isn't a question that's asked in the rest of the world.

Historically, the government has been everywhere in any historical transition. In the US, you have the "hidden developmental state." There's an ideology that the government is bad, but the US has had a very effective government. It's hidden. You can't mention it because of ideology.

In the broader social science of innovation, there are three constructions of policy:

- Market-based model: incentives: taxes, R&D
- Regulations
- Network governance

Something sociologists emphasize is that government is very good at bringing actors together. This paradigm is often missing in the economic approach.

Then there is the importance of timing of policy. [David] Mowery reminded us that we shouldn't separate innovation/diffusion; but you need some separation analytically.

Government has been very effective at innovation in governance: changing policies according to the phases. Wee see this in this case study: Lots of tinkering in the early years; the dominant design that comes from the Barnett provides more certainty for policy. As you move through this continuum, more market-based policies become more appropriate. In this case, the government did that very well. I'm not sure if it was deliberate, but in the '90s the government stepped back very appropriately in a way that allowed the markets to carry the technology forward. Was this by design, or by default?

Newell: I don't think this was by design. It was a small piece of DOE R&D that not many one paid attention to.

Crawley: It wasn't by design. We fought for our budget every year.

Jim Watson: Networked innovation seems very important to this story. As Richard said, this wasn't a good example in terms of climate innovation since natural gas is still a fossil fuel. Then there's physical infrastructure — major differences to things like EVs which don't benefit from the physical networks that natural gas enjoyed.

William Janeway: We have to distinguish between technology risk and market risk. Shale revolution had obvious technology risk; market risk came down to price. In other domains, eg, material science, it's not just that there's technology risk, but no one has any idea what the stuff is good for. It took 25 years to discover that the killer app for the laser was the supermarket checkout. We have no idea what graphene is going to be good for.

The role of the government occasionally has to be the early collaborative creative customer pulling providers and creating demand. In some sectors, where cost is still out of line with conventional sources, we can see enormous waste from subsidizing in a narrow sense like the German solar bubble, but we can separate tech risk from market risk and thinking of the role of government in creating demand.

Mowery: Addressing climate change is only partially a problem of innovation — if we really want to address climate change in the relevant time frame, then many of the technology solutions exist and the question is deployment/improvement.

If we look at federal mission-oriented R&D investment, it may be 60-90% of the budget. Market failure has almost nothing to do with it. Biomedical is 60-100x the investment in shale/fracking. The dysfunctional health care delivery system accelerates adoption, so it's an inadvertent demand pull.

The extent to which the government programs we've discussed today are unusual within DOE. DOE R&D funding in particular is highly cyclical. Fluctuation of R&D funding is the enemy of success/investment. Can we figure out the characteristics that enabled these programs that led to the shale revolution to survive over time and have some level of stability? Political salience is often the enemy of stability — the fact that they were small played to their benefit

Weak IP environment and data sharing in the early stages seems to have been very productive and useful. But here's the bad news: These were not simple problems that were solved, but much simpler to solve than tech problems associated with climate change — increasing complexity should caution us from drawing too many direct conclusions. It's going to take a diverse portfolio of approaches that go beyond even the diverse program that led to shale.

Nordhaus: I want to focus on this idea that none of this was planned — that it was a small backwater in DOE. That's different from what we heard earlier — networks were intentional in bringing in the industry collaboratively, in sharing information, in moving the Labs from weapons to energy, Bayh-Dole was an effort to get technology out of the Labs, the Sandia/Los Alamos partnership. It may not have been totally top-down, but there does seem to have been a fair amount of forethought in their design.

Burnett: We felt our program was designed from day 1 not to "create the shale revolution," but to explore the unconventional gas resource base. The gas base was a very nice target for the industry — we believed in natural gas as the "fuel of the future." Prices played a role, but that was already being resolved through partial deregulation by the time we really got going. I know about the politics at DOE but I do think there was a fair amount of design. This had to be cooperative! Look at the tiny amount of money compared to coal gasification, batteries, solar.

Crawley: We spent in 25 years what coal gasification spent in one year.

Kash: I was involved in the review of the ERDA R&D program and then the DOE R&D program. My takeaway: it was clearly a statement that all energy technologies had to be supported because you had to put together a coalition in Congress to support it. Because natural gas was less charged politically, it was turned over to professionals who were essentially left alone. But natural gas got money because everybody had to get a shot; that was the culture.

Newell: We need to make a distinction between government and cooperative industry innovation (e.g. Sematech). Lots of this was GRI-orchestrated and so very attuned to the needs of the industry. DOE Lab work also involved industry participation, but it's still useful to distinguish these two models.

Kash: GRI got its money because the federal government regulated the pipelines and allowed industry to add on an R&D charge in the same model of Bell Labs. That is an important model as we think about how to fund energy innovation!

Newell: Yes. We've heard similar ideas for wires charges for EPRI, but they don't go anywhere because of the competitive market structure today.

Burnett: No one in government was pushing for GRI — it was all the industry.

Kash: This is the exact same thing that happened with AT&T; the company brought it to the government, not the other way around. There's no question that the freedom from Congress is a benefit; you can stop projects that aren't going well. The cooperative R&D model is great — no idea why it doesn't happen more.

Long: I think we left the Labs behind because the Cold War ended; we used to be able to spin stuff off as a substrate based on Defense. The environmental voice became stronger; the mission became "be clean and safe," not "what can we achieve?" We lost out abilities because we didn't know what the mission was anymore. We've lost the ability to do mission-oriented research; it was lost at the end of the Cold War and we need to figure out how to get it back.

Margaret Taylor: There's so much conventional wisdom around today, like NSF 5-year funding plans with tons of paperwork without any administrative evaluation. Models like GRI/Bell Labs, etc. are not looked upon favorably today. The paperwork alone today kills research today. In nanotech, the industry went to the National Nanotechnology Science and Engineering Centers and asked for help, and the Centers basically all said no. Strong IP is the model today.

Northrop: Once Sandia got into gas funding, all of our work was industry-driven; it wasn't just GRI. We had advisory panels for the Multi-Well Experiment. There was the Nevada test site. There was the Partnership that Bob [Hanold] and I had. Joint projects with National Labs were developed, reviewed, ranked by industry and funded according that that ranking

Janeway: I agree with Jane Long on the "loss of the mission." How does climate change become a politically legitimizing mission? I don't have a clue. There's a professor at ETH Zurich named Monika Gisler who has done work on "social bubbles" — how political entrepreneurs generated consensus on some kind of mission (e.g. Apollo) to mobilize resources that the market would never do and that otherwise the public would never support. It takes timing and brings this discussion back into the broader social sciences.

