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A Sustainable Energy Economy: The Next Challenge for Systems Engineers

Preprint

Neil Snyder

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A Sustainable Energy Economy: The Next Challenge for Systems Engineers

Neil Snyder
National Renewable Energy Laboratory
neil_snyder@nrel.gov

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Abstract. The realities of shrinking fossil fuel reserves, growing global energy demand, and climate change concerns will force a change to a sustainable energy economy. Systems engineers need to take a leadership role in making the transition to this new energy economy. A study of large projects from the past provides some insights into methodologies that might be used to effect this transition; however, the complexity of the energy transition is far greater in some respects than on these earlier projects. The timeframe of this transition is measured in decades, the technologies involve numerous industries, and the spatial dimension involves the entire planet. Systems engineers will not only need new tools but will need to step into somewhat different roles than in the past. It is time to start planning for these new challenges, and INCOSE should play a key role in this planning.

Introduction

The world is entering a time of transition from a fossil-fuel energy economy to one powered by sustainable energy sources. This transition is being driven by large scale changes such as shrinking fossil fuel reserves, rapidly increasing energy demands in developing nations, and concerns over the impact of carbon emissions on global climate change. Specific issues relating to this transition are becoming more widely understood by the general public, but few comprehend the magnitude of changes that will be required in the coming decades. The projected changes in energy consumption from 2004 to 2030 are shown in Figure 1, while the growth in CO_2 emissions from 2003 to 2030 is shown in Figure 2; note that the Organization for Economic Cooperation and Development (OECD) includes 30 advanced countries. (EIA, 2007)

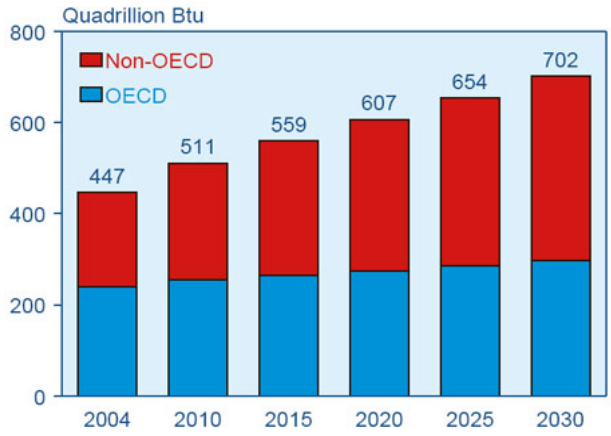


Figure 1. World Energy Consumption Trend

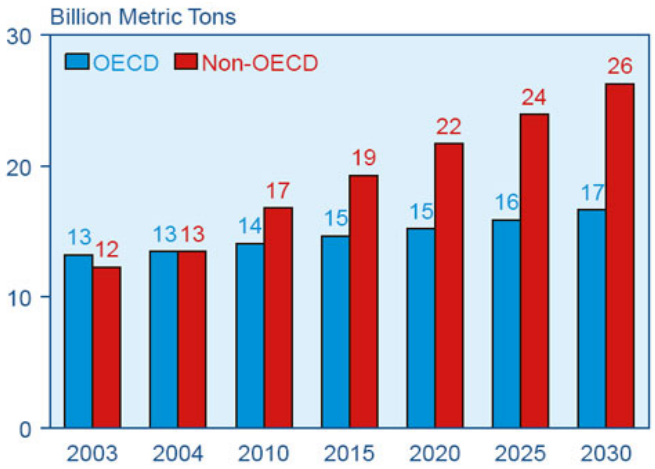


Figure 2. World CO_2 Production Trends

The energy transition is only beginning to occur, having been delayed by the availability in recent decades of abundant and relatively cheap fossil fuels. Despite the significant increases in fossil fuel prices over the past few years, current projections out to 2030 are for global fossil fuel use to increase at a faster rate than renewable or nuclear energy; see Figure 3. (EIA, 2007) By contrast, global oil and gas production are at or near peak, and will start to decline in the coming decades; the exact timing of these peaks is controversial, but past arguments that the peaks are far in the future seem to be disappearing. The Association for the Study of Peak Oil and Gas projects that peak production will occur around 2010; see Figure 4. (ASPO, 2007) It is not clear what type of supply/demand imbalance and resulting price increases will be required to cause a real movement toward sustainable energy, but whatever occurs will be a complicated political and economic situation. What can be reasonably assumed is that at some point a crisis mentality will develop, and rapid changes will be demanded.

