ENERGY INNOVATION AND FRACTALS

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Thank you for the invitation to speak today. Congratulations on your new battery lab and the renovation of your building.

This university has a rich tradition of energy research. After World War II, the University of Michigan launched the Phoenix Project, a nuclear research laboratory established to support the peaceful uses of atomic energy. Your location in the heart of the United States' automotive industry has helped make the University a world leader in transportation research, on wide-ranging topics including high energy density batteries, biofuels and traffic patterns. Your work on solar power, grid integration of renewables and other topics has won wide acclaim.

In this work and more, you are advancing knowledge and contributing to change in a sector that shapes all our lives. Modern life depends on energy systems. Energy issues play a central role in many of the great economic, environmental and security challenges of our time. Continued innovation in energy technologies will be central to meeting these challenges. We'll need universities such as this one to ask fresh questions, work across disciplines and consider new approaches.

That brings me to my topic today: energy innovation and fractals.

Now I suspect many of you are asking one of two questions:

> First, some of you are asking: "What's a fractal?"
>
> Second, almost all of you are asking: "What do energy innovation and fractals have to do with each other?"

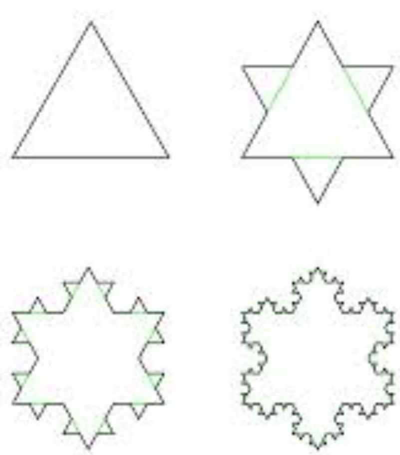
Let me take each question in turn.

FRACTALS

According to the American Heritage Science Dictionary, a fractal is a "geometric pattern exhibiting self-similarity in that small details of its structure viewed at any scale repeat elements of the overall pattern." A website devoted to fractals writes: "A fractal is a never-ending pattern. Fractals are infinitely complex patterns that are self-similar across different scales."

A classic fractal is the set of triangles below:

Another classic fractal, known as the Koch snowflake, is the following:



In each set of figures above, a pattern is repeated. (In the first, the middle part of each black triangle is replaced with an inverted white triangle. In the second, the middle part of each line segment is replaced with two sides of an equilateral triangle.) These patterns could be repeated indefinitely.

The term "fractal" was first used by the mathematician Benoit Mandelbrot in 1975. Building on antecedents dating back hundreds of years, Mandelbrot launched the new field of "fractal geometry." At his death in 2010, a fellow mathematician wrote "if we talk about impact inside mathematics, and applications in the sciences, he is one of the most important figures of the last 50 years." The science writer Arthur C.

Clarke was even more effusive, describing Mandelbrot's work on fractals as "one of the most astonishing discoveries in the history of mathematics."

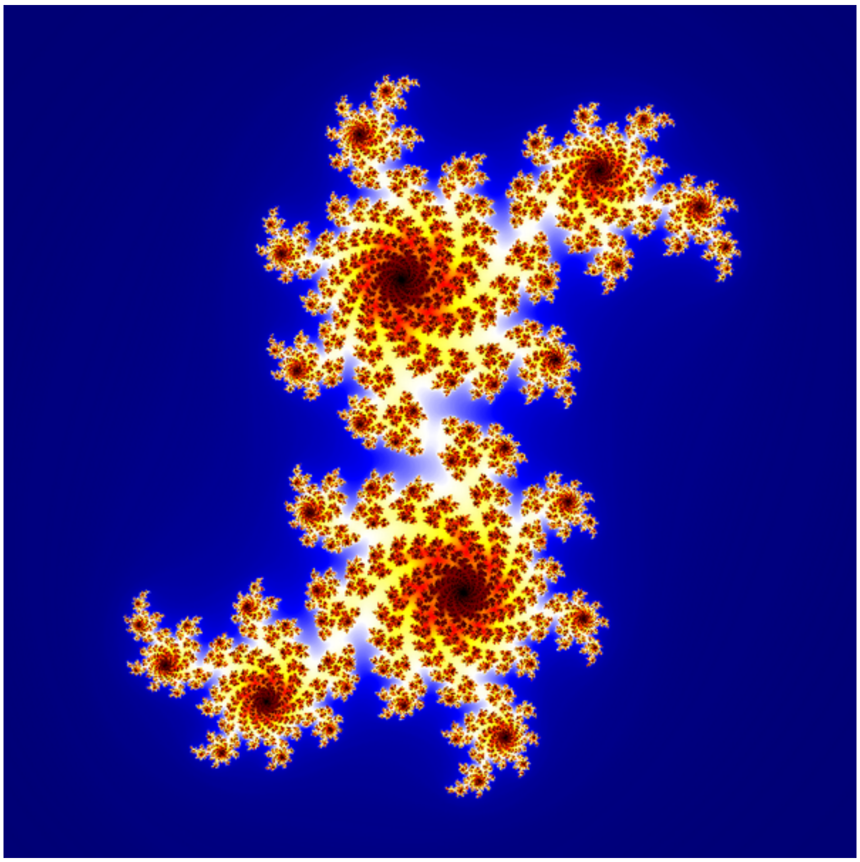
Mandelbrot's work on fractals has attracted wide interest in many areas. Scientists are exploring the fractal nature of many natural phenomena, including clouds, coastlines and the leaf below:

Fractals are used widely in financial analysis. In the words of one writer:

> "Financial markets are fractal…[I]t is impossible to look at an unlabeled price chart and determine whether it is an hourly, monthly, or even a 5 minute chart of the trading action. They all look the same. Markets are fractal."

Consider the following graph (of daily S&P 500 data from 2012 and 2013):

The aesthetic qualities of fractals have also captured widespread interest. There are many books and websites devoted to fractal art, with images such as the one below:



ENERGY INNOVATION AND FRACTALS

So what do energy innovation and fractals have to do with each other?

Today I'll explore three connections and, in the process, offer reflections on the state of energy innovation today.

Tool in Energy R&D

First, fractal analysis is being used as a tool in energy R&D. Researchers are using fractal geometry in their work on diverse energy technologies, from photovoltaics to fuel cells to carbon capture.

For example, a team of physicists and chemists from the University of Oregon is exploring ways to use fractals to improve solar energy conversion. The team hopes a better understanding of fractal branching patterns can help optimize collection of sunlight, improving the efficiency of solar panels. According to the project abstract, the team plans:

> "1) to simulate the electrical properties of solar devices with a fractal geometry in order to predict the fractal parameters that will provide efficient, novel solar devices; 2) to synthesize new inorganic clusters for use as inks for solar materials; and 3) to unite these two thrusts in the design of new solar materials with fractal geometries predicted to have properties mimicking the light-harvesting fractal patterns found in Nature."

Another team is looking at whether fractal structures can allow ultra light materials to support heavy loads. These materials would have many potential applications in energy technologies, from vehicles to building systems to wind turbines.

In addition, wind speeds are fractal. (Monthly and daily fluctuations in wind speed display the same patterns as fluctuations at hourly and shorter intervals, as confirmed by data from many locations.) That has implications for technologies that help utilities manage variable output from wind turbines.

Indeed a search of the U.S. Department of Energy's Techportal website, which offers information about intellectual property available for license, patents and patent applications, identifies 58 patents and applications that use the word "fractal." (They have titles such as "Process for applying control variables having a fractal structure" and "Methods for non-referential defect characterization using fractal encoding and active contours.") Not all of these patents and applications make central use of fractal geometry and not all relate directly to energy technologies, but the number of references in this DOE database suggests that fractal frameworks are making their way into the thinking of energy innovators.

<u>Framework for Institutional Analysis</u>

Another connection between fractals and energy innovation is institutional. A growing literature explores the fractal nature of institutions: In what ways are institutions similar at different scales? In what ways are they different? Are there lessons to be learned from understanding these similarities and differences? Would some large institutions be more effective if managers deliberately sought to promote "fractal" qualities, replicating in the institution as a whole characteristics that define smaller units within it?

Several thinkers have begun to ask these questions about institutions for energy innovation in particular. In an interesting paper on institutional issues in energy innovation, three scholars at Harvard's Kennedy School (V. Narayanamurti, L. Anadon and A. Sagar) suggest:

> "there are certain features for the management of innovation institutions that are important at every scale: from the individual researcher, to a research group, to divisions, and the overall institution…These features…could be thought of as fractal characteristics."

Another writer (B. Lum), discussing innovation within large companies, notes that

> "Innovation as a cultural characteristic starts with each person and before [innovation] can become systemic it has to grow from one person to two, two to four, four to eight and so on…Like a fractal that is governed by a formula and a set of parameters, the formula for innovation to take hold will depend on the individual's initiative and the supportive environment."

Work in this area is interesting, but preliminary. More work is needed to evaluate the potential for fractal frameworks to assist in designing and managing institutions for energy innovation.

<u>A Helpful Lesson</u>

So fractals are being used as a tool in energy R&D and may offer insights on institutional issues related to energy innovation. There's also a third connection: *The history of our understanding of fractals offers a helpful lesson about the potential for energy innovation today.*

Energy systems change slowly. It took a century for coal to replace wood as the principal energy source in the US. It took another century for oil to replace coal. As energy experts often remark, the technologies used in today's electric grid would be mostly familiar to Thomas Edison, who died in 1931. Solar and wind power first became a focus of national energy policy in the 1970s, yet provide less than 5% of U.S. electricity today.