Geels: With respect to climate change, we should start looking at how to diffuse technologies that are around today, because we're on the clock. How do we create demand? We need industry and policy together, but this can also lead to policy capture; can lead to incremental policies that aren't enough. We might need to think about technology-forcing policies; Clean Air Act, California's Zero Emission Mandate; Apollo/Manhattan. The tools we've talked about today aren't going to happen fast enough; we need to talk about civil society and public pressure. Industry and policy together aren't enough.

Crawley: Government never acts; they react. It's when we have a problem that the general public recognizes as a problem that government is pushed into action. In the war, it was a push for the atom bomb. In the 1970s, it was a push to fix energy shortages.

Kash: I don't know how the Internet fits into that framework. There are lots of cases in which government was the initiator. Absolute generalizations need to be avoided.

Gallagher: Let me riff on Frank [Geels'] remarks on market formation. Niche market formation and government procurement were not at all present in this case; it was almost like the absence of a market that enabled this infancy to take off.

Nordhaus: Didn't you have a niche market because of the deregulation of unconventional natural gas?

Gallagher: But the Mitchell play in the Barnett seems to have operated without a market.

Steward: Mitchell was looking towards the survival of his company.

Gallagher: In this way, the case study is very contrary to a lot of thinking and theory. In the climate domain, we absolutely need very broad market formation.

Shellenberger: Something really changed in ideology/framework. Jane describes a moment at the Labs. The founders of the shale revolution here tell us that they never thought of it as market failure. The political Right and Left both suffer from this. We've all heard of Proxmire's Golden Fleece Award — what a disservice. Further to the Left was Nader, who made a mess out of policy capture. Mitchell's work would be viewed as rent-seeking and Nader would find many allies on the libertarian Right who would agree with him.

We made a big push for an Apollo Program for energy in the 2000s with Peter Teague. We were dismissed by people with "good opinion" for reasons of rent-seeking, etc. The collapse of the stock market led to a emergency $90b investment in clean energy. But these were mostly short-term, deployment investments – the opposite of patient capital.

Here we are again looking at the same levels of R&D that we had before and the same level of policing about rent seeking and market failure. I don't see solar/wind/nuclear companies going to the federal government asking for a federal mission; they go to the government and ask for deployment subsidies for another year. Wind and solar companies lobby for the PTC/ITC. The nuclear industry just focuses on existing plants. This mission seems to be missing from every level of society

Janeway: Everyone should read Bill Bonvillian's article on the difference between DARPA and ARPA-E. DARPA was not addressing an industry with enormous lobbying power and embedded interests.

Hanold: The Partnership generated a life of its own that turned out to be more encompassing that we planned. Budgets went from $1 to almost $30 million in those years. Initial funding from oil programs was supplemented by gas funding with further additions from DOE defense and research funds (four different sources in a matter of a few years).

The importance of the independents can't be overstated. Hazel O'Leary came to the Department and was briefed on the Partnership and how much of it was industry-driven. We didn't have to solicit, industry came to us. President Clinton joined Secretary O'Leary at Los Alamos a few months later. Mark Murphy from Strata Production in New Mexico gave a strong message to the President: All these small companies don't have research departments. This message was effectively delivered. The Partnership generated what was missing; very simple agreements nothing like complicated RFPs/CRADAs; not much more than a handshake and we were in the field very soon.

Peter O'Connor: It's very critical to have an institution that has the freedom to think creatively, take risks, and fail. That used to be one of ARPA's strengths.

Nordhaus: Whether I'm in either framework, I can mostly apply the same basic ingredients that both Newell and Geels described to oil shales or to SynFuels and I could throw in a lot more money. Yet it's this smaller corner of DOE that was successful. What made shale gas different? Was it GRI? Is it just chance?

Northrop: Gas is there; we just have to extract it. Oil shales have to be processed. Coal liquefaction and coal gasification have to be processed. We were talking about reactor vessels the size of this room for coal gasification. The gas was there for the taking.

Nordhaus: That seems like a very good explanation retrospectively, but then why were we spending more money on everything else?

Burnett: We were spending more on electric vs. gas because of politics. On coal gasification, government did a great thing: we can build a huge facility in North Dakota and get very little gas out of it. We proved that it wasn't worth it! There was no coal industry pushing for gasification; they had a market for their product, forever. The gas producers weren't pushing for gasification either.

Jenkins: The sheer size of the potential resources seems to have mattered, as well as the homogeneity with the ultimate resource.

Burnett: There was no one in the '80s who thought we were going to produce shales with competitive prices for a long, long time. It just so happened that those technologies turned out to be the forerunners of what we needed to do. We knew the resource base; it just wasn't economically recoverable.

Julander: The key word is "potential" gas. We don't drill $10 gas anymore; we have unlimited $4 gas. With respect to climate change, most of my industry does not believe in climate change; I do. Do you think you can cure climate change without the acceptance of at least half the population? Why do we have tons of economists sitting in major companies and nobody saw $45 oil?

Newell: On the question of SynFuels etc.What role does government play in the spectrum of basic research through deployment and large-scale production? A key element of the SynFuels failure was the collapse of oil prices but also production targets; it was about production, not research; most analysts think this is a classic example of government going too far in the continuum from research to development to first-of-a-kind pilots to large-scale commercialization.

Jason Burwen: An RPS 30 today is different than SynFuels because we have functioning technologies today.

Newell: The thing that killed the ethanol tax credit is the volume of the budget cost. As the technology got more competitive and its market penetration expanded, the amount of total subsidy ballooned. It's the same with wind: the more competitive you get, you have to wean the subsidy off of the total amount tends to get too large politically.

Nordhaus: I hear several explanations. Richard Nelson offers the idea that technology targets are a bridge too far. Much more optimism among folks in these industries that oil shales and coal gas were viable; ironically, there was much greater skepticism towards shale gas than towards SynFuels.

Steward: The politics of 1973 have a big impact; people experienced life without oil, not life without gas.

Long: It became a total renaissance on all forms of energy; after the crisis ended, these programs atrophied.

Crawley: The DOE upper echelons that had a final say on the budgets spoke with oil industry higher-ups, who eventually said they don't need the government involved.

Northrop: The presidents of the companies didn't want government involved, but the heads of the research departments did.

Julander: Same with climate change today; scientists understand the problem, but the executives don't.

O'Connor: In an emergency you invest in the technology you know, so we invested in coal-to-liquid synfuels instead of shale gas.

Taylor: In the 1970s there was a "thousand flowers blooming" culture. Reagan famously killed energy research, tries to kill DOE. So how did this sort of stuff survive the politics?

Long: Scraping and begging.

Crawley: The Multiwell project was $40 million. DOE couldn't bank money, but the Labs could. So if I committed it to Sandia, I didn't have to justify it annually; I could make programs last 3-4 years instead.

