Engineering Clean Energy Systems

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Abstract. Clean energy development is the grandest systems engineering task of all time. Its scope is global and challenges are serous. Goals should be strategic, based on the desired end-state rather than arbitrary intermediate goals like 20% wind by 2030. Cost and performance should be evaluated at the system level not the component level. Decisions and value choices should be based on fact, rather than aspirations. The current phase is concept definition. We first need to clarify goals, and then develop strategic system scenarios; simple models of end-state system architecture based on known technology. Scenarios allow us to compare configurations to identify structure, priorities and focus. Classic systems engineering has a defined customer interface that, with some innovation, enables us to select concepts. The main advantage of a strategic systems engineering approach is that it allows us to focus our resources and to avoid big mistakes.

Introduction

Various professional and standards organizations have established a consistent set of system life cycle models (INCOSE 2011). Fig 1 is an overview of the main development stages in the form of a Gantt chart. This paper is about the concept definition stage, the importance of goals and how we develop feasible concepts. It is also about how to make decisions at the major milestones that mark the transition between phases.

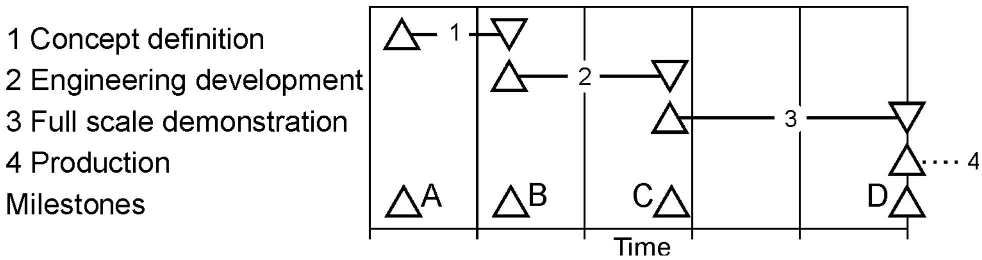

Figure 1 Generic engineering development plan

Milestone A initiates the program and establishes ground rules. The major milestones B-D are a combination of a critical design review and a management decision. The design review is "critical" in the sense of an independent critique of progress against the goal. The management decision is society's judgment about what to do next (continue, accelerate, decelerate, change direction, terminate). The plans are flexible in that they can accommodate new knowledge.

Clean energy systems are unique in the number and diversity of its stakeholders. Energy affects everyone and everyone has an opinion. This diversity can be accommodated in a novel decision structure.

Sooner or later, the world needs to transition to a post fossil fuel economy; huge reductions, 80-90%, in our consumption of fossil fuel. This goal is certain, clear and stable. Its timing could be sooner, if clean energy is cheap or if society views climate change as a existential crisis. Its timing could be later, if society views climate change fears as overblown. But fossil fuel is a finite resource and a post fossil fuel economy is inevitable.

The importance of clear and stable goals

Engineers have a broad spectrum of development tools, the choice of which depends on how well we can define a goal (Fig.2). At one end of the spectrum we have classical planning which requires a clear and stable goal. All decisions are based on achieving the goal. Set the goal, develop scenarios, choose one, and develop a plan. Classical planning has a long and storied history of producing efficient powerful systems. The main disadvantage is that a changing goal is a major disruption.

At the other end of the spectrum we have evolutionary development. Evolution has no goal; there is no overarching purpose. Decisions are made through local optimization, natural selection. Evolution is analogous to market based solutions, what sells now.

In between the two extremes we have various levels of agile development depending on the clarity of a goal. Agile development is a way to develop systems when the goal is fuzzy, or changing as is often the case with consumer products. Take the iPad as an example. Early market feedback is necessary to firm up requirements. Agile development emerged in the software industry during the information technology revolution. It is typified by techniques like spiral development, rapid prototyping, pair programming and refractoring.

Figure 2 Development approaches

Agile development can be thought of as a search for stability. It does not replace classical planning in areas where we have a clear and stable goal.

