Inexpensive, Clean, Reliable Energy Will Require Engineered Systems

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ABSTRACT

Although small emission reductions are easy, large reductions will demand engineered systems. Classical system engineering (SE) development begins with ultimate goals such as big (>90%) reductions in greenhouse gas emissions. The first SE phase, concept development, consists of system tradeoffs to clarify feasible concepts and focus development efforts. These system studies begin with simple concept models and then build complexity in stages to elucidate principles, interfaces, and requirements. The concept definition phase is classically concluded with a critical review followed by a management decision, a value choice. Overall, classical SE starts with the ultimate goals, then works backward to allocate requirements and figure out how to get there from here. Contrast this with today's forward migration approach. Migrating forward without a clear path to an ultimate goal runs the risk of dead end development, stuck with concepts that cannot reach the ultimate goal. This paper illustrates concept development needs for both wind systems and for civilian nuclear power. © 2014 Wiley Periodicals, Inc. Syst Eng 00: 1–12, 2014

Key words: clean energy; concept definition; wind systems; nuclear power

1. INTRODUCTION

In a book titled *Powering the Future*, the Nobel Laureate Robert Laughlin takes the view that the future of energy will be constrained by physical law and economic self-interest [Laughlin, 2011]. He backs up his judgments with numbers. These constraints are valuable to development engineers because they provide the basis for focusing attention and resources. Physical laws provide hard constraints, economics a softer constraint. Given society's performance goals, engineered solutions will be determined largely by physics and economics.

All engineering development projects have an ultimate purpose, a goal. Sometimes the goal is clear and stable. This

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is often the case with technology-driven projects like: put a man on the moon in 10 years; or power the world without fossil fuel; or big greenhouse gas (GHG) emission reductions. Sometimes that goal is fuzzy and uncertain as is often the case with human interface projects and consumer products.

Planning works best with clear and stable goals and long development cycles. The ultimate goal provides the knowledge to focus resources, avoid development paths that conflict with the goal, and avoid big mistakes such as dead end streets. The essence of planning is to periodically test progress against the ultimate goal. This approach is exemplified by classic waterfall development (Fig. 1), where the development program proceeds through a sequence of phases.

Clean energy today is at Milestone A. Phase 1, concept definition, systematically explores alternatives, feasible ways to achieve the goal. Concept definition concludes with Milestone B where society makes value choices about which concepts to pursue. There may be more than one. Phase 2,
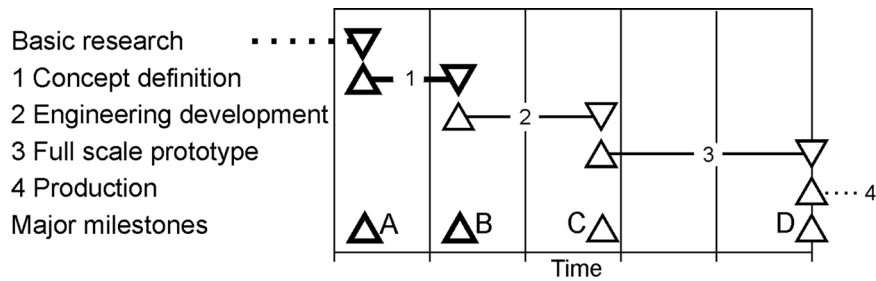
Figure 1. Classic waterfall development.

engineering development, consists of component testing to reduce the risks identified during phase 1. Milestone C is a decision to build full-scale prototypes. Value choices are made at all major milestones where program efforts can be terminated or redirected. Iterative agile development occurs mainly between the major milestones.

Clean energy development, with all of its stakeholders with conflicting interests, will be more difficult. The importance of the classic waterfall development model is that it identifies the development structure: phases and major decisions. Committing large resources to full-scale production (m/s D) without first having a clear idea of ultimate goals (m/s A) or a comprehensive analysis and comparison of alternatives (phase 1 concept definition) leads to big mistakes.

The waterfall system development should not be confused with a government acquisition program where, for political reasons, there is a tendency to rubber stamp the major milestones. In government acquisition, a decision to begin a program is pretty much a decision to purchase.

The Apollo moon program provides a superb example of classical planning.

1.1. 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. Kennedy's goal was brilliant. It captured the American spirit, the zeitgeist of the 1960s: to go where no man has gone before, to explore the final frontier (and beat the Russians).

At the time of Kennedy's announcement, the politicians assumed that a rocket could be launched from the surface of the earth to the surface of the moon and return, just like the comic book hero Flash Gordon did (Fig. 2). But the rocket scientists knew better. With a surface-to-surface concept, the rocket would be the size of Manhattan. 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 1 year to run the scenarios, do the system tradeoffs, and perform risk assessments. They chose the lunar orbit rendezvous and the rest is history [Launius, 1994].

Apollo teaches the basic concept development sequence: President Kennedy set the goal, a geopolitical decision;
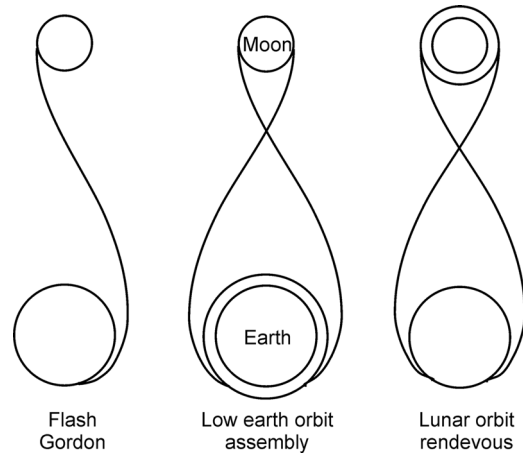

Figure 2. Apollo scenarios.

NASA developed and clarified three feasible scenarios; they chose one. NASA then developed the system engineering (SE) development plan.

Choosing the lunar orbit scenario was a technical judgment. The consensus was achieved when Wernher von Braun, chief advocate of the low earth orbit approach, conceded 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 or if they chose to develop all of them in parallel (all of the above).