Janeway: The budget crunch was only partly ideologically motivated by the Reagan Revolution. The market will always bedevil innovation in energy because there is a market and there always will be and it was always be cyclical. This is so unlike the tech revolution and the relationship between government and industry in tech in the 1950s through today. Bonvillian's thesis is that you're addressing established sources that make it problematic to make commitments where the economics challenge you in the first place.

Burnett: The NPC was filled with petroleum executives and was the only panel allowed. They pointed out that gas was 3 to 6% of the budget. In 1992 executives recommended increasing research in natural gas; budgets went down anyway.

Julander: In 2009, Aubrey, myself, the head of GE research, and a few others went to discuss natural gas as a solution to climate change in Copenhagen. Our success was limited to young people.

Taylor: We've been talking about the linear model and how we define basic science. We still measure science along the linear model. Arguably, the shale revolution was far beyond basic.

Shellenberger: Yes. Geothermal and IT led to shale gas which led to shale oil which are now killing OPEC. There's so much obliquity that it's almost impossible to pinpoint where these investments will come from. If you're someone who really cares about nuclear power it seems you should really want investments in solar.

Kash: Executives at US oil & gas and auto corporations were absolutely opposed to working with government until they got in trouble, even though we know the importance of cooperation. Many executives of these companies still believe that if government is involved it will slow progress. That this view is contrary to experience, it doesn't seem to win when it runs contrary to ideology.

Hanold: Working with many smaller independents was helpful. They didn't care if it was basic or applied research, they wanted problems solved.

Newell: There are grey areas, but sometimes you really can define basic research (fusion physics, material science). Once you get into the grey areas, it becomes a question of how far you push the applied research. Basic research receives broad consensus. You get the least agreement at production targets.

Burnett: We also need to talk about educating scientists and engineers in our universities.

Jenkins: What were the cost projections for shale gas? We see targets in clean energy towards technologies that are quite expensive.

Long: Part of what made shale gas happen is the total reduction of risk in these geologic formations that were very reliable. It's just an industrial process now and the risk element is very low. It's just geology now.

Steward: It's a combination of geology and engineering.

Peter Pearson: We've heard quite a bit about the unique nature of the collaboration here. Would the shale revolution have happened anyway, just a bit slower? Was this particular form of collaboration necessary for the journey that was undertaken? If we want to replicate something for new technologies, do you need this kind of rather unusual collaboration?

Steward: The Barnett happened exactly when we needed it to happen; if we had not had it when we did, gas prices would have gone to $20/mmBTU and our manufacturing capabilities would have gone into the gutter.

Golden: Counterfactuals are tricky. Credit the unpredictable process of learning by doing.

Shellenberger: Is this line of questioning even legitimate to innovation scholarship? How far should we go beyond really accurate historical descriptions?

Watson: With multiple cases and multiple technologies, comparing relative success or failure can produce value to counterfactuals. For instance, CCGTs have interesting similarities/differences.

Newell: Counterfactuals and comparisons are incredibly important; the conclusion otherwise is "do it all" and we don't have the money to do it all. It's all about decision-making subject to constraints.

Nordhaus: There are clearly things we can look across and identify as similarities and things that worked across multiple cases. But can we still say that had we done oil shales like we did shale gas, the answer is probably still no; and yet at the time the conventional wisdom was that oil shales were more promising than shale gas. There have to be multiple bets. We cannot pick one winner or one methodological pathway

Watson: I entirely agree; we must pick a portfolio, but there must also be a way of making decisions given a limited budget.

Alex Bozmoski: The conclusion seems to be that failures were so important to success that we had later. It feels like we're allowed to look back to history and consider what was done right, but not what was done wrong; the framework disqualifies the possibility of government doing something wrong if we need to tolerate failure. Name one thing we wasted money on? Richard Newell named production quotas; Section 29 credit seems to be a maybe. The lessons are being applied to programs that are spending much bigger money today.

Nordhaus: The shale investments were an absolute pittance compared to the benefits, especially with the oil price crash. There are plenty of cases of money wasted, but they are absolutely outweighed by the public benefits.

Taylor: What kinds of practices go into the R&D calculus today, where we have to fill out spreadsheets and coming up with projected jobs?

Burnett: USGS estimate in 1980 was virtually zero for shale gas; who was going to pursue a resource that didn't even exist? First step was creativity and optimism in looking for the resource base. We did have a cost-benefit methodology.

Session 4: The Implications of Growing Technological Complexity on Innovation

Don Kash

We performed a study that classified the 30 of the most important sectors traded in the international market and sorted them into four categories: 1) simple processes producing simple products, 2) simple processes producing complex products, 3) complex processes producing simple products and 4) complex processes producing complex products. What I found is that over time processes were becoming complex, even for simple products. For example, oil and gas are simple products. The processes used to produce them used to be simple but have become complex.

The view in the USGS when I was there in the late 1970s was that oil and gas from shale was uneconomic to extract. It took a synthesis of tacit and explicit knowledge in a sociotechnical system, or a network, to unlock this oil and gas.

Complex innovation rests on interactions among the components of a system, and the innovation of complex technologies relies heavily on network heuristics, trial and error. Gordon Moore said Intel operates on principle of minimum information and that innovation is a heuristic process. The Shale Revolution was in part the result, for example, of integrating crude plumbing (tacit knowledge) with sophisticated seismic technology (explicit knowledge). The mix of knowledge and capabilities necessary to carry out horizontal drilling and hydraulic fracturing was carried out by an evolving sociotechnical system or network.

There are 5 common features of networks that carry out innovation, they are seamless, diverse, continuously changing, not understood and always pursuing incremental innovation.

On intellectual property, I have found that patents often slow down the innovation of complex technologies. In legal battles, litigants are often not interested in winning but rather in tying up competitors. It seems that in the shale example, there was little emphasis on secrecy, perhaps due to the difficulty of holding secrets. The largest benefits went to the people and companies with early leases. The payoffs increased when people became interested in surrounding land, so this encouraged knowledge sharing.

Regarding culture, a common trope is that when the government gets involved, they'll screw it up. But in the case of the shale gas revolution, industry benefited from a network that included government via R&D, technology, open pipeline regulations, and new markets. There is often a central role of government and the role of government varies widely for different technologies. We celebrate individuals, entrepreneurs, and the free market, but innovations are products of networks and teams that often involve government. There is some hypocrisy in saying government always screws it up when the government is always involved. In an historical tracing of tech technology sectors, government was found to be critical to the survival of every sector.