With a clear and stable goal, classical planning is the proven approach for achieving that goal. Classical planning starts from where you want to be, and works backwards to develop a plan to get there from here. This is how we develop high reliability software for space satellites. Agile development starts from where we are and works forward, searching for a stable goal through a trial and error process. Agile development has not replaced classical planning; rather it is a useful tool when the goal is fuzzy or unstable.

Why a strategic goal is important. - In *America's Energy Future* (AEF) the National Academies were tasked to develop an evolutionary scenario. They concluded that "...there is no 'silver bullet' technology that can be deployed to overcome U.S. energy challenges. Contributions will be needed from the full array of currently available and emerging technologies" (NRC 2009). That is not a useful conclusion. A shotgun approach, developing everything, is unaffordable, ineffective and unnecessary. Second, this conclusion is factually conflicted; France today has an electric power grid that is 90% carbon free (80% nuclear, 10% hydro).

The AEF report is correct in that there are many technologies that can reduce emissions today. But how does that help? While there are many ways to achieve a 20% reduction, there are very few ways to achieve big reductions. Current policy and changing technology introduce confusion and markets can't tell the difference. Rather than asking the NRC how to improve what we have, we should be asking how to we get to where we want to go, the strategic goal. We should be setting strategic goals and tasking the NRC to develop strategic scenarios.

New goals demand new solutions

The fundamental goal is a large reduction in the consumption of fossil fuel. One driver is climate change; it would be prudent if not urgent to reduce CO_2 emissions. A second driver is concern over the environmental and health consequences of burning coal. A third driver is the finite resource of fossil fuel and the need for sustainable energy sources.

Obama's Copenhagen goal - In preparation for the 2009 Copenhagen Conference on Climate Change, President Obama declared that America's goal is to reduce CO_2 emissions to 83% below 2005 levels by 2050 (White House 2009). This is an excellent strategic goal, an excellent end state definition. It recognizes the desire for very big emission reductions. It recognizes that 100% reduction is unnecessary and probably unachievable within the next century. And the 2050 timeframe allows for the next generation of major infrastructure.

The Copenhagen goal should be contrasted with interim policy goals like 30% renewables by 2020 or 20% wind by 2030. These goals are guesses, not derived from the strategic goal with a comprehensive engineering plan. It is like knowing we have to build a 100 story skyscraper and deciding to build the first 20 stories now and worry about the remaining 80 stories and the design if the whole building later. The interim goals have no engineering value and become counterproductive when they are taken to be end-states in themselves.

Top-level requirements allocation - Figure 3 shows actual CO_2 emissions in the US in 2005 (DOE/EIA 2009). The first four bars indicate the amount of CO_2 emitted during the generation of electricity, the powering motor vehicles, natural gas heating and everything else (other). The black bar on the right side indicates 17% of the total. This is the Copenhagen goal, an 83% reduction in CO_2 emissions below 2005.