Energy scenarios will be more difficult because energy affects everyone and everyone has a different opinion about what is the best goal.

1.2. The Importance of "Strategic" Goals

Goals should be strategic expressions of the desired ultimate outcome. The best goals are technology neutral performance outcomes like "Put a man on the moon in 10 years and return him safely." This is a superb strategic goal. It is clear, unambiguous, challenging. It does not tell the rocket scientists how to do it, but states what needs to be done.

In contrast to Apollo's strategic goals, today's energy policy goals are guesses (30% renewables by 2020 or 20% wind by 2030). They are not derived from an ultimate performance requirement. There is an unsupported assumption that it is
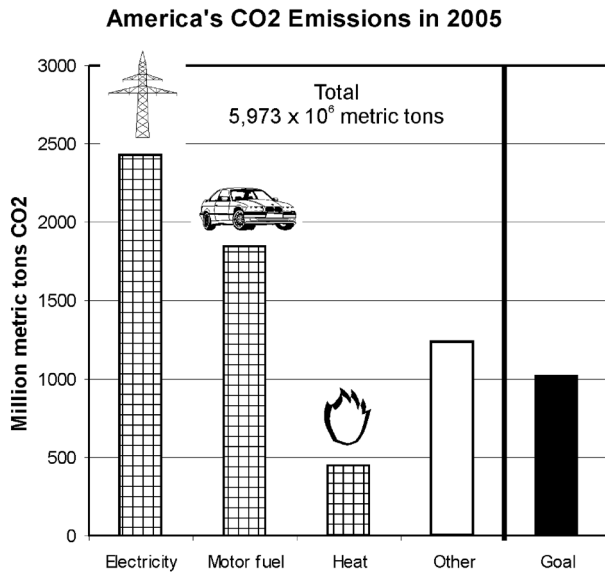
Figure 3. Copenhagen goal allocation.

possible to build on the interim achievement to reach an ultimate goal. This interim logic is like knowing that the eventual goal is a 100-story skyscraper and deciding to build the first 20 stories now and worry about the remaining 80 stories later. The correct strategic approach is to start with a structural concept design for the whole building.

Much of the controversy over clean energy today results from political confusion over goals. Goals are value judgments, an expression of society's needs. Does society want maximum renewables, energy independence, or zero carbon? This distinction is crucial because different goals can lead to incompatible architectures. A maximum renewables goal may lead to a system where the design driver is how to backup wind fluctuations. A zero carbon goal may lead to a nuclear solution where the design driver is how to level load. Does it make sense to design nuclear systems to backup wind?

1.3. Ultimate Clean Energy Goals

Two goals that are essentially equivalent:

1. To power the planet without fossil fuel.
2. Big (>90%) overall reduction in GHG emissions.

The next system development step is a top-level goal allocation. 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 [Whitehouse, 2009]. Figure 3 shows actual CO_2 emissions in the United States in 2005 [DOE/EIA, 2010]. The first four bars indicate the amount of CO_2 emitted during the generation of electricity, powering motor vehicles, natural gas space heating, and everything else (other). The red bar on the extreme right side indicates the Copenhagen goal, 17% of the total (an 83% reduction in CO_2 emissions below 2005 levels).

The "other" bar is 21% of the total. It consists of a hodge-podge 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.

Uniformly allocating an 83% requirement to all applications is a poor approach because some applications are more difficult than others. However, allocating a zero carbon requirement to the power grid enables applications like motor vehicle fuels or space heating to reduce emissions simply by shifting to electricity.

1.4. Planning with Changing Technology

Energy technology is qualitatively different than information technology (IT). The great IT breakthroughs (Lotus, Netscape, Yahoo, Google, Ebay, Facebook, Wii) were *entrepreneurial breakthroughs*, innovations in how to apply the hardware and software technology. College kids created new products with great social value. Companies went public in 2 years. By the 1960s, futurists predicted personal computers but had no clue about how people would actually use these devices. That made it difficult to set stable long-term goals.

In contrast to IT, clean energy has stable long-term goals and the technology is well defined, constrained by physics. A 10-year period following the introduction of electrical power in the 1880s saw awesome innovations including the induction motor, polyphase power transmission, transformers, light bulbs, and switchgear. But by the time the AC versus DC wars were settled in 1893, the basic system concepts were well defined [McNichol, 2006]. In the past 120 years, with the exception of nuclear fission as an energy source, the technology and system concepts have not changed.

Planning is based on what is known today including data-based learning curves forecasting cost/performance improvements. So long as the goals are stable, changing and improving technologies can be anticipated and incorporated into development plans. Forty-year life cycle military systems are routine. Technology change is accommodated with periodic technology refresh within stable system concepts. Changing technology is no reason to avoid classical planning as most innovations can be anticipated and incorporated into a flexible planning process.

1.5. The Importance of Whole System Goals

A system is a collection of components that are organized in a way that accomplishes a common purpose [Bude, 2009]. The whole is greater than the sum of the parts, that is, the system has properties beyond those of its parts [Rechtin, 1991]. A great example of the distinction between components and systems is how to provide electric power without fossil fuel. A wind turbine is a clean renewable component. But a reliable wind system requires backup for when there is no wind. Since natural gas is the lowest cost backup, inexpensive wind systems are not clean. Clean energy goals should be system-level goals not component goals.

Since 1893, the goal of the electric power industry was reliable electricity for everyone. This led to vertically integrated state-regulated utility monopolies. These utilities had

strong system engineering (SE) departments that invented the modern electric power system.

Around 1978 the goal expanded to lower cost. The Public Utility Regulatory Policies Act (PURPA) began the process of breaking up the electric utility industry [VanDoren, 1998]. PURPA encouraged elimination of most vertically integrated utilities that in turn eliminated their systems engineering capability. Today, regional systems operators and wholesale markets compete generators on the basis of price and availability. Although markets are useful for optimizing the distribution of resources, they cannot optimize system architecture because markets have no goal other than to maximize profit.