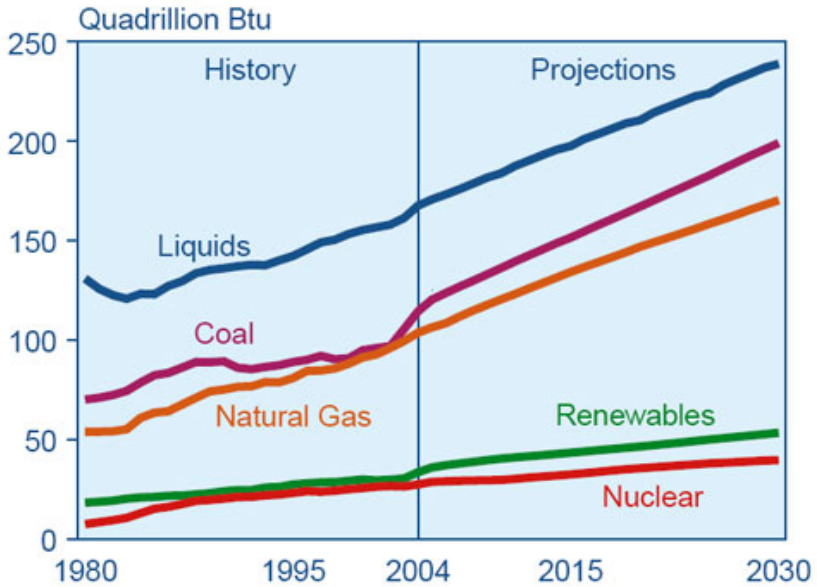


Figure 3. World Marketed Energy Use by Fuel Type

The coming changes will require new thinking across many fields, from international relations to public policy to microeconomics. However, the grand challenge will be the planning, development, and implementation of a new energy infrastructure on a global scale. A new generation of systems engineers will be needed to rise to this challenge. In addition, new tools and techniques will be necessary to deal with projects that have a far larger and more diverse set of stakeholders than in traditional aerospace/defense projects owned and funded by a single government or commercial entity.

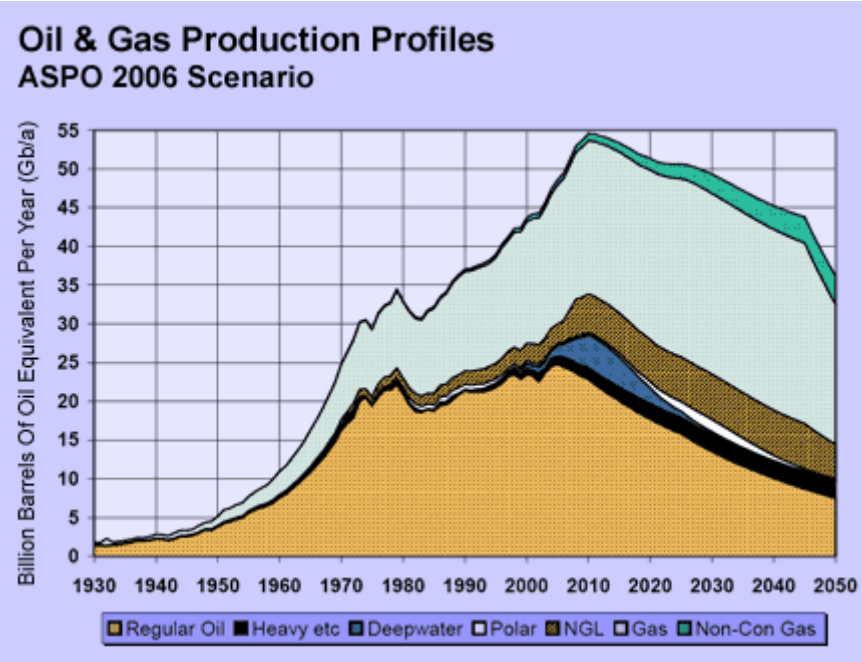


Figure 4. Oil & Gas Production Profiles

Historical Perspective

A reasonable first step in formulating a plan for dealing with a complex problem such as this is to consider comparable programs of the past. Five activities that provide a broad base of comparison are the basic development of our existing energy and transportation infrastructures, development of commercial nuclear energy, the Concorde supersonic transport, the manned space program in the 1960s, and the development of an information technology infrastructure over the past few decades.

