
A System Architect's Basic Guide to Understanding & Designing Next Generation Grid Systems

By

Gregory Sachs, PE

B.S., Marine Engineering Systems
US Merchant Marine Academy, 1999

Submitted to the System Design and Management Program in Partial Fulfillment of the Requirements for the Degree of Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology
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Signature of Author ________________________
Gregory Sachs
System Design and Management Program
May 2010

Certified by ________________________________
Stephen R. Connors, Thesis Supervisor
Director, Analysis Group for Regional Energy Alternatives
MIT Energy Initiative

Accepted by ________________________________
Dir System Design & Management Program

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Abstract

A strong and growing desire exists, throughout society, to consume electricity from clean and renewable energy sources, such as solar, wind, biomass, geothermal, and others. Due to the intermittent and variable nature of electricity from these sources, our current electricity grid is incapable of collecting, transmitting, and distributing this energy effectively.

The "Smart Grid" is a term which has come to represent this 'next generation' grid, capable of delivering, not only environmental benefits, but also key economic, reliability and energy security benefits as well.

Due to the high complexity of the electricity grid, a principle based System Architecture framework is presented as a tool for analyzing, defining, and outlining potential pathways for infrastructure transformation. Through applying this framework to the Smart Grid, beneficiaries and stakeholders are identified, upstream and downstream influences on design are analyzed, and a succinct outline of benefits and functions is produced.

The first phase of grid transformation is establishing a robust communications and measurement network. This network will enable customer participation and increase energy efficiency through smart metering, real time pricing, and demand response programs.

As penetration of renewables increases, the high variability and uncontrollability of additional energy sources will cause significant operation and control challenges. To mitigate this variability reserve margins will be adjusted and grid scale energy storage (such as compressed air, flow batteries, and plug-in hybrid electric vehicles or PHEV's) will begin to be introduced. Achieving over 15% renewable energy penetration marks the second phase of transformation.

The third phase is enabling mass adoption, whereby over 40% of our energy will come from renewable sources. This level of penetration will only be achieved through fast supply and demand balancing controls and large scale storage. Robust modeling must be developed to test various portfolio configurations.

Thesis Supervisor: Stephen Connors
Director, Analysis Group for Regional Energy Alternatives
Acknowledgements

It is with deep appreciation that I extend this thanks to all those who have contributed to my incredible experience here at MIT.

To my MIT friends and colleagues -
It is your camaraderie which makes the experience most meaningful and lasting.

To Pat Hale and the rest of the SDM staff -
Who manage and run a dynamic, effective, flexible, and incredibly relevant program.

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And to my parents & brother -
For your constant encouragement, unwavering support, and unconditional love.. all of which have made me who I am today.

Thank you.
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Introduction – Preparing For a New Age of Energy Delivery

The Electricity Paradigm shift
The enabling technologies in shifting from carbon to post carbon energy

THE GRID IN PERSPECTIVE

So what is the "Grid"? By one characterization, it is a vast array of cables connecting virtually every single building in North America. Through this network a most precious resource is delivered: energy. This energy is in the form of "electricity".

This, even in its simplest manifestation, is an amazing feat. Let it be a tribute to human society that we live in a world where this is possible. What we've done is a vast engineering achievement - a tribute to our capabilities, akin to other major infrastructure projects such as the national highway system or the global internet.

But how do these systems get designed? How do we continue to improve these systems? As we shall discuss in this paper, a System Architect is one who assimilates complex systems, removes ambiguity, and determines the optimal system design.

ELECTRICITY GRID = ENERGY DELIVERY NETWORK

PRIMARY OBJECTIVE: To deliver energy from point A to point B.

We've done a pretty good job with this; we generally accomplish our basic objective of keeping the lights on. Keeping this primary objective in mind is important as we evolve our system to meet new requirements, and determine how to design a 'smarter', more robust grid of the future.

Despite our ability to accomplish this core objective, even just in designing the grid we have today, we've realized that there are many other requirements to building an 'electricity/energy delivery network' than simply connecting wires between source and load.