Now the goal has expanded to low GHG emissions. To achieve this goal, a system perspective is particularly important because the intermittent generators (wind, solar, tides, waves, …) cannot stand alone. They must rely on the rest of the system to provide power when the intermittent resource is unavailable. Intermittency changes the architecture. It is not possible to swap a wind farm for a coal plant. The only way to assess the cost or emission performance of an intermittent generator is to evaluate the cost of the whole system with and without the intermittent generator.

2. WIND SCENARIO

This section illustrates classical system synthesis beginning with simple concept models. The construction of these models is an art form because the model needs to include the core structural components but no more. Too many parameters obscure fundamental principles. The purpose is to understand boundaries, constraints, principles, relationships, and interfaces. This clarifies the system form, its structure, the architecture. Once the architecture is understood, the model becomes the kernel from which complex real world system simulations are built.

2.1. The Elementary Model

The core structural issue with wind power is the fact that wind is a variable generator, yet the system must provide power on demand. As a result of intermittency, any reliable wind system must consist of wind plus something else. So the simplest concept model consists of a wind turbine plus a fossil fuel plant that together must provide constant power.

Figure 4 is a reliable system than can provide constant power. When there is no wind, the fossil fuel plant is running at 100% of capacity. When the wind turbine is operating at full power, the fossil fuel plant is shut down. That fossil fuel plant needs to efficiently stop and start to backup wind. This elementary model suggests important tentative conclusions about wind:

- Wind provides no system reliability; the fossil fuel plant needs to reliably carry full load when there is no wind.
- The fossil fuel plant needs to be dispatchable, that is it must start and stop as required to backup wind. Base load nuclear and intermittent solar do not qualify because they cannot start and stop as required to backup wind.
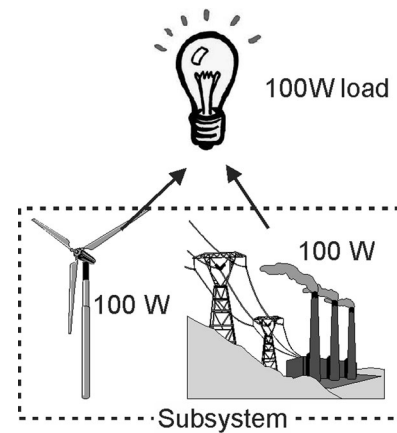

Figure 4. Wind + (fossil fuel) scenario.

- Reliable wind systems require full redundancy, two redundant sets of generators, each large enough to power the full load independently of the other.

2.2. Quantitative Wind Turbine

Wind turbine performance can be described more precisely. In most locations, wind statistics are well approximated by a Rayleigh density function [Cliff, 1977] that shows the probability, at any point in time that the wind is blowing at a certain speed. Wind turbines are characterized by a power curve showing turbine power production at a given wind speed. This information enables the calculation of a generation–duration curve showing the percentage of time the wind turbine power production is below a certain level at certain site. The generation duration curve presented in Figure 5 was calculated assuming Rayleigh statistics, a mean wind speed of 5.2 m/s and a [Vestas] 3 MW power curve.

The Figure 5 chart says that the wind turbine is producing 100% power 3% of the time and at least partial power 80% of the time. Conversely, 20% of the time wind production is zero. Area corresponds to energy. The area under the curve is 25% of the total. That is, the wind energy production over a long period of time is 25% of what it would be if the wind turbine were operating full time at full power. This is the definition of wind capacity factor, a property of the wind turbine and the site. Similarly, the area above the curve, 75% of the total, is system power that must come from something other than wind. Figure 5 shows that:

- When wind penetration equals capacity factor, wind is serving 100% of the load when wind is blowing hard. Adding more wind rapidly increases system cost because the system has more power than necessary and some of the wind must be curtailed (shut down).
- For constant load and no curtailment, the maximum wind energy that can be accepted by a system is equal to the capacity factor, in this case 25%. This corresponds to a system where energy production is one part wind to three parts something else (fossil fuel).
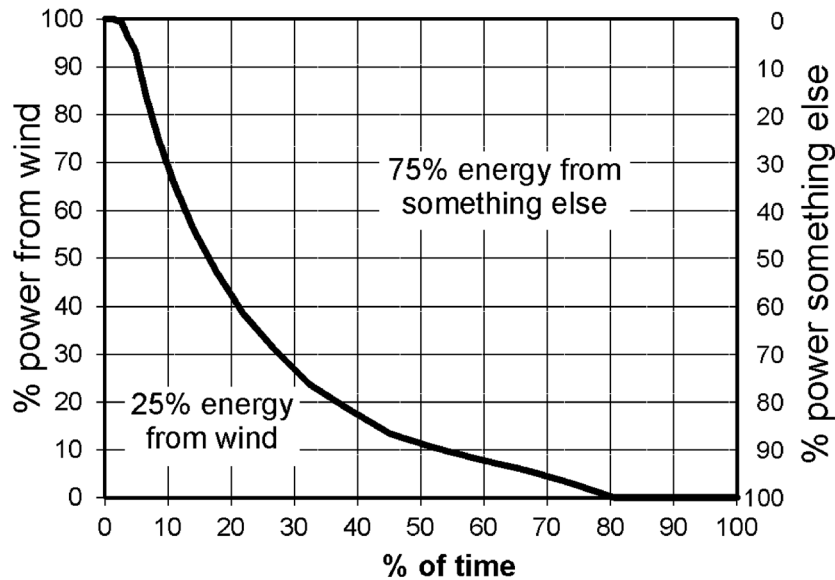
Figure 5. Generation duration.

2.3. Data Validation

Data presented in Figure 6 supports the theoretical analysis of Figure 5. Figure 6 shows data reported by Kempton et al. [2010]. These curves are derived from 5 years of wind data from 10 buoys along the U.S. Atlantic east coast from Maine to the Florida Keys.

Real wind data were adjusted using one-seventh power law to a 60 m wind turbine hub height. A wind turbine power curve was used to calculate the colored curves presented in Figure 6. Pgrid, the heavy black curve, is the interconnection of all the wind farms.