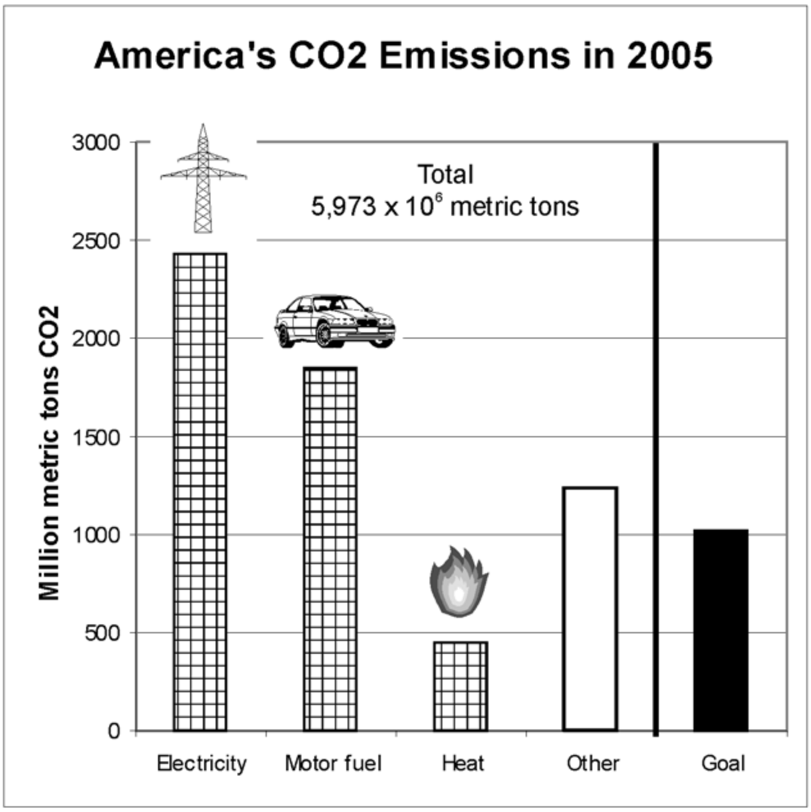

Figure 3 The challenge

The "other" bar is 21% of the total vs. the 17% goal. It consists of a hodgepodge of applications some of which are difficult to replace such as industrial and chemical processes, metallurgical coal, lubricants and petroleum fuel for aircraft and ships.

Fig. 3 identifies a clear strategy. A zero carbon electric power grid in conjunction with an electricity based motor vehicle fuel and electric heat gets us to within a few percentage points of the goal. Assuming that growth is offset by efficiencies, an 83% reduction in CO2 emissions is certainly feasible. *Since a variety of applications can be shifted to electricity, a key requirement is a zero carbon electricity grid*. Conversely we cannot achieve an 83% reduction without a zero-carbon electric power and zero-carbon motor vehicle fuel.

Electric power grid requirements - From 1882 through the mid 1970s the power industry's focus was on system development and build out; on reliability and government-stimulated electrification. Private electric power monopolies developed local networks that gradually began to be tied together. These monopolies had strong power systems engineering departments that invented the details of the modern electric power system.

Since the 1970s, the emphasis shifted from reliability to low cost. Worldwide deregulation broke up the monopolies and divided the system into competitive and monopolistic entities. Generation is competitive; long distance transmission and local distribution are regulated monopolies. Since the technology is stable, there was no longer a need for corporate power systems engineering departments. That capability is gone. In the US the electric power industry is highly fragmented, and its pieces are being regulated by a dozen different federal agencies. The broad and competent power systems engineering infrastructure was lost during deregulation.

More recently, the emphasis has shifted to sustainable: clean generators with little environmental impact in the form of resource consumption and waste generation. By the way we still want reliable and low cost.

As will be noted in the scenarios section, the introduction of intermittent generators like wind and solar changes the systems architecture and we do not have the competent engineering infrastructure to manage this change. We start making naive mistakes.

Nuclear power requirements The charter for the Blue Ribbon Commission on Americas Nuclear Future (BRC 2010) provides an awkwardly phrased goal that can be more succinctly summarized as: cheap, safe, sustainable and secure. Today's society wants civilian nuclear systems to be cheap (less expensive or at least competitive with alternatives), safe (from accidents and natural disasters), sustainable (clean with little waste or consumption of resources), and secure (from weapon proliferation and terror).

Pressurized Light Water Reactors (LWRs, ordinary water is coolant and moderator) were invented for submarine applications by Admiral Rickover's team. Rickover chose LWRs over liquid metal and gas cooled architectures because he could fit it into a submarine and he could keep the sailors safe. He did not care about cheap; safe was important but he was willing to pay for highly skilled and trained operators; sustainable was a non issue; secure meant don't tell the Russians. The resulting prototype submarine *Nautilus* worked superbly.