The contrast with some other sectors is striking. A century ago, almost no Americans listened to or watched electronic media of any kind. Since then, successive waves of new technologies -- from radio to movies to television to personal computers to smart phones with streaming video – have moved to market and changed lives. In 1990, there were roughly 11 million cell phones on the planet. Today there are more than 6 billion. Twenty years ago, few Americans even imagined a device that could locate you within 50 feet anywhere on the Earth and give you spoken instructions on how best to drive to your destination. Today, anyone can buy a GPS device for less than $100.

Why have energy systems changed slowly? In part, because energy assets tend to be long-lived. (Coal-fired power plants often last for more 50 years. Cars in the U.S. are on the road for an average of roughly 12 years.) In part, because of under-investment in R&D. (The electric utility sector invests less than 0.5% of its annual revenues in research and development.) In part, because incumbent industries often wield substantial political power and resist change. The physicist and energy thinker Steve Koonin summed up the relevant factors as "scale, ubiquity, longevity, interdependence and incumbency"

Yet interestingly, in the past half-decade, technologies in two areas have defied the general rule concerning the slow pace of change in the energy sector.

- The combination of hydraulic fracturing and horizontal drilling has transformed the U.S. and global energy markets, making vast reserves of natural gas economically recoverable for the first time. Shale gas production in the US went from less than 3 billion cubic feet per day in 2006 to more than 26 billion cubic feet per day in 2012 (roughly 40% of U.S. natural gas production).

- During roughly the same period, the cost of producing solar panels dropped by 80%, from roughly $4 per Watt in 2008 to roughly $0.70 today.

Both these innovations are bringing disruptive change to the energy industry, despite the factors discussed above.

- A decade ago, construction of natural gas import terminals was underway up and down the U.S. East Coast. Today, more than a dozen companies are seeking approval to export U.S. natural gas. For most of the past several decades, roughly 50% of U.S. electricity generation came from coal and roughly 20% from natural gas, month after month with little variation. Yet in one month last year, the shares of coal and natural gas were almost equal (at roughly 33% each).

- With the cost of solar panels so low and continuing to fall, orders are booming and valuations skyrocketing at some solar installation companies. Due to falling cost of solar panels and other factors, many experts are predicting transformational change in the U.S. utility industry in the decade ahead.

Have we entered an era in which the pace of change in the energy sector will quicken?

I believe so. Which brings us back – soon -- to fractals.

The inventor Ray Kurzweil writes about a “law of accelerating returns” when it comes to technological change. He notes that innovations from ancient times, such as stone tools, took hundreds to thousands of years to be widely-deployed; innovations from the Late Middle Ages, such as the printing press, took a decades to a century to be deployed; and some innovations from the 20th Century, such as the Internet, achieved mass penetration in years or decades. Kurzweil writes that “innovation is multiplicative, not additive.”

Why is that so? A vast popular and academic literature explores this topic. Among the most interesting observations are those from the author Steve Johnson, who highlights the role of “liquid networks” in facilitating innovation, noting that “individuals get smarter when they’re connected to the network.” Prof. Henry Chesbrough’s seminal work on “open innovation” notes a similar phenomenon with companies, which innovate more effectively when working with others than working alone.

We live in the era of the expanded possible. With billions of personal computers and smart phones connected in a global network – and powerful supercomputers -- the potential for energy innovation far exceeds anytime in human history. Many of the barriers that have slowed change in the energy sector remain, but disruptive innovations are far more likely to take aim at those barriers than ever before.

Consider -- by way of comparison -- the history of our understanding of fractals. Many of the core insights in mathematics date back thousands of years. Calculus dates back hundreds of years, to the dawn of the Enlightenment. Fractal geometry is a new field of mathematics -- which didn’t exist when I graduated high school. As the mathematician Stephen Wolfram wrote:

> “One might have thought that such a simple and fundamental form of regularity would have been studied for hundreds, if not thousands, of years. But it was not. In fact, it rose to prominence only over the past 30 or so years.”

It’s no coincidence that fractal geometry was born at the dawn of the computer age. Although work on recursive functions and other precursors to fractal geometry date back to at least the 17th Century, in the 1970’s Benoit Mandelbrot was able to prepare visualizations of those functions with tools unavailable to his predecessors. Mandelbrot’s genius and computer graphing tools combined to produce a startling intellectual innovation, with wide-reaching applications in mathematics, the sciences, financial markets and more.

Mandelbrot's breakthrough highlights the potential for energy innovation in the decades ahead. New tools offer the potential for breakthroughs in energy technology, even greater than those we've seen in shale gas and solar panels in recent years. Those breakthroughs could have far-reaching and unforeseen consequences. We cannot count on such breakthroughs, but we can shape conditions that make them more likely. We can also continue working on steady, incremental improvements, which may come more quickly and have more impact than in years past.

What implications are there for public policy? That's a topic for another speech and further research. But it's interesting to note that the U.S. federal government agency most widely-hailed for its success in energy innovation is ARPA-E, a small unit within the vast U.S. Department of Energy (DOE). (ARPA-E's tagline: "Changing What's Possible.") As a result of that success, one question DOE managers and others have asked in recent years is "how could we make DOE as a whole more like ARPA-E?"

That is a fractal question.