The blue curves to the left correspond well to the theoretical curve in Figure 5 because the capacity factor for those sites was about 0.25. Curves to the right have higher capacity factors, 0.35–0.37. Higher capacity factors reduce zero production time from 20% to 10%. Similar curves were published by Archer et al. [2007] from Midwest wind farm data.

2.4. System Cost Comparison

A good comparison can be obtained on the basis of "levelized cost" of electricity from new generators. Levelized cost is a life-cycle analysis that excludes subsidies, includes fuel escalation, inflation, and annualizes capital expenses. Think of levelized cost as the average cost of electricity over the life of the constant load system without incentives.

The Energy Information Administration [DOE/EIA, 2010a] publishes levelized cost estimates for 2016 installations. Given our constant load model, natural gas, coal, and nuclear generators are directly comparable because the generators are interchangeable. EIA cautions that the technology cost of electricity from wind plants cannot be compared with gas coal and nuclear because the wind plant is not interchangeable, wind cannot stand alone.

Comparisons require wind subsystems where the subsystem is interchangeable with gas, coal, and nuclear.

Figure 4 illustrates such a subsystem. Assume capacity factors of 35% offshore, 25% onshore. Whenever the wind blows the fossil fuel, plant can throttle back reducing the variable part of the natural gas plant. This means that the levelized cost of electricity is the technology cost of the wind plant (which EIA estimates to be 24.3 cts./kWh offshore, 9.7 cts. onshore), plus the cost of the gas generator (6.3 cts.), minus 35% or 25% of the variable part of the gas cost. Variable cost includes fuel plus operations and maintenance that is proportional to power production. EIA estimates the variable cost of natural gas to be 4.2 cts./kWh. The calculation is:

$$24.3 + 6.3 - (0.35 \times 4.2) = 29.1 \, \text{cts./kWh offshore}$$
$$9.7 + 6.3 - (0.25 \times 4.2) = 15.2 \, \text{cts./kWh onshore.}$$

Wind has additional system costs for transmission upgrades, balancing and storage. These estimates are controversial because they depend on wind penetration levels and the sophistication of grid management. Current estimates range between 0.5 and 5 cts./KWh [Taylor, 2012]. Figure 7 assumes 2 cts./KWh.

2.5. System Emissions Comparison

Clean components are not the same as clean systems. It is not possible to reduce system emissions by 25% with wind, and then get the other 75% "some other way." Wind commits that 75% of the system to start and stop (dispatchable) generation to backup wind. Fossil fuel is the best available technology that can start and stop to backup wind.

The U.S. Energy Information Agency estimates CO_2 power plant emission for new 2016 plants [DOE/EIA, 2010c and 2010dd]. The numbers, in pounds (#) of CO_2 per kilowatt hour (#CO_2/kWh), for natural gas combined cycle and
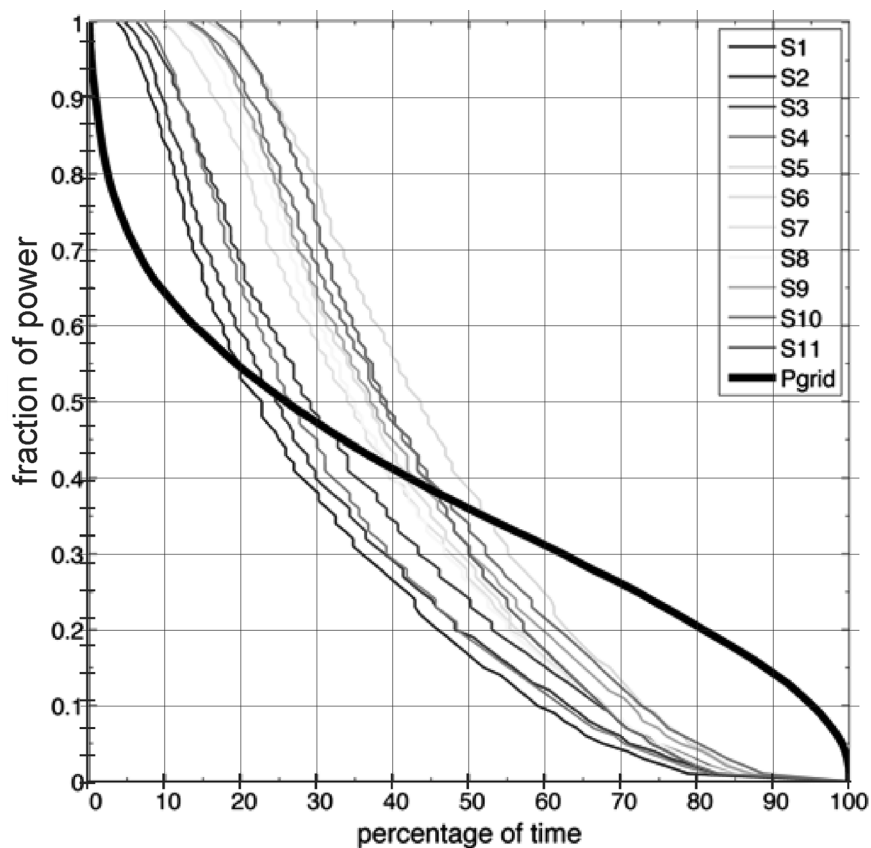
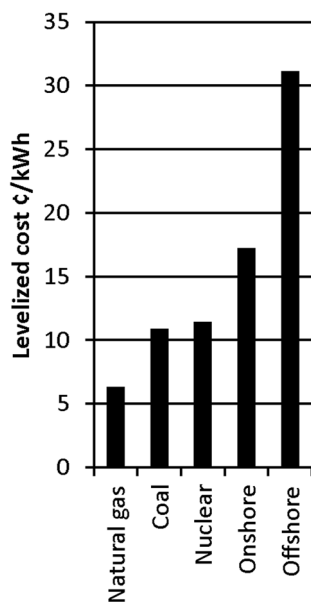**Figure 6.** Generation duration—data (Kempton).