The design basis for civilian nuclear power is the Shippingport Atomic Power Station. This reactor, brought on line in 1956, employed a LWR that was a larger, simplified version of the *Nautilus* reactor. Once the Navy demonstrated LWRs, it gave the technology to the electric utilities who built civilian reactors. There was no global optimization for civilian applications. Key decisions behind legacy LWR architecture are rooted in submarines and cold war priorities. Today's goal, particularly sustainability, is substantially different than submarine requirements. Different goals mean we must look for different solutions.

Lessons from Apollo

On May 25, 1961 before a joint session of Congress, President Kennedy announced that America would put a man on the moon before the end of the decade. NASA was instructed to execute this mission.

The politicians assumed that we could launch a rocket from the surface of the earth to the surface of the moon and return, just like the comic book hero Flash Gordon did it (Fig. 4). But our rocket scientists knew better. They wanted to build a large rocket in earth orbit and go from earth orbit to the moon and return. And then Dr John C. Houbolt in the bowels of NASA Langley kept saying no, no, no, the right way to do this is a lunar orbit rendezvous. Launch a rocket from the surface of the earth to a lunar orbit, drop a man down, pick him up and come home. It took NASA one year to run the scenarios, to do the system tradeoffs, and risk assessment. They chose the lunar orbit rendezvous and the rest is history. (Launius 1994)

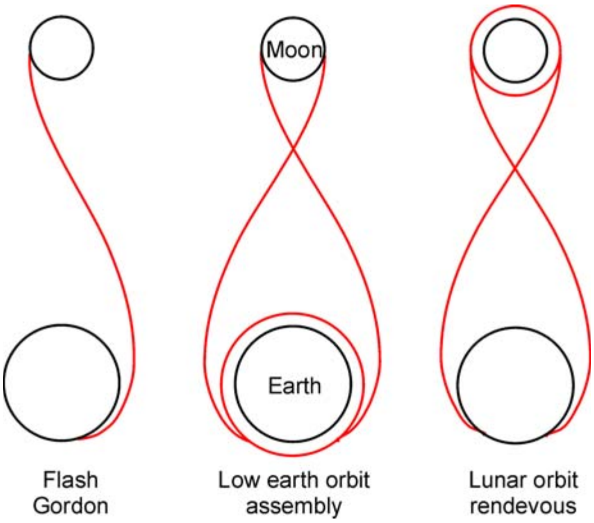

Figure 4 Apollo scenarios

For Apollo, choosing a scenario was a technical judgement. The consensus was achieved when Wernher von Braun, chief advocate of the low earth orbit approach, agreed that a lunar orbit rendezvous could work. Choosing the correct scenario was the key to Apollo’s success. America could not have put a man on the moon in 10 years if NASA chose either one of the other two scenarios.

Lessons - Apollo teaches a basic concept development sequence: President Kennedy set the goal, a geopolitical decision; NASA developed and clarified three technical scenarios; they then chose one, in Apollo’s case the decision was a technical consensus. NASA then developed the engineering plan.

Scenario development

We have a goal, the next concept development step should be scenarios development. A scenario is a simple model of end-state system configurations that enables cost/performance projections. The purpose of scenarios is to provide a factual definition of the feasibility of various choices.

Scenarios are based on known technologies including data based learning curves for cost and performance improvements. They ignore breakthroughs, current policy and legacy-system constraints. Policy and plans for how to get there from here comes later. The model contains enough detail to capture the structural relationships and produce rational estimates of cost, performance, schedule and risk. The model avoids unnecessary detail that would obscure structural relationships and introduces confusion. Models are constructed using common metrics to facilitate comparisons.

Strategic scenarios are logical end-states - The advantage of a good strategic goal is that it provides the stable basis for planning. With a clear and stable goal and known technology we can find unambiguous solutions, logical end-states. The solution is logical in that it involves very few arbitrary assumptions. Engineers can present the strategic scenario with confidence that it can achieve the goal. There may be more than one feasible alternative that then requires a value choice.