In other words, while a canoe might have the ability to get us from point A to point B, it may be inadequate as we consider other important requirements. For example, we may need to get there faster - requiring an engine, or need it to operate in rough water – requiring a cover to keep the water out, or to accommodate more people and equipment – requiring it to be larger.

While two wires originally connected source and load, the system quickly grew. We needed more power - so wires became larger, we needed to transmit energy over large distances – DC became AC and two wires became three, so we could use transformers and benefit from 3 phase transmission, we needed to protect equipment – so we began using fuses and breakers, we needed to measure the amount of energy delivered – so we designed meters and a marketplace for buying and selling electricity.
Quickly our canoe became a boat, which became a ship, with many complex systems within, all contributing to the primary objective of simply transporting you from point A to point B.

This is what we might call our "Grid 1.x", an infinitely complex array of wires, transformers, meters and breakers, all accomplishing their tasks as necessary to ensure you have a hot brewed cup of coffee in the morning.

**SEEKING GRID 2.0**

No doubt, we live in interesting and exciting times. We all now find ourselves participating in what seems to be a new social movement, marked by intense connectivity and information about each other and our world. With this social movement we have created new social norms and expectations. Among other things, we expect information, quickly and accurately, we seem to have a newfound respect for our environment and the impacts we have on it.

Not only have our expectations changed, but our rapid growth and changing society has placed new requirements on those things which provide our basic services (aka, the electricity grid).

We've done a pretty good job of designing and improving Grid 1.x, but now what..? We currently have a grid which delivers energy from centralized sources, typically burning fossil fuel or converting nuclear energy, in one direction to homes and business with little to no information about how it is used.

How do we accommodate alternative sources such as wind and solar? How do we ensure participation by customers? How do we make the grid "smarter" such that it reacts to changing conditions?

More importantly we should step back and ask, how do we even determine what EXACTLY are the key objectives and new system requirements? Only then can we determine how this system should take form and what tools do we need to accomplish this?

Be this the role of the System Architect.

**THIS PAPER: A FRAMEWORK FOR UNDERSTANDING & DESIGNING A "SMART GRID"**

OBJECTIVES: This paper..
- Is intended to be a basic guide to existing and future system architects
- Is both a technical review of aspects of the Smart Grid AND..
- A characterization of System Architectural principles and methodologies
- Ask the basic questions for assessing and critiquing existing projects and architectures
- Shall present various methods and metrics which could be used by future architects to model actual smart grids
REFERENCE: This paper...
- Is a synthesis of other great work by EPRI, the DOE, and countless others
- Provides references to bodies of work for future research
- Summarizes fundamental concepts from the System Design & Management curriculum at MIT

**PAPER IN REVIEW**

*Introduction – Preparing for New Age of Energy Delivery,* is intended to put the basic questions and paper objectives in context.

*Part I. System Architecture Fundamentals,* is a brief introduction to the principle based architectural framework necessary to understand and characterize infinitely complex systems such as the power grid.

*Part II. Methodology Applied: Simple Electricity Grid,* uses the basic System Architecture principles (presented in Part I) to characterize the growth and evolution of our existing grid. This exercise is illustrative and provides a foundation for analyzing more complex grid networks.

*Part III. Characterizing the "Smart Grid",* applies the system architecture framework to clearly outline "smart grid" benefits, goals/objectives, functions, technologies and architectural next steps.

*Part IV. Grid Infrastructure Transformation – Beyond 2.0,* applies system architecture methods to outline an infrastructure transformation pathway, and suggests visions of a 10, 20 & 30 year grid vision.

*Part V. Observations & Conclusions in Framework Application,* summarizes the key observations and conclusions of this paper.

The *Appendices* provide helpful supportive information, and are referenced throughout the paper.
Part I. System Architecture Fundamentals

The basic Architecting Process (Review of core MIT-SDM concepts)
Laying the foundation for Architectural Analysis for more complex systems (i.e., the Smart Grid)

OVERVIEW

In this section we briefly outline the fundamental concepts of the System Architecture field of study. Our objective is laying the foundation for analysis of complex systems, specifically existing and next generation electricity distribution systems (the "Grid").