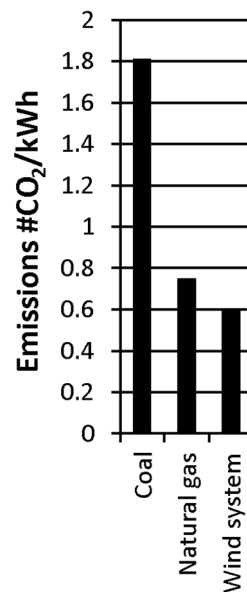

Figure 7. Levelized cost.

Figure 8. System emissions.

advanced coal (gasification) are presented in Figure 8. Shifting from coal to natural gas reduces CO_2 emission a lot, from 1.81 to 0.75 #CO_2/kWh.

As with cost comparisons, the emission impact of wind must compare systems with equivalent reliability. A reliable wind system consists of a wind plant and a natural gas plant. This system is interchangeable with a base load generator.

The popular assumption is that emissions are proportional to power production. If that were true adding wind (with a national average capacity factor of 0.25) would reduce the natural gas emissions by 25%. But the gas is no longer operating at constant power. It is continuously starting and stopping to backup wind. It is like driving a car in city traffic rather than at constant highway speed, efficiency drops. Katzenstein [2009] is the best available study of the impact of wind on system emissions. They use real wind data and a data-based model of the generator. At 20% penetration, they predict 77% effectiveness in reducing CO_2 emissions from natural gas. Seventy-seven percent of the 25% reduction is a 19% overall reduction in CO_2 emission. This means that a wind + natural gas system can reduce natural gas CO_2 emission by 19% from 0.75 to 0.60 #CO_2/kWh. For nitrous oxides, Katzenstein estimates 30–50% effectiveness. A 40% effectiveness and a 0.25 capacity factor means that wind systems reduce nitrous oxide emission by 10% below gas emissions.

- Shifting from coal to natural gas provides big (>50%) CO_2 emission reductions.
- Adding 25% wind to natural gas reduces CO_2 by 19%, nitrous oxide by 10%.

2.6. Wind Plus Storage

A little storage can help electric power systems through load leveling, firm capacity, regulation, replace spinning reserves (generators turning but not generating power), and manage rapid change and startup after system failure [Denholm, 2010]. But the popular perception is that some sort of super battery can "solve" the intermittency problem making wind + storage a stand-alone subsystem (super battery refers to generic storage, not necessarily an electrochemical cell).

Figure 9 presents wind and load data in MW for the Irish grid for 2012. Load is actual load. Wind is actual wind scaled up (assuming the same footprint) so that average wind equals average load. The exercise is to calculate the size of an ideal battery, no losses, necessary match wind, and load. The answer is a very big battery. Assuming lithium ion at projected high volume costs, the battery would cost 8× the gross nation product of Ireland [Gilligan, 2012].

But the serious problem is logical; any finite-sized battery will eventually be overwhelmed by too many low-wind days. Hence wind + storage alone is not a reliable system. Wind + storage + something else that can reliably manage full load by itself would work.

Budischak et al. [2013] developed a concept model of the PJM (a regional system operator for Pennsylvania, New Jersey and Maryland) grid. The remarkable conclusion is that a 99.9% carbon-free system can be achieved with modest storage by overbuilding wind. In Budischak's 99.9% scenario, wind generates 3× the amount of electricity needed to meet electrical load. The 99.9% scenario suggests a design concept for reliable wind systems, articulated here for the first time:

1. Build enough fossil fuel to reliably carry full peak load with no wind.

2. Then add wind + storage to reduce fossil fuel consumption to 0.1%.

Budischak calculates a land-based annual wind capacity factor of 41% whereas actual PJM capacity factor for 2011 was 27% [Baker, 2012]. This difference needs to be explained. The system cost of the 99.9% scenario was estimated at about 38 cts./kWh. This wholesale cost excludes transmission, distribution, and social taxes. It is directly comparable with the 6.3 cts. for natural gas and the 11 cts. for nuclear cited in Section 2.4. The concept exhibits peculiarities such as the fossil fuel generators operate at near full power for a few hours per year in July. Although this wind system scenario concept is theoretically sound, it needs system development to rigorously assess cost, performance, and risk.

2.7. SE Contributions to Wind System Concepts

System concept models also teach the following important lessons:

- Reliable systems must be able to reliably manage worst case events (no wind). There is no guarantee, even with interconnected wind farms, that wind will be blowing somewhere.
- System reliability comes from the parallel connection of many generators with statistically independent failure rates. Large Generators with nameplate capacity comparable to load (like cumulative wind) contribute little to system reliability.
- Fair market value of wind is variable cost of backup. Estimates that include only the capital cost of intermittent generators ignore system costs, mainly underutilized backup.
- With a constant load, an impasse exists when wind penetration equals capacity factor. Without curtailment wind penetration is thus limited to about 25% of system production; the remaining 75% comes from dispatchable backup.
- The concept of wind plus storage alone has no reliability. Any finite size storage can be overwhelmed by to many low-wind days.
- Large (3×) curtailment plus storage can reduce fossil fuel consumption to 0.1% .
- 99.9% wind systems need serious system development and critical system design review.