Kelly Sims Gallagher

Historically, as a percentage of US DOE Energy RD&D, gas RD&D was tiny compared to all other priorities. Data from IEA ETIP shows that globally, nuclear fission and fusion captured the largest fractions of R&D investments in the past. At present, according to the Global Energy Assessment (GEA) chapter which I played a large role in drafting, the majority of investments are in China – their energy R&D, including those at state-owned enterprises are now double the US R&D investments in energy and in all energy subsectors, including fossil, nuclear, and renewables. There has been a global diversification of R&D investment. Input dollars are relatively easy to collect and may not be representative of R&D outcomes, but can still be instructive and indicative. Also, in the GEA, R&D dollars were split up by sub-sectors such as electricity, renewables, nuclear, fossil supply, end use and efficiency.

In my book, *Globalization of Clean Energy Technology – Lessons from China*, four case studies are examined: gas turbines, solar PV, EV batteries and coal gasification. China has been taking a much more global approach to innovation.

The shale case fits within national innovation system, but globalization has changed innovation. There are four major barriers to global diffusion: IP, cost, capital, policy failure (market formation/ind, tech/innovation, export, market-formation).

Energy innovation has become a global phenomenon. There is often a need for market formation (natural or induced), and access to capital to respond to market demand, which was a huge competitive advantage in China compared to US and Germany. Chinese companies have hired many overseas Chinese and foreigners. China has been doing mostly process innovations. The need for market formation shows up in the gas turbine example.

Steward: Government can and should be a positive influence. Some other countries don't do it well. Chinese visitors talked to Dan Steward back when nobody in US knew about the Barnett, but they didn't have deadlines. There is animosity between companies and government, but that's normal – e.g. production vs. service companies. The main difference is the development of trust. I connected with and trusted Norm. I could tell that Norm cared. A public-private relationship requires trust. There are accusations of cozy relationship, regulatory capture, information asymmetry issues. This is why an adversarial relationship has been proposed. Management by adversity is common (Red team blue team).

Watson: Innovations in shale may not have been US-only: 3D imaging and directional drilling had roots in the UK. It is also clear that technology adaptation and innovation is needed for each different geology.

Julander: Melanie Kenderdine from MIT, now Secretary Moniz's right hand at DOE, and Kyle Simpson, now at Hogan Lovells, created the Research Partnership to Secure Energy for America (REPSEA). This was done in an attempt to carry on the work of GRI.

Gallagher: US developed its technologies early, before globalization. It appears China necessarily had to take different approach, one that considers global markets and knowledge.

Pearson: How did the development of technical capability factor into innovation systems?

Gallagher: It varied by sector. When she visited a Chinese Jeep factory, she found people were "not allowed to do anything." They have hired foreign technical PhDs and China has been trying to learn from other countries.

Golden: China seems interested in learning from others' experience on a number of fronts, including intellectual property law. I was invited once to give a talk on US patent law in China and found participants at the conference to already be very knowledgeable about US law.

Shellenberger: Sounds like there was a lot of spillover, trust, and interactions. Let's think about setting up a testbed for nuclear. The IT industry relied on IP – do we need that? How do we create a GRI or national lab to be a convener for nuclear? Sounds like we would need the freedom to spend money, advisory from industry, and trust needed for tacit knowledge to be disseminated.

Kash: We did case studies in seven countries and tried to measure trust as a factor in innovation in each culture. In the Chinese culture trust was low outside of personal networks. Second-lowest was the US, in which every move required the involvement of lawyers. To suggest a very different cultural role for trust I would use the example, of the Philips-Sony invention of the audio CD, a technology they developed together. The Dutch and Japanese agreed to split costs of development and then become competitors after the development was complete. They decided on the split of development costs after the industry accepted their design. It takes deliberate effort in the United States to get people to cooperate- Intel trains its people to work in teams and this is difficult in the U.S because we all want to stand out, to shine. Jefferson won the argument, Hamilton won the facts. Make sure an innovation system gets money from outside government.

Gallagher: Globalization and diversity is important – international education, overcoming language barriers, and overcoming cultural suspicions require intentional commitment and formalization.

Geels: There is much more competition in the world via innovation, and the global movement of information and capital. No sectors are low-tech – there are new pervasive technologies: ICT, materials. "Open innovation" is important. Markets are fragmented and people have multitudes of choices. The original social movements were started from the labour vs. capital battle. Now there are new demands that make the economy more complex - social and environmental performance.

Burwen: What is a breakthrough? Microseismic – was that incremental or a breakthrough? How can we communicate success and/or identify breakthroughs?

Burnett: If something is unplanned, I would consider that a breakthrough. We ran international gas conferences. Technologists do talk to each other. DOE and GRI collaborated significantly with China on coal gasification. Another example of globalization: In 1981, I visited Japan and noticed flexible gas piping. It was approved later in 1988 in America to replace iron gas piping (and reduced jobs). Tankless hot water heaters in Japan also took a while to diffuse into the American market. One factor was that the Japanese companies were scared of the American lawyers. There is a need to consider the time perspective.

Session 5: Coal to Gas in the Context of Energy Transitions

Peter O'Connor

The main transition from wood to coal in the US didn't occur until 1850-1920. Settlers are coming mostly from England, and knew about coal, and England had already undergone transitions. But when they first came to the US, they reverted to wood as it was in abundance. My point here is that the progression up the energy ladder isn't always linear. In the early 1800s, some settlers tried to sell coal but most people couldn't figure out how to use it and had to learn how to burn it. Coal peaks around 1920.

In the US, oil doesn't take off until the car takes off. Kerosene wasn't sufficient to drive the fuel's wider diffusion. From 1920-1970 was the transition from coal to hydrocarbons.

Nuclear comes online around 1970; In the 1980s, some people believed it would be the next transition and would overtake other sources, just as coal had overtaken wood before it. That didn't happen. Others thought it wouldn't happen. Nuclear isn't providing superior end-uses like oil did. Just changing fuels in power plants is not going to make nuclear the next best thing. You did see drop off in coal during the recession. Oil drops too. Gas holds steady through the recession and grows after.

Having outlined the trends, I tried to uncover the reasons for the transition? So I started by reading Smil. He identifies the following reasons:

Possible reasons for the transition from wood to coal:

- Declining availability of fuel wood.
- Higher quality of fossil fuels & lower cost.

Possible reasons for the transition from fossil to renewables:

- Problem is that fossil fuels are adequate;
- new energies not qualitatively superior; not substantially cheaper.

But it doesn't seem obvious what makes one resource 'qualitatively superior' to another? Settlers shifted from coal to wood, also in part because wood was superior for smelting iron. Only when they had mastered coking did coal become superior. The problem is that 'qualitative superior' is not defined well.

The transition from wood to coal in railroads: part of the reason for the fall in the cost of coal was due to its higher spatial energy density (White 1979) but there is actually little evidence that inherent properties mattered or even that the cost of wood was increasing for railroads. Most of the price difference was actually because they could lay tracks through coal mine and get more fuel from an acre.