Some basic questions to be answered:
- What is the study of System Architecture? Why is it so important?
- How does it fit in context with the system/product development and deployment process?
- What are the key defining concepts?
- What is a System Architecting process which can be followed?
- How can this framework be used to assess existing and define new architectures?
- How can it be applied to the electric grid?

Recurring Concepts & Vocabulary

In order to fully understand and appreciate the complexity of the grid and how to characterize its various systems, it is necessary for the reader to develop a vocabulary of important System Architecture terms. Each term refers to an important concept repeated regularly throughout this paper. A glossary is provided in the appendix to help in providing definitions for each of these terms. To assist in identification of these terms and recurring concepts the terms have been bolded occasionally throughout the paper.

SYSTEM ARCHITECTURE IN CONTEXT

Systems Architecture broadly interpreted is a field of research, study and practice whose main goal is the design and safe and efficient operation of man-made products, services and infrastructures. System Architecture narrowly interpreted is a principle based goal-oriented framework, accounting for all life cycle influences, facilitating convergence on optimal system design. (1)

Systems Architecting can be characterized within the greater context of the Systems Engineering field of study. In short, where System Architecture is focused on the creative process of system definition, which incorporates consideration all lifecycle influences, Systems Engineering encompasses the actual act of seeing the system/product through detailed analysis and delivery.
FROM CONCEPTION TO DEPLOYMENT: ROLE OF THE ARCHITECT

There are many models which describe the system or product development process (PDP). As suggested, this process incorporates the architecting process. Below we outline the typical generic four stage PDP.

**Generic Product Development Process:**
1. Conceive (envision)
   a. Define mission
   b. Conceptual design
2. Design
   a. Preliminary design
   b. Detailed design
3. Implement (develop)
   a. Element Creation
   b. Integration, System Test
4. Operate (deploy)
   a. Life cycle support
   b. Evolution

Each of these stages occurs generally in chronological order, while not always the case. The majority of the System Architect's work is during the (1) Conceive and (2) Design stages, however he/she must consider all stages of the process.
Why the System Architecture Process is so Important?

The architecting process is so important for several reasons. Architecting...

- ..is the most abstract, highest level function in product/system development process
- ..is done by the smallest number of people (sometimes by one)
- ..has some of the greatest impact on eventual success
- ..factors in the greatest number of considerations
- ..is not primarily concerned with detailed or quantitative data

ARCHITECTING PROCESS / KEY CONCEPTS

While there is no set or succinct procedure for the architecting process, the following suggested procedure / framework is helpful. Summarized within this procedure are also the fundamental concepts we shall use throughout this paper.

Beneficiary & Stakeholder Needs & Objectives – Our starting point (Steps 1, 2 & 3) is to arrive at a clear set of goals or objectives (terms can be used interchangeably). While this seems obvious enough, this is often cited as one of the most challenging steps — reducing ambiguity. To assist in this process a framework is suggested which considers upstream and downstream influences, further described in the Appendix. This step incorporates clearly defining the primary beneficiaries and stakeholders. Ultimately we seek succinct statements of benefit, at the appropriate level of detail, which describes the values delivered by the system or subsystems.

Functional Requirements – There may be many ways in which the benefit (previously defined) can be delivered. Our next objective (Step 4) will be to consider specific functions which can deliver this value/benefit. These statements of function are solution neutral and don’t necessarily suggest any specific "concept" or method by which this function can be accomplished.

Concept Synthesis / General Form Definition – With a clear set of desired functions, we can now creatively consider potential concepts and forms to perform the function (Steps 5, 6, 7 & 8). Especially during these early stages of the design process (assigning form to function), weighing the concept, form, system boundaries, and influences (previously defined) are highly coupled. (One important reason that these elements must be considered together is because a solution might be irreducibly complex.)