Wind scenarios – Wind power is an excellent example of the importance of strategic system scenarios. Consider a model electric power system. Assume that it is closed, no imports or exports; constant load, no daily or seasonal variation; and that we will satisfy that load with natural gas generators and wind turbines.

The model reaches maximum wind penetration when the nameplate capacity of the installed wind turbines equals the system load. For this condition, wind turbines provide 100% of the system power when the wind is blowing hard and all the natural gas generators are shut down. We cannot add more wind because if we did we would have to curtail wind production, shut down some wind turbines, just when they are most productive because the system cannot accept the power.

If we further assume a reference power curve (Vestas 2011); a mean wind speed (4.2 m/s); and Rayleigh wind fluctuation statistics we can calculate the system power percentage curve presented in Fig. 5. At maximum wind penetration, 75% of the energy comes from natural gas generators, 25% from wind. For 20% of the time wind turbines are producing nothing and 100% of the power comes from natural gas.

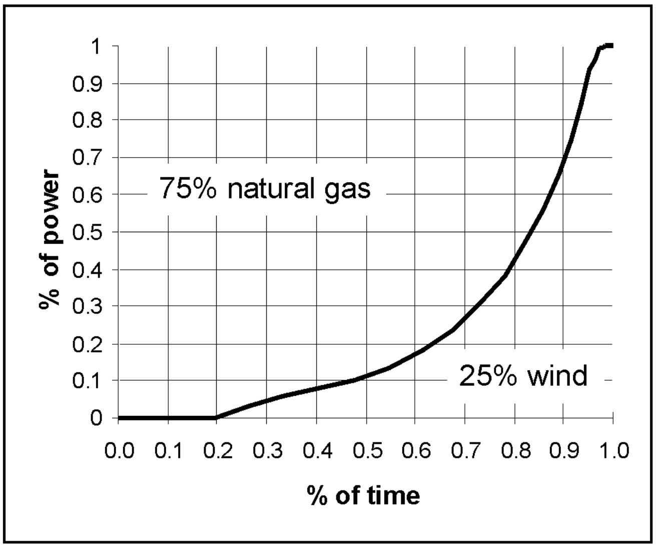

Figure 5 Wind power-percentage chart

But how does the system get to zero carbon when 75% of the energy comes from fossil fuel? Wind scenarios need to be expanded to include long distance transmission, storage, and curtailment. Existing simulations (EWITS 2010) suggest that while all of these strategies help a little, none of them changes the game. The majority of the power must still come from backup generators. Another dimension to wind system scenarios is wind plus a zero carbon backup generator such as wind+hydro, wind+geopthermal, or wind+nuclear. From this perspective, a system like wind+geothermal must be compared with geothermal-only to see if wind adds value. Still another perspective is wind + fossil fuel as a low cost interim solution.

A little wind can reduce emissions a little on a high carbon grid. But it is not at all clear how wind contributes any value to a zero carbon grid.

Solar PV scenarios - Solar PV is quite different than wind. Even though it is intermittent, solar PV is more repeatable. Every blue-sky day is quite similar to any other blue-sky day anywhere on the planet and overnight storage would make a big difference. Also, solar tends to be positively correlated with air conditioning load while wind tends to be negatively correlated with extreme temperatures and peak loads. Solar PV scenarios can explore the extent to which the technology is a fundamental contributor to a zero carbon grid.

Nuclear system scenarios – The nuclear power goal is: cheap, safe, sustainable and secure (BRC 2010). Of these attributes, sustainability is new and is a system driver. While the operation of nuclear power plants involves no greenhouse gas release, the disposition of spent nuclear fuel is a key technical and political issue that drives the whole concept.

Nuclear systems have two loosely coupled components. One part is the reactor and the plant; the other is the fuel cycle. In the US, the reactors have been designed, developed and deployed by private industry with the concurrence of the Nuclear Regulatory Commission. That part of the industry is intensely competitive and simple passive safe concepts are emerging. In contrast, the government has been responsible for the fuel and waste disposal. We are in serious need of a sustainable fuel cycle concept.