As for the transition from wood to coal in home heating, there is less good data. Urbanization helped bring the coal cost down slightly. Wood was still prevalent for most of early 20th century. In 1940, 23% of homes were heated by wood; 50% by coal but the data before that isn't very good.

Coal to gas in home heating – post-1940, possible explanations:

- Cleaner? (Turnheim and Geels, 2012);
- Smoke control ordinances in US in some places (Tarr 1981)
- Other important factors are declining cost of gas and less labour intensive to use.
- What is energy quality? Cleanliness and ease of handling fuel?

Coal to oil/gas in other sectors was influenced by labor strikes, as mine strikes affected productivity. Gravimetric density and ease of handling was part of the reason for the switch in the Britain Royal Navy (less manpower needs – no men needed for stoking fires).

In between 1900-1920, energy intensity actually increases. The millwork is showing diminishing returns of scale. The dryshaft system couldn't be scaled up past a certain point. This is the time where we're increasing horsepower without getting returns. In 1920, by bringing innovations together from gun industry, meatpacking, and the electrification of industries, we see improvements in productivity and energy intensity, especially with the Ford T assembly line. You have flat period in 60s where energy intensity isn't really improving and 70s goes down too.

Efficiency allows use of higher-cost resources/energy input while reducing costs of energy services. This is sometimes done intentionally or indirectly. Efficiently alone does not stop climate change or resource depletion, but it makes it easier and less costly to do so.

End-use technologies compete on performance. Lighting revolution was not changing energy resource – it was going from oil lamps to gas lighting to electric lighting. Quality was the key driver. Electric light could be used in theatres, printing presses, factories with flammable environment. Safety helped accelerate adoption. Quality of energy service matters – even if a car costs more, the quality is better for the individual, so they will pay for it. When looking at energy services, you have to look at the associated non-energy benefits.

Historical record shows innovation and flexibility – lack of lock-in; innovation in different sectors, like water pumps. The 1880s ice harvest is an interesting case as it actually drove efforts to develop refrigeration.

Overall energy intensity tends to decline, but not automatic or inevitable, often stagnates for decades.

Energy density is not the be-all, end-all of quality as electrification makes it less of a consideration, it drives a big wedge between energy service and energy supply and the energy carrier is so dense (at the end use point) that you can use less dense fuels going into it. Shale used in electricity plants.

Spatial energy density remains relevant (but less so for PV/wind than for biomass because it requires less energy to move electricity from PV/wind than to move the feedstock for biomass).

Safety/cleanliness are "quality" aspects with immediate impact, consequence. By contrast CO2 emissions have little direct impact. In other words, climate change is not the same as prior forms of air pollution.

Peter Pearson

The British gas regime – coal gas lighting industry in 19th century - developed as offshoot of existing technology: the distillation of "pneumatic chemistry". It was aided by coal-based economy and scientific knowledge and mechanical skills of era.

From distributed standalone model to urban piped network; the network was developed by German merchant Gas Light and Coke Company which was the world's first public gas supply company, focused on gas sales. It drew on path-breaking, integrated, tightly coupled network in London that existed even before the railroads. From this point on, there was a rapid spread of the gas supply networks in Britain. In 1829 there were 200 companies.

First transition: Market-led transition, government and state enabled environment where inventors and manufacturers could flourish. However, there were growing concerns about quality of service and reliability by the mid-1800s. Because of growing disruption of streets, and concerns around monopoly power, there was a push for regulation, which came in the form of the gasworks Clauses Act. By 1882, 490 private or municipally owned firms existed. It's worth noting that all of these firms were seeking profits, even the public ones.

Second transition:1880-1914: Services broadened, and the industry expanded the consumer base, cut costs and raise quality. The industry extend services from lighting to heating and cooking (lady demons adverts). Broadened consumer base by pre-pay slot meters and hire purchase. Worked to cut costs. Eventually used more efficient incandescent mantles. By 1914, working class users in their millions.

Third transition:1915-1947: Despite rapid growth, the industry is increasingly fragmented and somewhat dysfunctional. By the Late 1930s, it is the largest gas industry but disorganized and not competitive, expensive. By 1941, senior industry person called it incoherent industry.

Fourth transition:1948-77: state-led re-organization. Post WWII, the Labour government brought idea of nationalizing energy industry and now we have state-owned companies led by Gas Council with 8 area boards; distributed structure, rationalized industry and reorganized with vertical integration. Industry accepted that it was challenged and tried to address problems on demand and supply sides. They tried various things including promoting central and space heating services (60s) and experimented with niche technologies: coal gasification; gas from reforming oil; and imported LNG to meet peak loads (Louisiana, then Algeria). In the end, coal and gas industries both agreed that gas from reforming oil was a bad bet.

In the 1960s, North Sea Exploration was showing promise. The Gas Council was involved in exploration and was the monopsony buyer in UK natural gas regime. By 1966, Council converted entire system to natural gas; reorganized industry and developed lng terminals and built national grid from LNG backbone pipeline. The Gas Act of 1972 reinforced the centralization of the regime and the state-led transition. It took 10-years to complete the challenging appliance conversion to natural gas from coal (as a feedstock). It was very difficult because they had to go into every establishment and household and engage with users in way industry never had. The switch ultimately paid off.

What is interesting in this transition is that it was a State-led response, it recognized challenges and opportunities in markets and the associated costs; it undertook extensive R&D and allowed niche experimentation; and it even took risk in converting end-use technology. And even if it was successful, it did leave stranded hundreds of town gas production assets.

Fifth Transition:1978-2000: Return to the market: with 1970s oil price shocks, liberalization and free market economics movement, there was another shift in policy. In 1979 Thatcher was elected and the first industry she privatized was gas. The industry wasn't broken up though; British Gas was sold as a vertically integrated monopoly in transmission, supply, and distribution of gas. New regulator was appointed.

By 1990, privatization accelerates: State-owned Central Electricity Generating Board split into duopoly, regional electricity companies bought into Combined Cycle Gas Turbines, operated by them and IPPs, and facilitated by regulator wanting competition. By 1995, 15 CCGs expected to come online, displacing coal in "dash for gas".

Had major effects on UK CO2, SO2, and NOX emissions and meeting international obligations. Up until that point, the UK was feeling squeezed (known as Dirty Man of Europe). The dash for gas, though not done on environmental grounds, led to a significant shift in UK policy stance and made it more bullish on climate goals. That said, some suggest that having made that change, UK relaxed a bit because it was so easy.

6^{th} Transition: the Low-Carbon Transition?
UK pathways to meet 80 percent GHG targets suggest need to go from gas as heating fuel to: electric heat pumps, biomass boilers, etc. Correspondingly, there is pressure from UK and international gas industry to enhance gas industry. Whether or not that is compatible with climate goals will depend on speed/nature of move to renewables and the success of CCS.