Detailed Form & Iteration – The principle of iteration is fundamental to System Architecting. Only through repeated comparison and consideration can we converge on optimal solutions and define requirements for subsystems (Steps 9 & 10). It will generally be necessary to start over at the beginning for other layers of decomposition.
### Table 1 – Generic System Architecting Process

<table>
<thead>
<tr>
<th>GENERIC SYSTEM ARCHITECTING PROCESS</th>
</tr>
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<tbody>
<tr>
<td>1. <strong>Primary Beneficiary Needs</strong> -</td>
</tr>
<tr>
<td>Identify primary <strong>beneficiaries</strong>, determine their <strong>needs</strong>,</td>
</tr>
<tr>
<td>...carefully considering various <strong>upstream &amp; downstream influences</strong>, <strong>context</strong>, etc.</td>
</tr>
<tr>
<td>2. <strong>Other Stakeholder Needs</strong> -</td>
</tr>
<tr>
<td>Identify other <strong>stakeholders</strong>, determine their <strong>needs</strong>,</td>
</tr>
<tr>
<td>...carefully considering various <strong>upstream &amp; downstream influences</strong>, <strong>context</strong>, etc.</td>
</tr>
<tr>
<td>3. <strong>Succinct &amp; specific statement of benefit</strong> -</td>
</tr>
<tr>
<td>For each of the parties above, from these needs, identify specific <strong>statements of benefit</strong> to be obtained from the yet undefined system or product.</td>
</tr>
<tr>
<td>(a) Benefit is defined as <strong>value at cost</strong>. Therefore benefits should have objectively measurable components. (b) Benefits must ultimately be defined for both the <strong>whole product system</strong> (top or existing layer) and for all <strong>subsystems</strong> at the first (or next) layer of decomposition (i.e., what is the 'source(s) of benefit'). Terminology should be used specific to that layer of abstraction/decomposition. Multiple iterations may be necessary to define current and next level benefits (see #10). (c) Ideally benefits can be defined by some sort of mutually exclusive categorization to ensure completeness.</td>
</tr>
<tr>
<td>4. <strong>Prioritize the Benefits</strong> -</td>
</tr>
<tr>
<td>Prioritize the <strong>benefits</strong> based on the importance or influence of the beneficiary or stakeholder. Prioritization may be necessary based on system complexity and because tradeoffs between competing benefits are typically required.</td>
</tr>
<tr>
<td>5. <strong>Statement of Function</strong> -</td>
</tr>
<tr>
<td>From these benefits, consider <strong>solution neutral statements of function</strong> which deliver the benefits outlined. <strong>Statements of function</strong> consist of a <strong>process</strong> and <strong>operand</strong> (an operand is the thing which undergoes a transformation delivering the value). Functions should address benefits both (a) whole product system benefits (currently layer benefits), and (b) first layer decomposition benefits (the layer beneath the existing).</td>
</tr>
<tr>
<td>6. <strong>Creatively Consider Concept</strong> -</td>
</tr>
<tr>
<td>Creatively consider the statements arriving at potential <strong>whole product system concepts</strong> which would deliver the desired value.</td>
</tr>
<tr>
<td>7. <strong>Define Boundaries</strong> -</td>
</tr>
<tr>
<td>Define whole system and <strong>subsystem boundaries</strong>; consider what must pass across boundaries.</td>
</tr>
<tr>
<td>8. <strong>Creatively Assign Form</strong> -</td>
</tr>
<tr>
<td>Creatively assign <strong>form</strong>, physical or a process (such as in software or economics), based on various concepts.</td>
</tr>
</tbody>
</table>
9. **Iterate Within System to Define Design**
   Iteratively and creatively consider form, concept and function, including secondary or lower priority
   benefits and system interfaces, ultimately converging on optimal design.

10. **Repeat for Subsystems**
    Repeat procedure as necessary for subsystems which make up current and subsequent layers of
    decomposition/abstraction.

The figures below are helpful in considering the Architecting process. Note, however, that while these
figures and the process above suggest a linear process, all aspects (including operations) are considered
throughout.