Nuclear scenario development starts by identifying the broad panoply of options: fuels, fuel cycles, thermodynamic power cycles, reactor types, coolants, moderators, size, and disposal options (various geologic disposals, deep boreholes, disposal in the seabed, outer space, transmutation of long-lived isotopes). Much of the work has already been done. It exists in bits and pieces in a variety of places. (NAS 1999), (Wigeland et al. 2009)

This information forms the basis for system scenarios that enables the consistent comparison of system architectures (Fig. 6). Gaps need to be filled in with a variety of engineering studies, theoretical analysis, tradeoffs and critical item tests to clearly identify feasibility, defined here as a low risk of fatal flaws. Scenarios are subjected to a formal independent technical review so that the information can be expressed as generally accepted fact with few technical challenges.

Given the system scenarios, the next step would be to choose one. Given the history of nuclear power, this choice has a strong political component. As noted in a later section of this paper, systems engineering has a defined customer interface that can be adapted to manage this political choice.

Nuclear System Scenario Summary

Value criteria		Weight	Option 1	Option 2	***	Option n
Cheap	Capital cost					
	Operating cost					
	Power system					
Safe	Reactor					
	Fuel cycle					
Sustainable	Fuel					
	Climate					
	Waste					
Secure	Energy security					
	Non-proliferation					
	Counter-terroism					

Figure 6

Motor vehicle fuels - The earlier top-level requirements allocation showed that a zero-carbon motor vehicle fuel is essential to achieving large CO_2 emission reduction. Given a zero-carbon grid, a natural solution is an electricity based motor vehicle fuel, some sort of electrochemical cell. The best type of cell is unclear.

Closed cell batteries have been receiving significant attention from DOE and may have a viable market as Plug-in Electric Vehicles for city driving. Batteries also have a market for regenerative breaking like the Prius.

Hydrogen fuel cells have long been recognized as a feasible choice for automotive fuel (Burns et al. 2002). There are many ways to implement H_2 fuel cells. However handling H_2 at sufficient densities for on-vehicle storage and the safe transportation of H_2 present significant challenges. Ammonia (NH_3) has the potential to solve some of hydrogen's handling problems (Faleschini et al, ~2000).

The development of a zero carbon motor vehicle fuel is primarily a systems challenge and is contingent on a zero carbon electric power grid. Many studies suffer from a lack of focus (NRC 2004). We could use strategic scenario development to clearly identify the most promising technologies and pathways.

Systems not components

We can calculate the cost of electricity by dividing total system cost, suitably discounted to fairly compare capital cost with operating expense, by total power produced. If components are functionally interchangeable, as a natural gas plant can be exchanged with a coal plant, then we can directly compare the cost of electricity produced by those components.

But we cannot simply compare the cost of electricity from components that are not functionally interchangeable, like a coal plant with a wind farm. The reason for this is that unlike the coal plant, the wind farm cannot stand-alone. To achieve the same level of reliability, wind requires backup generators and the system has substantially more nameplate capacity than would be required if there were no wind.

A common misconception is that we can swap a wind farm for a coal plant. This is what the U.S. Department of Energy's Energy Information Agency assumes when it compares the cost of electricity from new generating technologies. Also, it is exactly what the U.S. Federal Energy Regulatory Agency assumes when it sets up market rules that compete electricity on a kWh basis without allocating all wind specific systems costs to wind.

Likewise, clean components do not mean clean systems. While wind turbines are clean, systems that employ wind turbines are not because they employ fossil fuel generators to provide backup power when there is no wind. Large wind penetration causes fossil fuel generators to operate less efficiently (start and stop, partial power) and generate more pollution per kWh than they would if there were no wind. It is like driving in stop and go city traffic as opposed to constant speed. Eventually, wind induced cycling of coal plants can destabilize pollution abatement equipment causing them to emit more CO_2, NO_x and SO_x than they would if they were operating at constant power (Bennett, McBee 2011). Empirically based wind system emission studies tend to show disappointing emission performance (UDO 2011).