Carl: What was Thatcher's role in transition from coal to gas and, to what degree, was her adversarial relationship with the unions (throughout the 1980s) a factor?

Pearson: I would say that it played a part but ultimately was more of a coincidence, the coal and gas industry needed to change.

Shellenberger: What do experts think will be the role of new end uses in pulling new energy supplies into market? They weren't a factor in the shale revolution but were in other transitions such as cars, steam engines.

Pearson: In lighting it has been particularly important in UK and internationally; it is one area where technological change in end-uses is most striking. Major improvements in reducing cost of light came from efficiency and end-use conversion. In transport and heating, it hasn't been as much there. With each transition in lighting, you could observe improvements in cost and quality.

O'Connor: Shale goes to electricity so the quality aspect isn't going to be felt, isn't important even if it is important from an emissions perspective.

Jenkins: Ultimately, it is the characteristics of energy carrier that determines end-use. Evolution of end-uses is tied to intermediate carriers. However, climate change is related to the quality of fuels, which historically has not been an important driver of energy transitions. In other words, the historic precedents are not like what we're trying to do now.

O'Connor: If you're seeking reduction of emissions, then you've got a problem. It's not clear that current tech (low-carbon) is offering that much extra, in terms of advantages, than existing.

Jenkins: Historical precedents for transitions similar in kind to the one we're hoping to achieve are more recent and mostly policy driven and often a question of resource scarcity.

Nordhaus: O'Connor argument that spatial density matters less for wind and solar, as opposed to biomass, is contingent on existence of a grid.

Pearson: Yes and there is a real challenge there. In some analysis we've done, even the high integration of renewables scenarios still necessitate a grid. But the grid isn't earning as much money as it would be in centralized system so the question is how to balance the systems.

Newell: 1) We should include in the discussion of transitions the movement toward electrification, not only changes in primary fuel source question. Electrification has given rise to new end uses that aren't more feasible with other energy sources so we can rely on electrification to drive the transition. 2) We haven't talked about scale. As scale of energy consumption increased, meeting these vaster quantities (if they tried to do it through wood) becomes impossible and encouraged transition to coal 3) When talking about transitions, we often focus on shares but thing that's most striking is all of energy sources have gotten bigger, nothing has gone down. All layered on top of each other. For issues like the environment, the absolute scale is what ultimately matters.

O'Connor: The point about scale is important. The Pony Express effect: when certain technologies demonstrate an appetite for a new energy service, they can make themselves irrelevant/obsolete because of increasing scale. Scale matters a lot.

Taylor: 1) Jesse point on transition based on quality of fuel; certainly in the case of air pollution, policy drove the transition and was reactive to the excessive pollution through clean air legislation. 2) Consumer acceptance of new end-uses is an important point and I wonder if demonstration – adoption is easier for front-loader? Or End-loader? 4) We also have to understand the infrastructure for supply.

Watson: I want to make two points. 1) Not all problems will concern shit in energy end use or quality of fuel, for instance the challenge of storage is neither one nor the other. It's not a benefit to user really. What's the role of storage? What type of feature is that? 2) On gas as bridge: what we found in our modeling analysis is that in the US, you could expand until a certain point, consistent with the 2-degree target. In the UK, the case is less clear and it will depend on how quickly it can be ramped up and improvements to CCS.

O'Connor: Storage is essentially a carrier. Batteries have spillover benefits – storage not to decarbonize but to allow people to use their phones everywhere. Other kinds of storage could be enabling tech for renewable, but I don't think it's end-use driver in the same way.

Pearson: On storage – storage was major part of UK gas industry and when they brought in LNG, there were big storage issues. One of the challenges of the switch to gas is that you were storing twice as much energy. Modern problem is that no actor in the energy sector really has the incentive to build storage units.

Carl: One of the things that strikes me, and surprises me, is that scarcity didn't play a uniform role in energy transitions – or implicit scarcity. Which just shows that looking at oil prices for signs of a shift to renewables is quite naïve.

O'Connor: Certainly the history of energy transitions suggests it's more of a substitution curve, rather than a resource depletion curve.

Nuvolari: What Pete O'Connor showed us was aggregate data, I'd be curious to find out what these transitions look like on a sectorial level. One is likely to find much more heterogeneity when looking in the chronology/timing of these transitions from the perspective of individual sectors (manufacturing, transport, etc.)

Shellenberger: Is the assumption of people in the room that we are going to renewables; is that a fair assumption? Is nuclear dead?

Pearson: I certainly didn't want to suggest that renewables are the only way forward. Ultimately low-carbon is low-carbon and I don't want to privilege one source over another. In terms of nuclear, I think the costs are a pretty substantial problem.

Shellenberger: And what do people think of the hydrogen economy?

Pearson: If we are talking of hydrogen as a carrier, it may be useful and we shouldn't rule it out but I'm not a true believer in the 'hydrogen economy'.

Newell: There is some fuel cell optimism among major industry players; there is significant bifurcation in views between electrification and fuel cells in the auto industry. Time will tell who is right, or maybe we will have competing platforms.

Kash: Looking at economic drivers – I'm skeptical. One of the interesting things about yesterday is that many of the people who were driving the shale revolution weren't people who were going to make money; they were technological artists who were passionate about what they were doing. For these people I was struck by how often the factors that cause people to drive technological change are best summarized by the desire to make it better. Clearly economics is important but it is only one factor.

Session 6: Putting the Pieces Together

Shellenberger: This last panel will give us an opportunity to reflect and answer any questions you all have. We'll also discuss potential new projects and follow-ups to this workshop.

Nordhaus: I'm struck again by the complexity of the case. Every time we think we've gotten to the bottom of it, we discover some new element. It raises the question of whether we can ever truly get to the bottom of case studies like these.

I'd also emphasize that the conventional wisdom about what was likely to be a breakthrough in unconventional fuels turns out to have been totally wrong. All the confidence and money was in tight sands and coal gasification, yet it is shales that have turned out to be the most productive.

A key lesson seems to be that the innovation systems that you create are ultimately the thing that really matters. That means you need to make a lot of shots on goal; not just for VCs but in the public sector as well. You need a willingness to fail and engage a diverse portfolio of bets.

For our own part, Breakthrough has gone through its own evolution in understanding innovation systems. To years ago we led the movement to advocate for $300 billion spent over ten years in clean energy innovation. Now we are much closer to understanding how difficult and complex innovation systems really are. This has actually increased our skepticism that any schedule or target will guide our emissions reductions. It's all going to be based on technological trajectories – all the more reason to make the best innovation system you can make, make lots of bets, make it work internationally, and hope for the best.