**Figure 2 – Graphical Representation of Deployment Process (2)**

The illustrations above serve to provide a visual representation of the deployment process. It is critical
to realize that, while the deployment process is linear and flows downward (as shown), the actual
"architecting process" accounts for all upstream (needs) and downstream (operations) influences
simultaneously in arriving at design. In other words, consideration of this illustration is contained in
namely in steps 1 & 2 above.

**METHODOLOGY APPLIED: SIMPLE SYSTEMS**
*Practical Application on Non-Complex Systems*

Understanding the concepts presented above are very important and best illustrated through simple
examples. We will build on these concepts in the next section as we discuss the architecture of the
current electricity grid.

The following simple examples are provided to illustrate the process and basic concepts above.

Please refer to the Appendix for more supporting information about System Architecting processes.
### Table 2 - System Architecture Methodology Applied to Simple Systems

<table>
<thead>
<tr>
<th>Step</th>
<th>Cup</th>
<th>Motorboat</th>
</tr>
</thead>
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<tr>
<td>1. Primary beneficiary need</td>
<td>Quench thirst</td>
<td>Get to the island, quickly but cheaply.</td>
</tr>
<tr>
<td>2. Other stakeholders needs</td>
<td>No other stakeholders</td>
<td>Regulator requires it to be safely done. Society requires that it be done without polluting.</td>
</tr>
<tr>
<td>3. Succinct &amp; specific statement of benefit (value)</td>
<td>Consume water (or other fluid) ⇒ Collect and hold the water so it can be drank</td>
<td>Move from one location to another, crossing water.</td>
</tr>
<tr>
<td>4. Prioritize the benefits</td>
<td>NA</td>
<td>Primary objective is not to be fast; rather to get there!</td>
</tr>
<tr>
<td>5. Solution neutral statement of function (Consisting of a process and operand)</td>
<td>&quot;Contain fluid&quot; is a solution neutral statement.</td>
<td>&quot;Transport people and/or equipment&quot; is a solution neutral statement.</td>
</tr>
<tr>
<td>7. Define boundaries</td>
<td>Single system, no subsystems.</td>
<td>Selecting a boat concept, we realize that there are many systems to consider... Floating system; Propulsion system; Safety system</td>
</tr>
<tr>
<td>8. Creatively assign form</td>
<td>Using a physical surface concept: Cupped hands -or- Concave impermeable surface (aka, a cup!)</td>
<td>Floating system: Flat bottom boat or sleek? Canoe or ship? Aluminum or fiberglass? Propulsion system: Human (paddle)? Sail? Motorized?</td>
</tr>
<tr>
<td>9. Iteratively consider form, concept and function, including secondary benefits, converging on design.</td>
<td>Account for other needs, such as the container keep the fluid cold (add insulation), or allow to be turned upside down (add a cap), or that it be 'green' or biodegradable (use recycled paper).</td>
<td>Based on the options above, balancing tradeoffs between speed, safely and cheaply... We may ultimately converge on a simple aluminum boat, with an efficient outboard motor, and a life jacket</td>
</tr>
<tr>
<td>10. Repeat for subsystems</td>
<td>NA</td>
<td>Each of the systems above could be broken down when analyzing subsequent layers of decomposition. Outboard motor: Spin propeller (next layer) ⇒ Fuel delivery system; Drive train system; Exhaust system... Fuel Delivery: Inject Fuel (next layer) ⇒ Fuel suction system; Fuel filtration system; Fuel proportioning system...</td>
</tr>
</tbody>
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Part II. Methodology Applied: Simple Electricity Grid

10 STEPS APPLIED TO EXISTING GRID

We now apply the methodology above to defining a basic Grid Architecture.

Step 1. Primary beneficiary need(s)

Primary Beneficiary Needs: CUSTOMER
From a general perspective, we could define some needs as:

- Operate machinery
- See at night
- Stay warm at night
- Power my computer
- ...etc

In each case, we could ultimately define a need as having "useful energy". There are many solutions which have been used over time to describe how to fulfill this need for useful energy: Horses to operate the machinery; oil to burn lamps to see at night; wood to burn to keep warm...