Basic Energy and Transportation Infrastructures. The development of the energy and transportation infrastructure in use today had its beginnings in the 19th century, following the development of oil and gas resources. The development of the fossil fuel infrastructure, and the societal changes that went along with it, was a fairly slow process by modern standards. Automobiles did not become common until the early 1900s, airplanes in the 1930s, and jet aircraft in the 1960s. The electrical energy infrastructure developed in parallel at a similar pace. In the late 1870s Thomas Edison initiated the process of electrification, centered on interior illumination. Separate industries eventually developed, focusing on appliance and equipment manufacture, electrical production, and electrical distribution. The electrical infrastructure

evolved based upon centralized production, a concept which continues to this day. The transmission grids that could interconnect various generation plants and distribute the electricity widely to customers were developed in the 1920s. Throughout all this activity the electrification process was primarily conducted by the private sector, and financial considerations were among the drivers for how the process proceeded; however, without Federal intervention during the 1930s, electrification in rural areas might have continued to lag behind that in urban areas due to the difficulty in making it profitable. (Friedlander, 1996)

This infrastructure development can be described as an evolutionary process, not as a designed system. The primary entities in the development process were a variety of private corporations, not the government. The driving forces were typical market forces: the desire by individuals and industries for new products and services, and the desire of industries to provide them in order to make a profit. There was no overarching grand strategy to this development, nor was there a set of requirements or an architecture in place from the beginning. And perhaps most important, the infrastructure evolved over a period of decades rather than years.

Commercial Nuclear Energy. The concept of utilizing nuclear fission for commercial energy development was first formulated shortly after the Second World War. The initial technology development was performed by the government, but in 1955 the Atomic Energy Commission began a program to jointly fund nuclear power plants by both government and industry. Two years later, the first full scale nuclear power plant went into operation in Shippingport PA. During the following 35 years, most of the more than 100 commercial nuclear plants in the US were built, and at peak they produced nearly 22% of US electricity. Accidents at Three Mile Island in Pennsylvania and Chernobyl in Russia led to the curtailment of construction of any additional plants. (DOE, 2002)

The government contribution to commercial nuclear power was significant. The National Reactor Testing Station (now Idaho National Laboratory) was created in 1949, and since that time 52 reactors have been built and tested there. The development of reactors was for multiple purposes, especially the development of the nuclear navy, but the technologies for commercial plants grew out of these efforts. Because of security concerns about nuclear materials and safety concerns about unplanned nuclear criticalities, the government has always exercised a significant amount of control over nuclear industries; thus, even though private industry has invested huge amounts of money into commercial nuclear energy, the overall program must be viewed as a public/private partnership.

Concorde Supersonic Transport. The development of a supersonic transport (SST) aircraft occurred in parallel on both sides of the Atlantic, but in the end only the British/French Concorde made it to commercial service. British aircraft companies began looking at development of an SST in 1955, and in 1956 a joint government-industry committee was formed. This committee funded 400 technical papers on the subject, leading to a final report in 1959 that recommended development of two different versions of an SST. The concept of creating a joint venture for the SST was initiated in 1962, and in November 1962 an intergovernmental agreement between France and Britain was signed, with funding shared equally by both governments. The subsystem development was divided between companies in the two countries, and a daily air service was established to shuttle engineers back and forth to coordinate the development process. The first flight tests occurred in 1969, and the first production aircraft went into service in 1973.

The noteworthy feature of this program is that it was not only a government / industry partnership, but that it was also a partnership between two neighboring countries. Another feature is that this high-visibility program was not executed on a particularly ambitious schedule. About three years were spent in basic research and development before a decision to proceed with the program was made. Following the go decision, the development process leading to flight testing took ten years, and then an additional four years passed before a production aircraft finally entered commercial service.