Shellenberger: I want to discuss a paradox that has been made clear in this case study: the short-term urgency of the funding agencies combined with the long-term commitment to vision. It also seems that being marginal and in the shadows had a protective effect on both the entrepreneurs and the public researchers. They were doing things that, seen in the light of day, might look like rent-seeking to policymakers. Of course there was lots of pressure as well – enormous pressure on Dan [Steward] and Nick [Steinsberger] from the [Mitchell Energy] CEO while being protected by Mitchell himself.

O'Connor: I thought the IP/patent aspects were very interesting. Franklin didn't patent his stove, whereas Watt did patent his steam engine, which delayed the diffusion for decades until after the patent had expired. I'd also note that government research in this case was often open-source.

Nuvolari: You need to leave the space open for something like the shale revolution to happen again. The IP piece is critical. The low-IP environment was essential to allowing the agents to interact fruitfully. On funding, there was space to let the plurality of agents work without pretending to orchestrate everything. There's a need to create a diversity of these institutions with different kinds of technologies. That could be quite useful. All in all this case is humbling, but also refreshing.

Keller: This case fits encouragingly within the broader innovation scholarship. I'd pick out a few core lessons. The first is on how the government involves itself in a complex technology and a complex production environment. Decentralization is important. Support multiple pathways, sometimes even multiple pathways in the same technology. The market is also important. There has to be a connection to actual needs and problems. I'd also agree on the importance of these "bubbles" in which people are protected from the market and which enable collaboration.

Burnett: Complex technologies result from networks. It's funny, I've been working in the space all my life, and I have never heard until this meeting of "innovation scholarship." I'm not making fun of it. I'm excited by it!

I disagree slightly with Margaret [Taylor] on how important money or entrepreneurship is. Aubrey McClendon was inspired by making money.

The term "CCS" has come up a few times in this meeting. I'd just say that burying carbon is an inefficient way to solve the carbon problem. In South Carolina, Boeing is building airplanes out of carbon. Why don't we create a market for carbon?

I can say a few words about the demise of GRI. If GRI was so good, what happened? The industry was being deregulated in the 1990s, so there's a large tendency to blame deregulation for what happened to GRI. That's not quite right. In my view, the disintegration of the industry – producers, pipelines, and LDCs – in thinking they had any kind of common ground played a much bigger role. The different entities lost the ability to share common ground over R&D.

There was also the end-use problem. We had lots of pressure to increase end-use research in order to increase demand for natural gas through new end-use technologies. Large opponents of GRI – the Iron & Steel Institute, fertilizer producers, and the like – did not want us to increase demand for natural gas with new technologies. With increased demand comes increased prices. So these folks came after us in our annual review. They were after use throughout the 1990s. At a certain point, we gave up, and created a monumental settlement to create a 7-year end to the funding unit. That was 1997. By 2004 there was no more funding from the pipelines.

We looked for other funding sources. We looked for funding from royalties and patents. We tried to use the federal royalty trust fund for a while. We took ownership in companies in an attempt to become an incubator (Pinnacle was one of these companies, Capstone was another).

The problem is that you can't live off the royalty system if you're trying to invest in a basket of technologies. The boards of directors decided we should merge with the Institute for Gas Technology, and we did and we became the Gas Technology Institute. GTI gets funding state-by-state from gas distribution companies. They hired me later to develop a plan to go back to the pipelines for funding. But GTI wanted funding for end-use research, and I told them they would never get a penny for end-use, based on my experience in the 90s.

Gallagher: I would note from this case that practical problem-solving turns out to have been so important. There was also the importance of leadership, at Mitchell, at DOE, and at the Labs. The complexity of the case is really striking. Such a unique set of circumstances makes it really hard to generalize from the case.

Kash: We live in a society structured by innovation-to-obsolescence cycles. The winners are the people who get the innovation done early. And our society is one where innovations are mostly incremental and the networks that carry out innovations are characterized by inertia. That is, they immediately start pursuing the next innovation once they have succeeded with the last.

While entrepreneurs can be terribly important, they're rare as hens' teeth. The George Mitchells of the world aren't all that common. If you expect to be successful in energy with entrepreneurs, you're in trouble.

If you expect to be successful in this ballgame, the best model to look at is the Department of Defense. DoD has turned out more innovations than any other system in the world and they do it with B+ engineers. It's not dominated by intellectual giants. It's run by military people who actually have a reputation for being rigid and populated by average people.

Shale gas was the product of a system. Not matter what system you look at, there's a policy network behind it. One of the greatest problems with innovation today is equity-funded companies that have to perform on a quarterly basis. No matter where you are in that system when things get tough, one of the first things to go is R&D. You can't have an initial innovation system if you have to have profits go up every quarter.

Watson: I agree with Don [Kash's] point, which makes the case for government, if you get it right. The question is, can we expect to get breakthroughs while spending the relatively modest amounts of money that was spent on shale? GRI is an exceptional example. I was reminded of UK example, the Low Carbon Networks Fund. It's accomplished by regulated funding from the power grid for smart grid technologies. A point on political economy. Shale gas has obviously become very contentious. Even in the case of it being developed, how did all this happen while it challenged oil and gas companies? How did coal let this happen?

Burwen: I don't want to just repeat everyone else who has made note of all the idiosyncracies in this case, but it really was idiosyncratic. There are numerous things that happened in this story that defy our expectations for good innovation policy.

Political interference by Senator Byrd.

Shale gas enjoyed a relatively minor share of the R&D budget.

There was a lack of labor mobility. Low gas prices made a cohesive team at Mitchell because people couldn't leave.

The was a lack of geographic scalability. Lack of scale isn't something that you usually think of as fostering innovation. But it created more willingness for open sharing.

Taylor: Outside of energy, some of Jason's points do resonate. I'm reminded of the case of steamships and sailboats. Even in the presence of a step-wise technological step forward, the older incumbents continue to innovate and find new markets. Just because there's a new technology, you can still find a way to make the old one work. The internal combustion engine always seems to come back, even in the face of air pollution standards. So don't write off innovation in the incumbents. We haven't talked enough about process versus product innovations. We don't patent as much in process technologies, so we should expect to see a higher role for tacit knowledge in a case like shale. We see this in a lot of industries. Shale gas in inherently a process. It's an art to each formation. In addition to the failure of the quarterly time frame, access to capital comes into play. Angel investors, VCs, etc. Under-the-radar R&D. DOE has reorganized so many times, often in an effort to centralize that actually makes people targets.

Jenkins: When I first left Breakthrough for MIT, I thought of my work as policy engineering. Now I think of my work less as engineering and more as ecology. Machines don't change; they're cause-and-effect. We may wish we had the same type of engineering ability in policy or innovation, but we don't. It's more like ecology. These systems change and adapt over time. You can't step in the same river twice. You have to keep adapting your policies and interventions. There's a need to be humble just like in ecological intervention, but not so humble that we don't think we should make any intervention. We need to thing more about things that tend to work and be patient when they don't. Unfortunately, politicians sure want machines and not fuzzy institutions.