However, given our time and place in history, we know that all these needs can be fulfilled by a specific type of energy: Electrical Energy. We define this as "Electricity".

Revised, Primary Beneficiary Needs: CUSTOMER

- Inexpensive Energy ("Electricity")
- High Quality (Proper Voltage, Frequency & Quantity)
- Reliable (Available 24 x 7, winter or summer, and during bad weather)

Step 2. Other stakeholders needs

For clarification, some of the upstream and downstream categories have been assigned.

Stakeholder Needs: GRID OWNER/OPERATORS & GENERATORS
(Note that, depending on the context, grid owner/operators or Generators may also be considered secondary beneficiaries.)

- Method of transporting/distributing electricity over long and short distances
- Methods for securing and directing electricity to specific locations
- Can be operated safety (downstream influence)
- Method of measuring electricity delivered (upstream influence)
- Economic mechanism for generators to sell, and retailers/customers to purchase the electricity
- Method for controlling and dispatching generators

Stakeholder Needs: REGULATOR

- Reliable electricity delivery
- Cost effective electricity
- (environmental)
**Stakeholder Needs: SOCIETY**

- Minimal environmental impact (upstream influences)
- Jobs / Employment

There are many other stakeholders and needs. For the sake of this exercise, we shall limit to the above.

**Steps 3 & 4. Succinct & specific statement of benefit (value). Prioritize the benefits**

Clearly, a common thread can be extracted from the above statements of need and translated into a few basic benefit categories:

**FIRST:** Generally reliable energy/electricity delivery
**SECOND:** Safe operation & delivery of electricity
**THIRD:** Cost effective electricity
**FOURTH:** Minimal environmental impact

Foremost, in most first-world countries, ensuring the electricity is generally available is paramount. (Higher level reliability issues such as temporary outages and brown outs will be weighed in evaluating a next generation grid.) From the consumer standpoint, while cost is very important, the threshold for cost is likely pretty high before they would decide to go without the electricity in the first place. Although interrelated, before cost, regulators and grid operators will ensure that safe operation is not compromised. Next, it must be cost effective, and last environmentally friendly.

We would expect the 'relative weight' on these benefits to shift as context changes. (Ie, Environmental benefits to become more important.)

Note also that these benefits are still rather generic, and could become much more specific. In other words, they could be written referring to specific benefits in derived from to specific subsystems. As we will see when we discuss benefits derived from a "Smart Grid" (Part II), "Reliability" decomposes into "Power Interruptions" and "Power Quality". And subsequently "Power Interruptions" decomposes into "Momentary" vs "Temporary droops" in voltage (Ie, brown out).

**Step 5. Solution neutral statement(s) of function (process and operand):**

Primary Value Statement (Whole product system)
- **Electricity Distribution**

Specific Value Statements (First Layer Decomposition)
- **Electron Channeling** (wires/conductors)
- **Short Circuit Protection** (breakers, fuses, safety switches)
- **Kilowatt-Hour Measurement** (energy meters)
- **Energy/Electricity Supply** (power plants)
- **Supply Regulation** (governors)
- **Voltage & Frequency Monitoring** (characteristic meters)
- **Economic Electricity Exchange** (wholesale market)
**Step 6. 'Whole-Product System' Level Concepts**

Foremost, we must select the concept(s) at the whole product system level by which the primary benefit is delivered. As we could see, each of the suggested options would fundamentally and drastically change all elements of form (next steps) and system boundaries.

Electricity/Energy Distribution concepts include:
- Moving electrons through wires (*Method of choice*)
- Electro-Magnetic waves through air
- Small generators at each load

Having selected 'moving electrons through wires', there are alternative concepts, which have impacts at the whole product system level, for how the electrons are driven:
- Sinusoidal Alternating Current
- Direct Current
- Square-wave Alternating Current

In considering these high level architectural concepts, we can see how the evolutionary and iterative process has played out through history. First with considering non-electricity forms of energy delivery, followed by DC, followed by AC, each offering a proposed higher degree of benefit.