3. Nuclear Power Scenarios

If the goal is to power the planet without fossil fuel, nuclear fission is certainly a candidate. The questions are social acceptability and whether nuclear fission can scale to become a dominant energy source. The following goals can be allocated to civilian nuclear power:

- Cheap—at least competitive with alternatives.
- Safe—minimal risk from accidents and natural disasters. This is a matter of design.
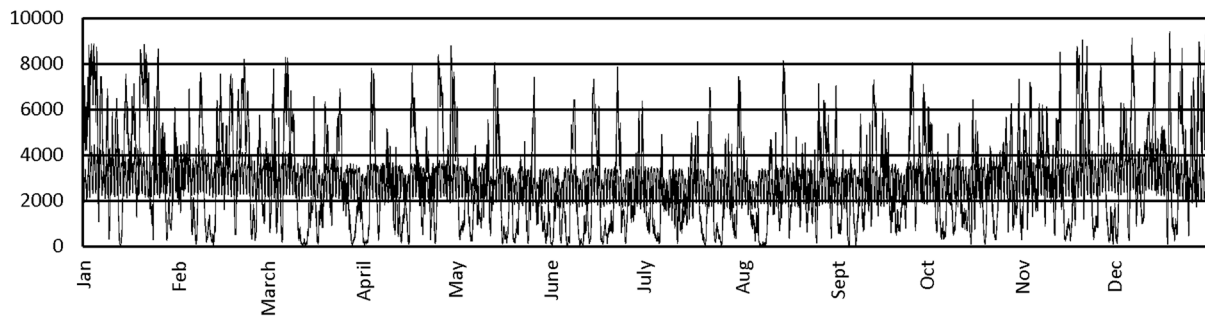
Figure 9. EirGrid 2012 load and adjusted wind.

- Sustainable—minimal demand for resources and waste management systems that do not place an undue burden on future generations.
- Secure—from weapon proliferation and terrorism. This is a management issue; the French concept of leasing fuel is one workable approach.

Of these four goals, sustainability is the requirement that will drive high-level system concepts. Sustainability refers both to sufficient fissile fuel to power the planet for thousands of years and to socially acceptable waste management systems. A valid objection to nuclear power today is the toxic longevity of nuclear waste.

3.1. The Need for Concept Definition Tradeoffs

Legacy nuclear power refers to the systems that are currently in operation. The key design decisions were rooted in submarines and cold war plutonium production. In 1948, Admiral Nimitz authorized the development of a nuclear powered submarine. Admiral Hyman Rickover's group chose pressurized light water reactors over other architectures because the reactor could be safely fit into a submarine. To Rickover, system cost was not very important; safety was achieved by highly skilled and trained operators; sustainability was a nonissue; secure meant do not tell the Russians.

Rickover's prototype submarine, *The Nautilus*, was launched in 1954, just 7 years after project start, and it worked superbly. He then scaled up and simplified the *Nautilus* reactor for civilian nuclear power as the Shippingport Atomic Power Station (activated in 1957). President Eisenhower gave the technology to the electric utilities who then commercialized civilian reactors. Legacy pressurized light water reactors are large-scale versions of the *Nautilus* concept [Weinberg, 1994].

Legacy systems are expedient; there has never been a high-level systematic optimization of systems for civilian nuclear power. Since sustainability is a new goal, it is time to step back and take a fresh look at nuclear power concepts; to identify civilian systems that are cheap, safe, sustainable and secure. *This is not happening.* Although the nuclear power industry has matured over the past 50 years it has also stagnated as the result of social resistance. There has been little in the way of new ideas or progress towards the goals.

3.2. Legacy Nuclear Does Not Scale

Current practice in the United States is a single–pass enriched uranium oxide fuel cycle with pressurized light water reactors. The plan is to dispose of used nuclear fuel in a geological repository like Yucca Mountain. Once the repository fills up, build another, then another. Each repository would be radioactive–toxic and need protection from disruption for up to a million years. These concepts do not scale to power all of the planet's energy needs for three reasons:

- The legacy fuel cycle burns ^{235}U, the only naturally occurring fissile isotope. The planet has enough ^{235}U to supply all of the world's energy needs of all types for only 7.8 years [Laughlin, 2011a].
- Powering the planet with legacy nuclear systems would require building 2.5 Yucca Mountains per year. This eventually results in a large number of repositories, each vulnerable to rare but catastrophic events.
- Geological repositories are open systems [MacFarlane, 2006]. It is unrealistic to expect civilization to maintain repositories for a million years.

3.3. Burn the Actinides

One strategy for reducing the toxic longevity of nuclear waste is to recycle the waste and burn the actinides as fuel. Legacy spent fuel consists of a large amount of ^{238}U plus two components: fission products and the actinides. Fission products are atoms with an atomic weight roughly half that of uranium. They are the inevitable consequence of nuclear fission and their quantity is proportional the power produced. Most fission products decay back down to ambient radioactive levels in about 200 years. The second major component of used nuclear fuel is the actinides, atoms where the nucleus has absorbed a neutron but has not yet split. The major actinide is plutonium that can be separated and burned in existing reactors as fuel.

Figure 10 is a chart of the ^{235}U fuel cycle waste radioactivity as a function of time [Federov et al. 2010d]. The chart shows that actinides and daughters from single pass waste disposal will have higher radioactivity levels than natural uranium for several hundred thousand years. Separating the long lived isotopes reduces time-to-ambient to ∼200 years.
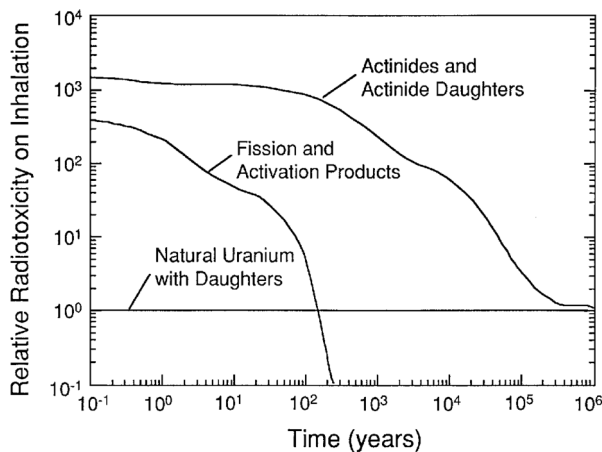
Figure 10. ^{235}U–^{239}Pu fuel cycle wastes.

3.4. Thorium Cycles

Since the actinides are the primary source of toxic longevity, a second strategy is to switch to a thorium cycle, which does not produce much actinides in the first place.