Manned Space Program. The manned space program is frequently cited as the prime example of how to execute a monumental technical program. From the beginning of this program in 1958, NASA employed the approach of having a strong program manager who was empowered with the authority to control all aspects of the program; this approach, while common today, had been developed through experience with aeronautics programs over the previous fifty years. The initial Mercury program was largely executed with internal resources, primarily relying on existing technologies. As the overall program expanded toward the much more complex Apollo program, the management approach needed to evolve to be able to deal with hundreds of subcontractors. NASA adopted the approach used on the Minuteman ICBM program to expand to program office authority over all of the far-flung elements of the manned space program. (Launius, 2007)

Classical aerospace systems engineering was developed on this and other programs in the 1960s to deal with the management of technical complexity. Systems engineering became the key process for exercising technical control over development and manufacturing activities that were beyond the direct oversight of the government or prime contractor engineering team. The NASA program management approach to manned space flight included strong systems engineering, systems integration, and configuration management, in addition to aggressive program planning. However, while the approach was very successful, it was extremely expensive, and as such it may not be the perfect model for programs with more modest resources. (Launius, 2007)

Information Technology Infrastructure. The development of IT to the ubiquitous technology that it is today is was not necessarily a classical systems development process. It is true that information systems include many diverse kinds of systems, and that the IT industry has replaced aerospace as the primary employer of systems engineers. It is also true that government programs provided major funding in the early years of modern IT research and development, and that the government continues to be the driving force behind the expanding complexity of networks. (Eischen, 2000) However, the driver for the expansion of IT into all aspects of our lives has been consumer demand for a myriad of new IT products. This mixture of public and private sector demand and funding has not operated under any master plan; rather, entrepreneurs have responded to each technology advance with innovative ways to apply the latest technologies, driven by the profit motive.

Need for Systems Engineering

The five “programs” discussed above provide a useful perspective regarding the development of very large programs in general, as well as the need for systems engineering in particular. The development of basic energy and transportation infrastructures was an unguided, primarily private sector process; there was no formal systems engineering involved. In contrast, the

development of commercial nuclear energy was a public/private partnership, and while some of this activity pre-dated the creation of formal systems engineering processes in the 1960s, it certainly proceeded under a rigorous technical structure with tight quality control standards. The Concorde was also a public/private partnership involving two countries; the relatively slow pace at which this program was executed suggest that systems engineering and/or program management processes were less than mature. The manned space program was completely funded by the government, but utilized hundreds of subcontractors to build hardware and software; this program was perhaps the prototype for full-scale use of formal systems engineering processes. Finally, the development of the present information technology infrastructure diverges back to a largely private sector activity not driven by government spending, breaking what otherwise might appear to be a pattern toward government domination of large programs; however, this program has expanded the application of systems engineering as a central element of technical management. Two general conclusions can be suggested from this limited set of data. First, very large "programs" can be driven primarily by the private sector, the public sector, or some combination of the two. Second, the need for systems engineering in recent decades has been driven by growing complexity, either by sheer size and number of contractors as in the manned space program, or by the need for standardization and intercommunication on a global scale as in IT development.

Another perspective is whether or not these programs were vital to the society of their day. This does not mean that the program was not useful to the advancement of society (all were), but whether it was vital to protect health or economic welfare. Basic energy and nuclear energy development enabled society to advance in countless ways, but had they not developed when they did society would not have been adversely impacted. The Concorde was in commercial service for over 30 years, but had limited capacity and very high ticket prices; thus, it benefitted only a relatively small number of wealthy people, and some would argue that it had negative environmental impacts on the larger society. The manned space program had many technology spin-offs and may have been psychologically important at the height of the Cold War, but it did not directly prevent real war or benefit consumers. Finally, the development of IT has revolutionized our world, and included among the benefits are advances in medical technology that save lives; however, if these developments had occurred decades later our society would have continued to survive and prosper. None of these example programs dealt with issues that were as critical as the present energy situation. As mentioned in the introduction, there are real risks of energy resource shortages, and perhaps climate changes, which could have staggering impacts on the global economy if a rapid transition to a stable energy supply is not made

One other comparison is to consider the nature of systems engineering that will be required for an energy transformation, in comparison to other large programs of recent years. In *The Hitchins-Kasser-Massie (HKM) Framework for Systems Engineering* (Kasser, 2007), the concept of a five-layer model of systems engineering is proposed; the layers, from top to bottom, are: socioeconomic, supply chain, business, system, and product. Kasser's paper goes on to describe how various activities work at various levels of the framework, from military platforms that are focused on the system level to information systems that touch all but the top level. The sustainable energy transformation will be even broader, covering all five levels, and in fact at the present time a great deal of the developmental activity is at the socio-economic layer. The current research and development activities in sustainable energy are heavily focused on one issue: cost reduction; the case for sustainable energy is not being made on affordability to the consumer, but in fact cost is the primary obstacle. With that said, a major challenge is to find

ways to drive consumers, industries, and governments toward a pathway that is not presently economical, on the basis of projected resource shortages and climate changes in the coming decades. A case must be built for the general public that the change to sustainable energy is absolutely necessary; while much of the effort in building this case falls in the systems analysis arena, there is a need for systems engineers who can create an easily-understood vision of advanced energy systems at the extremely big picture level.