**Steps 7,8. Define boundaries; considering potential form**

With the primary concept selected, it is now possible to define sub-system boundaries, each with varying capabilities of delivering the detailed benefits above.

Sample Grid Subsystems Include:
- Transmission/Distribution Systems
  - High voltage (bulk power) transmission system
  - Low voltage (individual user) distribution System
- Individual components, AKA, small independent systems
  - Breaker/protection systems
  - Metering systems
- Master operation/dispatch & control system

Note the overlapping nature of Step 8, which is assigning form. By definition form can only be considered based its concept, and subsystem boundaries and interfaces.

**Steps 8,9,10. Creatively assign form; iterate & converge on optimal design**

Unless we are working at a whole product system level, most frequently (especially for large existing infrastructures) we will be considering architecting on a subsystem level.

It is important to realize that, while we have arrived a subsystem level architecture definition in '8 steps' (for the sake of this exercise), in practice the System Architect will have likely applied this methodology hundreds or thousands of times to their specific subsystem or component of choice at the appropriate level of decomposition.
While not the focus of this paper, numerous specific methodologies and tools exist to assist in studying effects, weighing tradeoffs, and ultimately converging on the optimal system design.

Clearly there are an infinitely large number of components to the grid. However, to illustrate mapping of functions, assets (same as technologies), and benefits, the sample table below is provided. While the table below shows specific assets associate with specific functions, often a certain asset may deliver multiple functions and multiple benefits.

**Key:**
- **Benefits** - Bold Black
- **Functions** - Bold Blue
- **Assets** (Technologies) - Bold Red

**Table 3 – Simple Electricity Grid Mapping of Benefits, Function & Assets**

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Functions</th>
<th>Assets</th>
<th>Energy</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Channeling</td>
<td>Short Circuit Protection</td>
<td>Energy Measurement</td>
<td>Energy / Electricity Supply</td>
<td>Economic Electricity Exchange</td>
</tr>
<tr>
<td>Wires / conductors</td>
<td>Breakers; fuses</td>
<td>Household Meters</td>
<td>Power Plants</td>
<td>Wholesale Market</td>
</tr>
</tbody>
</table>

**Reliable Delivery**
- Generally accepted as most effective way to route electricity to desired destination
- Prevent against permanent damage causing long outages
- Suppliers of electricity
- Mechanism by which power is sold and available

**Safe Operation**
- Generally accepted as safe
- Protects against short circuits; allows branches to be isolated

**Cost Effective / Electricity Savings**
- Overhead lines generally cheapest
- Fuses may be most cost effective, but less convenient
- Allows customer to know consumption, potential losses & savings
- Various types of generation provide more/less savings
- Mechanism by which generators compete to deliver cost effective energy

**Minimal Environmental Impact**
- Tradeoffs between processing & use of aluminum and copper
- Energy used will be related to environmental impact
- Future penalties (ie Carbon Tax) may drive efficiency or alternatives
KEY OBSERVATIONS

No Energy Storage

One key observation from this exercise is that the existing grid itself is not designed for bulk energy storage. While some small scale storage is inherent in spinning machines (or exists for frequency regulation purposes), its primary intent is the transfer of energy, not storage of it. In other words, at every instant in time the amount of energy generated (i.e., pushed into the grid) exactly matches how much is being demanded.

Samples of bulk energy storage may include:
- Gasoline
- Battery Electrolyte
- Flywheels
- Elevated reservoirs

As we shall see, storage will be one (of many) key components of our next generation grid.

PDP vs Infrastructure Evolution

Stated simply, the 'grid' isn't simply a product, it's a massive system comprised of innumerable smaller systems and products. Infrastructure transformation takes place as the emergent outcome of these systems changes. Throughout Part IV we will contextualize the philosophical difference between infrastructure transformation and a product development processes.

Next Steps?

Next we begin to consider improvements to our existing grid...