Figure 11 is a similar chart for a thorium–uranium cycle [Hargraves et al. 2010]. This cycle produces much less plutonium and other actinides though radioactivity from fission products is roughly the same. While the thorium–uranium cycle is not without its problems, it inherently produces less long-lived isotopes than the uranium–plutonium cycle.
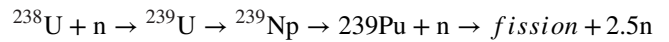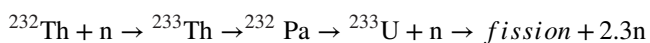
Fission products (isotopes with roughly half the atomic weight of the fissile element) constitute ∼3% of legacy spent nuclear fuel. If world scale nuclear fission required disposal only of fission products, the quantity would amount to one Yucca Mountain sized facility every 30 years and decay-to-ambient would be ∼200 years. This is consistent with Laughlin's estimate that powering the world with nuclear would generate a cubic football field of fission products every year [Laughlin, 2011b].

The main point of this section is that there is ample opportunity to further reduce the nuclear waste problem through recycling, transmutation, reactor design, and/or operation. There has been little R&D in this direction. Since the 1940s, nuclear waste management has been the poor stepchild of nuclear power development, and many experts seem unfazed by million year geologic repositories.

3.5. Neutron Economy

Nuclear fission occurs when a free neutron is absorbed by the nucleus of a fissile isotope. The fissile nucleus splits releasing enormous energy and additional free neutrons. Free neutrons are valuable and a primary metric for all reactors, especially breeder reactors.

A "fissile" isotope has a nucleus that splits (fissions) upon the capture of a neutron. A breeder reactor burns fissile material and converts "fertile" isotopes into fissile isotopes. There are two primary paths:

$$^{232}\text{Th} + \text{n} \rightarrow {}^{233}\text{Th} \rightarrow {}^{232}\text{Pa} \rightarrow {}^{233}\text{U} + \text{n} \rightarrow fission + 2.3\text{n}$$

$$^{238}\text{U} + \text{n} \rightarrow {}^{239}\text{U} \rightarrow {}^{239}\text{Np} \rightarrow 239\text{Pu} + \text{n} \rightarrow fission + 2.5\text{n}$$

The thorium path requires 2 neutrons and releases 2.3. The uranium path also requires 2 neutrons and releases 2.5. The question is whether the excess 0.3 or 0.5 neutrons are enough to overcome losses in practical reactors. If the losses exceed excess neutrons, breakeven breeding will require augmentation with either accelerators or lasers.

"Neutron economy" is a balance sheet describing the ways neutrons are used in a breeder reactor, as in fission, leakage, and absorption. A desired use is to breed more fissile material. An undesired use is absorption into a neutron poison. The neutron economy is a "first design driver" that can help to determine the best practical reactor performance. Thus, exploratory reactor design results are needed to create reactor simulations that estimate the neutron economy. System architects and engineers cannot realistically parameterize system designs suitable for exploratory power grid concepts until reasonable performance numbers can be extracted from a number of point reactor designs. The primary goal of this effort is to devise computational tools to scope the initial design of environmentally safe nuclear processes and reduce prototype testing requirements.

3.6. Fertile Resources

Fertile isotopes, ^{232}Th and ^{238}U, can be transmuted into the fissile isotopes ^{233}U and ^{239}Pu that do not occur in useful amounts in nature. Planet surveys have identified sufficient fertile isotopes ^{232}Th and ^{238}U to supply all of the world's energy needs of all types for about 2100 years [Laughlin, 2011c].

In contrast, ^{235}U is the only naturally occurring fissile isotope. The planet has enough ^{235}U to supply all of the world's energy needs of all types as a primary fuel for only 7.8 years [Laughlin, 2011a]. But ^{235}U is needed as a source of neutrons to start up breeder reactors. The planet has enough ^{235}U to startup enough breeders to power the planet, but not much more. Using ^{235}U as a primary fuel is equivalent to burning seed corn.

3.7. System Candidates

Powering the planet with nuclear fission will require ∼8 × 10^{17} Watt-hour/year of sustainable primary energy. The Generation IV International Forum (GIF) has the goal to develop the next generation nuclear reactor, available for deployment by 2030. There is a significant difference between these goals. The Gen IV goal is constrained by 2030 completion and certain assumptions about the pace of development. Society needs to see conceptual feasibility independent of time and money; because time and money depend on what society sees. Our goal is broader, constrained by current knowledge, resulting in the following alternatives:

- Supercritical water cooled reactor
- Molten salt reactor
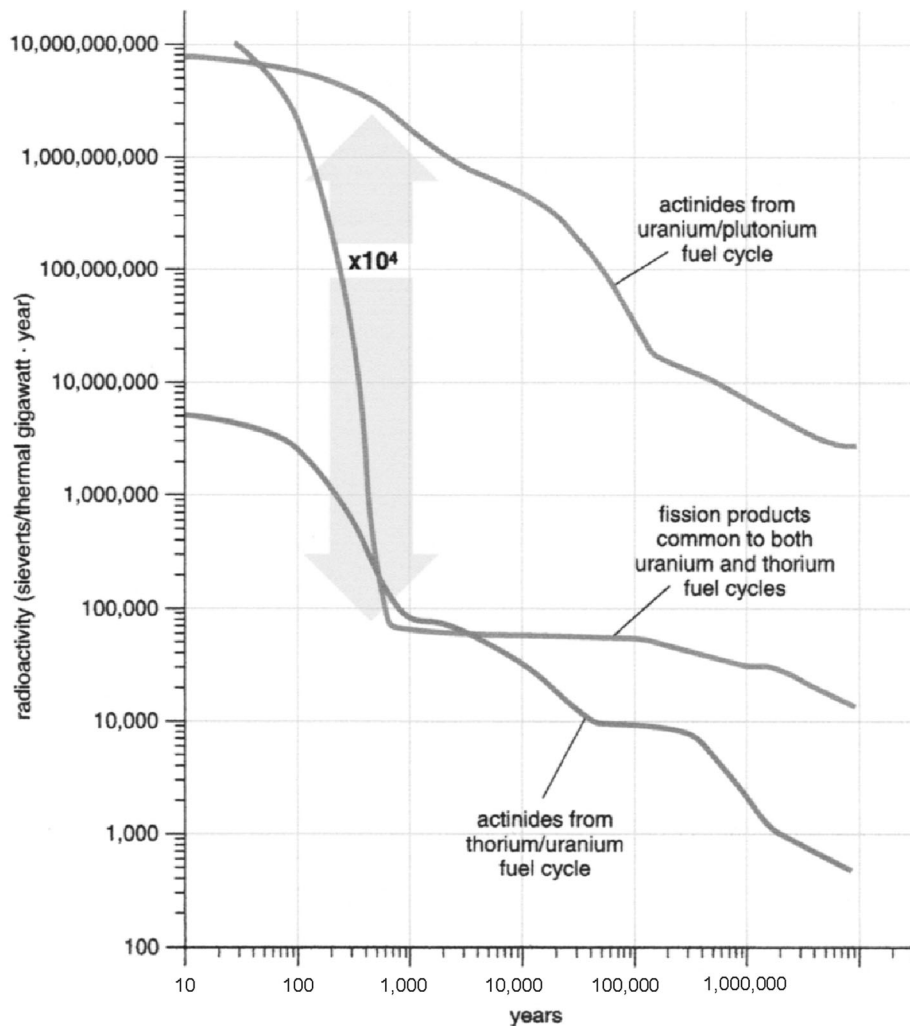- Gas-cooled fast reactor
- Sodium cooled fast reactor