Cost and performance needs to be assessed at the system level.

Changing technology

For the most part, technology change is predictable and is routinely incorporated into the planning process. It is possible for a scientific discovery, like the fact that the uranium nucleus can fission, will radically disrupt our planning. But most of what people view as technology breakthroughs are really entrepreneurial breakthroughs, and unlikely to be disruptive.

Based on the extraordinary breakthroughs in "information technology" a common expectation is to see the same qualitative breakthroughs in clean energy. The great IT breakthroughs (Lotus, Netscape, Yahoo, Google, Ebay, Facebook, Wii) were entrepreneurial breakthroughs, innovations in how we *apply* the hardware and software technology. College kids created new products with great social value and companies went public in two years. In contrast, the underlying technology has been evolving in a steady and predictable fashion. In the 1960's we knew about microprocessors and futurists predicted personal computers. We had no clue about how people would actually use these devices. In the same time frame we knew all about the advantages of packet switching over circuit switching but we did not yet have enough hardware performance to implement the Internet and no clue as to its impact.

Game changing technology can drive the development process in its early stages. In the 1880-90s, we saw awesome electrical innovations including the induction motor, polyphase power transmission, transformers, light bulbs and switchgear. But by the time the AC vs DC wars were settled in 1896, it was all over. In the past 115-years, electric power technologies, with the exception of nuclear fission as an energy source, have matured slowly and steadily.

Discovering some unknown "game changing" technology, like a 1,000:1 improvement in batteries, is unlikely. Battery chemistries are a finite set. Every feasible chemical approach is known and has been researched in depth over 150 years. While 10-20% improvements are feasible with better materials, we should not expect big improvements.

Classical systems engineering enables us to focus our resources by pointing to where we need better technology. Innovation and changing technology are incorporated into a flexible planning process. In contrast changing goals would be disruptive and it is very important to identify the correct goals.

We know what we need to know to plan our future. The first step is to confirm the goals.

Decisions

Unlike Apollo, discovering the "best" nuclear power system involves both technical judgements and value choices. While a particular scenario may be technically compelling, only society can decide on the balance between cheap safe, sustainable and secure. The problem is akin to hiring an architect to build a "dream house." Only the client has the competence to make the final decision.

Governance, roles and responsibilities, becomes important for sound decisions. There are three main roles as illustrated in Fig. 7. These roles need to be separate and distinct, no one role should dominate, and there should be a healthy tension between the roles. A visible formal interface between roles can be helpful.

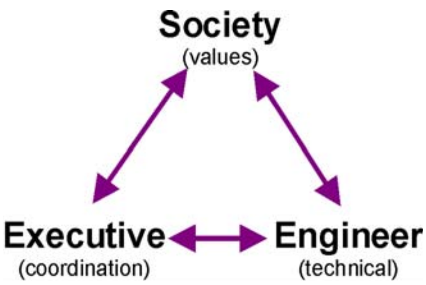

Figure 7
Roles & responsibilities

For U.S. clean energy development, the **Executive** role is the executive level of the Department of Energy (DOE). The primary responsibility is overall coordination and program management.

The **Engineer** (and science) role is varied depending on the task. This technical role can consist of scientists and engineers at government laboratories, government contractors, cooperative private industry and cooperative governments of other nations. In the U.S. the National Research Council has the right skills. The primary responsibility is execution and technical judgements.

Society makes value choices. A surrogate team that is constructed by a formula would fill this role. In the U.S. this could be the Legislative committee responsible for DOE's budget. This team can convene from time to time as necessary to make program value decisions such as whether the program should be re-directed between phases.

Clean energy is a global challenge and how these roles map into an international structure will require attention

Lessons from large public works projects - Traditionally, the interface between the customer and the contractor has been a source of conflict during engineering development. This even occurs with military systems procurement where both stakeholders (contractor and customer) are well defined, educated, and come from the same culture. With energy systems, types of stakeholders are far more diverse. A novel challenge to clean energy systems development is the number, diversity of types, and ignorance of stakeholders. Energy affects everyone and everyone has an opinion. Think public education.