The actual systems engineering work required to support multiple layers for an energy transformation will of course be of different types. The lower level efforts, at the system level, can be conducted based upon conventional systems engineering practice, although some adjustments may be needed to work within the energy and process industries that have not traditionally practiced systems engineering. The intermediate level efforts, focusing on the supply chain, will need to employ systems of systems methodologies; these methodologies are still developing, and here again may require some tailoring to the energy industries. The top level efforts, dealing with socioeconomic issues, will likely be the biggest challenge, for two reasons. First, they are largely needed now, in an environment of limited data and very limited stakeholder acceptance of the need for this transformation. Second, as noted above, this has not been an area of significant systems engineering practice in the past, so tools and techniques need to be developed to support the effort.

Systems engineering support at the socioeconomic level must focus on the extremely big picture. The timeframes are measured in decades, the technologies involve numerous industries, and the spatial dimension involves the entire planet. The initial approach to addressing issues at this level is to expand on the concepts being developed for dealing with systems of systems. Currently, tools being developed for energy systems of systems include development pathway analysis, techno-economic analysis, transition scenario analysis, and life cycle analysis; these various analysis tools can be scaled up to address more global issues. From an engineering perspective, basic requirements analysis is still the first step in technical development, especially from a mission analysis perspective; the energy transformation needs to be defined as one or more potential "missions". The requirements gathering process needs to touch a very broad and diverse set of stakeholders, and the development of requirements needs to be performed in an environment of uncertainty. The composite of requirements from different "missions" may lead to multiple potential requirements "sets" that need to be de-conflicted; one method for doing this may be to develop different potential developmental pathways, with trade study processes ultimately being used to down-select to the optimal suite of pathways.

Challenges to Application of Systems Engineering

There are several challenges to applying systems engineering practice to the development of a sustainable energy economy. Three general issues are significant in the near term: conducting systems engineering at the sociopolitical level, gaining acceptance of systems engineering in energy-related industries, and providing the necessary numbers of qualified systems engineers.

The need to conduct systems engineering activities at the sociopolitical level creates several challenges. First, there is not a strong body of knowledge to guide activities at this level. Second, leaders with a political agenda rarely welcome logical, structured analyses and recommendations unless the conclusions align with their agenda. Third, the sheer number of potential stakeholders at this level makes it difficult to converge on a standard set of requirements, particularly with respect to the siting of energy facilities and infrastructure. All of these factors need to be addressed by creation of a body of knowledge from experiences with

very large and complex systems that are developed and managed by multiple industrial or governmental entities.

Systems engineering is well established in the aerospace/defense and IT industries, but is largely unknown in the energy, transportation, and infrastructure industries. This does not mean that systems level thinking does not occur in these industries; the chemical process industries, for example, have well-established methods for designing process plants, and they use structured project management approaches such as stage-gate management to regulate various phases of a project lifecycle. The issue is that there is reluctance to adopt methodologies and terminology from other industries, particularly if there is a perception that what has always worked for them is good enough. Also, the existing methods used may not scale up well to deal with the high-level, complex systems of systems issues. The response to this challenge is that those seeking to practice systems engineering in new industries should first gain a thorough understanding of what technical management methods are already being used in the industry, and then systems engineering processes should be tailored to fill in gaps; throughout the process, invoking unique terminology from aerospace or other areas that are foreign to that industry should be avoided.