Figure 11. ^{232}Th–^{233}U fuel cycle waste (Hargraves).

- Lead-cooled fast reactor
- Liquid fluoride thorium reactors
- Traveling wave reactor
- Accelerator driven concepts
- Laser-driven concepts

The required task is classic system tradeoffs. For each candidate, layout concept maps, architecture, design drivers, risks, assess overall cost and performance, and compare with goals to characterize overall feasibility.

3.8. SE Contribution to Nuclear Power Concepts

Around the world, nuclear power R&D is largely independently directed, point designs with little coordination, no ultimate goal or purpose; lots of road maps but few strategically chosen destinations. R&D is largely directed at improving legacy systems. Advanced R&D is dominated by point design prototypes: a traveling wave reactor, high-temperature gas reactor, liquid fluoride thorium reactor, various small modular reactors. The search is for the miracle solution [Gates, 2010],

the killer app. All of this is useful, but inefficient because there is no focus to simplify complexity, and development cycles are long and expensive.

Synthesizing system architecture consists of two processes: aggregation and partitioning [Rechtin 1991a]. Candidate system concepts were identified in Section 3.7. Concept maps aggregate components into generalized functions. Nuclear fission systems have a number of functional components:

- Primary fuel: ^{235}U, ^{238}U, ^{232}Th
- Fuel form: liquid vs. solid
- Core design
- Fuel cycle: Wigner and Urey, two legends in nuclear power development, insisted that civilian reactors ought to be chemical plants where solid fuel elements were replaced by liquids [Weinberg, 1997].
- Primary coolant: H_2O, D_2O, Na, Pb, He, CO_2
- Heat exchange: single loop–dual loop
- Heat engine: Rankine cycle, Brayton cycle
- Recycling: batch or continuous. Is this a primary design driver?

- Waste management: Waste product history (Figs. 10 and 11) need to be overlaid with more rigor including radioactive isotopes, daughter products, chemical poisons and gases. A sensitivity analysis to reactor conditions and postprocessing would allow a quantitative comparison of various fuel cycles and ~100% burn from the perspective of toxic longevity.

Concept maps help configure systems that allow a comparison based on cost, performance, and risk. Civilian nuclear power needs a rigorous concept definition phase. Concept definition concludes with a narrow set of choices and recommendations for engineering development. Classical SE development does not build prototypes until critical item testing provides objective and high confidence that investment in a prototype is justified.

4. CONCLUSIONS

This paper advocates a classical SE approach for clean energy development. The first step is a clear definition of the ultimate goal. The goal chosen for this paper is how to power the world without fossil fuel. An equivalent goal could be a large (>90%) reduction in GHG emissions. SE allocates these goals to energy sectors. Either goal requires low <10% emission fossil fuel electric power system.

Given the ultimate goal and its allocation, the next step is the concept definition phase; to clarify technically feasible alternatives. The concept definition phase is classically concluded with milestone B, a critical review followed by a management decision, a value choice. This paper explored two scenarios, wind and nuclear power.

For wind systems, this paper articulated a general design principle for building low emission wind systems.

1. Build enough fossil fuel capacity to reliably satisfy peak demand with no wind.
2. Add wind + storage to reduce fossil fuel consumption to <10%.

For the PJM region the Budischak paper meets the 0.1% carbon goal by overbuilding wind and discarding two-third of the wind generated electricity. Cost will be significant. This design concept needs rigorous system development to clarify costs, performance, and risks.

Nuclear power presents a different set of challenges. Society wants nuclear systems that are cheap, safe, sustainable, and secure. A primary obstruction is waste disposal in geologic repositories toxic for >100,000 years. This paper presents evidence that there are options for building socially acceptable civilian nuclear power systems. These options are not being developed with vigor because experts are not focused on the ultimate goal.

The most serious barrier to progress today is management defects. Society has not expressed an ultimate goal and seems unaware of the importance of an ultimate goal. As a result, a variety of stakeholders guess at interim goals that conflict with each other. Similar, there is no executive, no architect, no honest broker providing a coordination mechanism. Given a clean and stable ultimate goal, the classic critical system design review provides a good mechanism to clarify fact and provide stakeholders with the knowledge they need to adapt, self-organize, and to focus their efforts.

Apollo put a man on the moon in 10 years. Adm. Rickover developed the light water nuclear reactor and launched the submarine *Nautilus* in 7 years. Like these projects, clean energy development is primarily a systems engineering development project and could evolve quickly if there was a mandate to do so. The primary barrier is an inadequate concept definition phase.

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