Crawley: I think we may be giving [Sen. Robert] Byrd too much credit. If there had never been an ESGP, Mitchell would have developed his program. Much of the work came out of the Advanced Petroleum Technology program in DOE. There was lots of National Labs work as well.

Shellenberger: So is the 1975-2000 innovation system still in place, or are we over disciplining innovation today? Do we need a GRI for these other technologies? Do these institutes exist? It seems today the industry associations tend to concentrate on lobbying for deployment subsidies.

Jenkins: I'm hesitant to say that we need a GRI for everything. That feels too simplistic. We can glean insights from the GRI process that we can use to reform our current system. We need somebody to play the role of network creator/sustainer against challenges from incumbents. We need to balance funding. The importance of the portfolio of path that cuts across the innovation system. Science, R&D, and diffusion aren't separable. GRI simply tackled technology problems.

Burnett: There is a literature out there on other consortia. One case is the Advanced Battery Consortium. There are other cases where a GRI-like organization with some independence about how it spends its money and has a mandate to spend with industry input. They're not separate from politics, but they have come independence.

Flegal: There needs to be a shift in the relationship between federal research and the public in order to foster mission-oriented research. Need to build more trust between the public and the research community. And as Jane Long was saying, we need to consider more robust, earlier, and more proactive regulation of novel technologies to foster social license.

Hanold: I want to mention one interesting example of public-private collaboration in the oil and gas sector, which I think offers a good model for mission-driven R&D. It was called the Partnership Program and was headed by Dave and I. It created a novel way for national labs-industry interaction, it was initiated 1988 with 2 labs, 4 projects (oil funds) but grew by 1994 to 4 labs, 20 projects (oil and gas funds) and peaked in 1995-98 to 9 labs, >50 projects (oil, gas, defense, energy research funds). It lasted through 2005 - 18 years, very long duration for a DOE program but was ultimately killed by George W. Bush. The Objectives of the partnership were to transfer technologies from DOE weapons & energy programs to industry and develop innovative ways to interact with industry to expedite this transfer, and utilize industry guidance to ensure industry needs are addressed. The Partnership's underlying principles were flexibility and industry driven, it had a) active industry interfaces - industry review panels; b) joint national lab-industry participation for all projects; c) flexible agreements only as necessary - informal to formal; d) flexible cost sharing - DOE funds labs, industry fund their efforts (ie no cross over of funding); e) simple and concise procedures: labs handle interfaces with DOE, 2 page proposals, 30 min presentations before industry review panels, each reviewer completes 1 page evaluation per project that day, industry rankings decide (consistent with funds and DOE approval, which we almost always got). The Partnership existed for 18 years. That's unheard of! Why did this happen? Industry like what we were doing and things were being produced that had a future in the energy industry.

Warpinski: We may be overcomplicating the innovation in the shale revolution. It was 18 years of George Mitchell's perseverance to get to waterfracs. It would have happened eventually without microseismic; it was driven by one person's persistence.

Northrop: The Partnership projects were often focused on mapping and understanding the geology and just to push back a little against what Norm said, let me read the names of 10 projects that we funded:

- Multi-station seismic receiver
- Microborehole seismic instrumentation
- Advanced borehole telemetry systems
- Wireless telemetry tool
- Fracture mapping and slimhole geophone array
- Advanced synthetic diamond drill bits
- Tiltmeter hydraulic fracture imaging
- Increased effectiveness of hydraulic fracturing through adv. computational tech.
- Testing advanced computational tools for 3D seismic analysis
- New methods of modeling and processing seismic data

Mitchell Energy participated in the last two of these. All these projects were Lab-funded; industry brought their own people to the table and funded the industry side of things.

Burnett: Generally speaking, the industry funding was drilling the well and allowing us to put stuff down the well. By the late 1980s, it was $20 million from us, $10-20m from DOE, another $20 of "in-kind" funding from industry. This wasn't shale research; we were funding technologies.

No doubt that you need a George Mitchell, but I'm a technology believer; if those technologies had not been there, George Mitchell might have gone broke and there'd by no story or books now. It might have failed without this bundle of knowledge.

Mitchell wasn't just an entrepreneur; he was very intelligent and he wasn't just lucky; he got involved in these technologies. As an example, he joined our board of directors in 1988 so he could influence our direction (as well as other industry executives on the board). But I'm reluctant to simplify it as simple as Norm did.

Jenkins: You need an appropriately risk-tolerant pool of capital; Mitchell provided that for quite a long time. We can think about ways to de-risk the process; FDA's staging of the process for instance, similar to Mitchell selling to Devon. How do we trace the various sources of capital and how were they influenced by the potential reward and how did this influence their patience?

Nordhaus: So what do we all thinks are the next steps, including the release of our paper? We'd love comments, peer-review reactions formally or informally. We're also potentially interested in follow-up workshops to expand out from the shale case study to broader questions about energy, the environment, and the economy. Are folks interested in reconsidering the role that energy plays in the economy and as a driver of economic growth? Is it like any other input? Experience suggests energy is different than copper. We also want to explore "Green Growth" — what does that really mean? There's good reason to suggest that green jobs and a clean energy economy would be solar panel job creation; but now we believe this profoundly misunderstands how energy works in the economy. Long-term drivers of growth have also been drivers of decarbonization, land-sparing, etc.

Shellenberger: This case presents some tough questions around the pace of decarbonization. It took a long time to create a low-cost, low-carbon alternative and it's taking a long time for gas to replace coal. We're looking at a pretty slow pace of change. It's worth considering the implications of that for climate/energy policy.

Gallagher: Charlie Wilson and I have spent a lot of years talking about pace — can you accelerate the pace of energy innovation? Hard to understand, which is why we haven't written anything yet! It would probably be worth a workshop to generate the right ideas.

Bozmoski: We need to apply these lessons to folks not in the room. Who are the rogue renewable energy guys who are willing to reconsider the deployment subsidy strategy, or would be willing to participate in a mission-oriented paradigm for RD&D? We would need a technology-neutral setting.

Jenkins: I'd caution against technology neutrality. We can't design policy neutrality. I'm worried about feeding the "don't pick winners" attitude on the Hill. It does take a long time for the innovations to come together, but if you look at the deployment rates of a truly zero-carbon technology, then the emissions reductions would look better than the case of coal-to-gas.

Watson: Tech neutrality is important. And it's not just a technology speed story; technology in the context of institutions and social change.

Pearson: These are socio-technical issues. They need deep breadth of understanding. I support the notion of thinking more about energy and economic growth; the literature is remarkably underdeveloped. Economists and economic historians struggle to understand the contribution to growth that energy provides in economic growth.