There is a significant and growing shortage of scientists and engineers with experience in the energy field, and the systems engineering field is in similar shape. Nearly half of personnel in the U.S. energy industries will be eligible for retirement within the next 10 years. There will be a 38 percent shortage of engineers and geoscientists by 2009, and enrollment in petroleum engineering and geosciences has dropped by 75 percent over the past 25 years. (NPC, 2007) The author's personal experience in trying to hire qualified systems engineers in recent years has mirrored these statistics. Systems engineers with solid SE training and experience in building process systems or other hardware are not readily available; the older folks from the big aerospace days have either retired or moved on to other professions when the big cutbacks occurred, and those graduating within the past 15 years or so have focused on the lucrative IT fields rather than the traditional core engineering fields (civil, mechanical, electrical, chemical). The author's observations are based upon the traditional definition of a systems engineer that would typically be recognized by INCOSE members; it certainly would not be correct to say that only individuals with a systems engineering pedigree are capable of big-picture, systematic thinking. In any event, a pipeline for developing engineers with the necessary holistic viewpoint must be developed in order to have the professional workforce necessary for an energy transformation.

Each of the challenges listed above can be addressed through collaboration among INCOSE members; however, given the highlighted differences between energy systems development and traditional industries employing systems engineering, a new focus is required to develop the domain-specific knowledge needed. The recent formation of an infrastructure working group within INCOSE is a first step, but what is really needed is a larger number of practitioners from the infrastructure industries into INCOSE, so that a larger and more diverse body of knowledge can be developed.

Additional Research Needs

There are extensive research needs across numerous academic disciplines in support of a transition to a sustainable energy economy, and systems engineering is no exception to this situation. Principally, the needs are in the area of complex systems of systems development and in tailoring processes to the energy and infrastructure industries. Interest in system of systems thinking is coming from multiple sectors, so a special additional focus in that area is probably

not necessary. By contrast, tailoring of systems engineering processes to the energy and infrastructure industries has not been performed widely, and there is limited communication between practitioners at the places where it is being done. INCOSE should take a leading role in this process tailoring, building upon the skills possessed by many of its members from the aerospace/defense sector in the development of process and hardware systems.

Conclusions

The need for a transition to a sustainable energy economy is a reality that will play out during the lifetime of most of us. This change will have a massive impact on all levels of the global society, from governments to industries to individuals. Systems engineering skills and talent will be needed to enable this transition to succeed. There are many challenges to be addressed, and INCOSE should step up to embrace these challenges and should support the research needed to solve them.

References

Association for the Study of Peak Oil and Gas (ASPO), "Peak Oil Primer" (1 November 2007) http://www.energybulletin.net/primer.php

Eischen, Kyle, "Information Technology: History, Practice and Implications for Development" (November 1, 2000). *Center for Global, International and Regional Studies*. Paper CGIRS-2000-4. http://repositories.cdlib.org/cgirs/CGIRS-2000-4

Francis, Christopher, The History of Concorde" (2004) http://www.christopherfrancis.co.uk/Concord.htm

Friedlander, Amy, "Power and Light: Electricity in the U.S. Energy Infrastructure, 1870-1940". (1996)

Kasser, Joseph, "The Hitchins-Kasser-Massie (HKM) Framework for Systems Engineering. (2007)

Launius, Roger, "Managing NASA's Complex Space Flight Programs: The Apollo Experience". (Spring 2007) http://appel.nasa.gov/ask/issues/26/26pr_managing.php

National Petroleum Council (NPC), "Facing the Hard Truths about Energy", Draft Report. (July 18, 2007)

US Department of Energy (DOE), "The History of Nuclear Energy", DOE/NE-0088. (2002)

US Energy Information Administration (EIA), "International Energy Outlook 2007", DOE/EIA-0484 (2007)

Biography

Neil Snyder has been a practicing systems engineer and project manager for over 25 years. He has worked in the aerospace, defense, environmental, and energy industries, and has worked for a variety of companies including Lockheed Martin, Bechtel, CSC, SAIC, and Midwest Research Institute / Battelle; he is also a retired Air Force Reserve officer. He holds an MS degree in Civil Engineering and an MBA in Project Management, and is a registered Professional Engineer and a certified Project Management Professional. He is currently the Executive Director of Systems Integration at the National Renewable Energy Laboratory in Golden CO, where he is leading efforts to address the very large scale issues relating to renewable energy development and integration.

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The realities of shrinking fossil fuel reserves, growing global energy demand, and climate change concerns will force a change to a sustainable energy economy. To help with this transition, systems engineers will need new tools and have somewhat different roles than in the past. This paper discusses large, past projects that may provide insights to help systems engineers plan for the challenge of transitioning to a sustainable energy economy.

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