Informed stakeholders simplify the politics by mitigating hype. We need to experiment with novel methods for engaging stakeholders in design reviews and management decisions. Classical engineering provides structure mechanisms to push back against lobbyists and special interests. Large public works projects provide guidance. Like energy systems, large public works projects involve consensus decision-making by many diverse types of stakeholders.

The new Woodrow Wilson bridge (Interstate 95 across the Potomac River near Washington DC) shows how to separate technology from value choices. Development proceeded through two steps:

1. Engineers explored the full range of options: tunnels, high bridge, draw bridge. This factual analysis (akin to system scenario development) took about a year.
2. Value choice made through extensive iterative interface with the public: local town hall meetings, briefings with local, state and federal politicians. This took several years including one false start. (And this was for another bridge, not something as complex and broad as clean energy.)

Figure 8 The new Woodrow Wilson Bridge

While clean energy systems are a more complex engineering problem, classical engineering provides the structure to engage many types of stakeholders. Open design reviews using web-based tools can engage many types of stakeholders while focusing on objective fact. It is during these design reviews that advocates and special interests have the opportunity to express their views. To the extent that they are technically sound, they are incorporated into the final scenario. Likewise novel processes for management decision milestones can result in more informed value judgments.

Conclusions

Developing clean energy systems is the grandest systems engineering challenge of all time. Transitioning to a post fossil fuel economy will require large reductions in fossil fuel consumption. This is the strategic goal, the end state.

So far, we have been developing clean energy with an evolutionary science-based approach that relies on innovation, markets and entrepreneuralism. Current policy and legacy systems lead to confusion and there are lots of ways to reduce emissions today. This science-based approach will inevitably commit resources to technologies that conflict with the goal because the strategic goal, the end state, is not part of a planning process.

In contrast, a systems engineering approach has much in common with strategic planning. The sequence is to identify the goal, develop strategic scenarios and then choose one. This process is how we put a man on the moon, how we build bridges and many major complex systems. Systems engineering has a long and storied record of success and is the optimum process when we have a clear and stable goal.

The Copenhagen goal called for an 83% reduction in CO_2 emissions by 2050. A top-level requirements allocation shows that there are two main sub goals: zero-carbon electric power; and zero-carbon motor vehicle fuel. While the strategic goal is feasible, it cannot be achieved without both of these sub goals. A high priority is zero carbon electric power.

Engineering development consists of a sequence of phases separated by critical design reviews and management decision milestones. After confirming goals, we are in the Concept Definition phase. The next step is strategic scenario analysis, simple system models that explore feasible solutions unconstrained by legacy systems and current policy. Planning is based on evidence, what we know today including data based learning curve extrapolations. Strategic scenarios provide a comprehensive set of technically feasible choices. Society can then judge which scenarios offer best value thereby creating a vision with priorities. This vision provides the basis for engineering development plans that allocate different technologies to different stages of development with different priorities.

The number and diversity of stakeholders complicates the decision-making process. Stakeholder management lessons can be learned form large public works projects.

Decision-making is simplified by separating factual judgments from value judgments. Disciplined engineering development provides the structure to do this through critical design reviews and management decision milestones. Engaging skeptics and advocates of different approaches minimizes the opportunity for spin and hype. Political leaders then have a factual basis for policymaking.

People follow leaders because the leader has a compelling vision and a credible plant to achieve that vision. A clear vision derived from competent scenarios provides the basis for global leadership.

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Biography

Alex Pavlak is a Ph.D. Professional Engineer with 40 years' experience managing a variety of R&D programs. His core competencies are systems architecture, energy systems and combining systems engineering with fact-based policy making. He received his Ph.D in mechanical engineering from Stevens Institute of Technology.

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