What benefits do we want? What benefits do we need? How do the design requirements differ for a Smart Grid? What is the actual form of the Smart Grid? How should the Architect define it? What makes one form better than another?
Part III. Characterizing the "Smart Grid"

INTRODUCTION

The traditional objective of electric system planning and operation functions is to supply electricity demand at minimum cost with acceptable levels of reliability and environmental impact. In so far as meeting this objective, we have done quite well. Our current electricity grid is quite effective at accomplishing the tasks as outlined in previously. Unfortunately, the requirements and context has changed and the existing grid no longer servers our needs.

In this part we comprehensively reevaluate and redefine the design requirements for a next generation (near-term) grid using the System Architecture framework and methodology previously demonstrated.

Once defined (Part III), in this framework will then provide a basis for discussing, not just the near-term "next generation" grid, but also medium-term and 'endgame' grid architectures (Part IV).

CHARACTERIZING THE QUESTION

Definitions by the Authorities..

Defining the "Smart Grid" is a widely discussed topic, answered on numerous websites, articles and white papers. Example definitions:

A "Smart Grid"...

..is a next-generation electrical power system that is typified by the increased use of communications and information technology in the generation, delivery and consumption of electrical energy. –IEEE

..incorporates information and communications technology into every aspect of electricity generation, delivery and consumption in order to: (a) Minimize environmental impact; (b) Enhance markets; (c) Improve reliability and service; and (d) Reduce costs and improve efficiency. –EPRI

..is an automated, widely distributed energy delivery network that is characterized by a two-way flow of electricity and information, and enhanced monitoring. ...which incorporates the benefits of advanced communications and information technologies to deliver real-time information and enable the near-instantaneous balance of supply and demand on the electrical grid. –DOE

1 http://smartgrid.ieee.org/about-smartgrid
2 http://smartgrid.epri.com/
3 http://smartgrid.gov/about_smart_grid
Answers vary widely, even among major authorities on the topic. Some definitions focus on benefits of a Smart Grid, others focus on products or equipment, most leave one still scratching their head. Surely there are common themes in each of the definitions above, but to gain a clear and concise understanding requires a careful analysis. In short, the Smart Grid is many things; how you decide to characterize and represent those things is by its nature a challenge.

A primary goal of this section is to apply our basic architectural framework to redefine what the "smart grid" should be and what it should be trying to accomplish.

**BOTTOM-UP Concept: Grid 2.0 → "Smart Grid" Defined**

Instead of attempting to define it outright (aka, top-down), we should change our perspective. Instead we...

- ...ask ourselves what fundamental characteristics we would want of a next generation grid, what beneficiaries and stakeholders would want out of an optimally designed power delivery network and then..
- ...write up those definitions and label that the "Smart Grid".

In other words, we should perform the role of a System Architect.

**Alternate Definition:** The 'Next Generation Grid' (aka, Smart Grid or Grid 2.0) is the synthesis of a new set of functional objectives determined through the consideration of beneficiary and stakeholder needs, and upstream and downstream influences.

**EXISTING FRAMEWORKS**

Thanks to the hard work by existing industry agencies, many models and characterizations have already been presented to characterize the various aspects of the Smart Grid. It is important to review some of these existing models as they provide a comparative context for our System Architecture based framework. The models below are also provided to also assist in obtaining a 'big picture' understanding of the domain. (Additional information and models are provided in the Appendix.)

This work is generally presented and/or facilitated by stakeholders in the industry, such as the Institute for Electrical & Electronic Engineers (IEEE), the National Energy & Technology Laboratory (NETL), the Electric Power Research Institute (EPRI), and many others.

**Sample 'Characteristics' of the Smart Grid**

Building on the definitions presented above, the following table and illustration provides a quick summary of the differences between our existing grid and a smart grid:

---

4 As another example, consider the difficulty in trying to define what an 'economy' is in a simple sentence. It is many things, and even authorities may vary widely on a definition statement.
Table 4 – Summarized Differences between Current & Next Generation Grid Systems (4)

<table>
<thead>
<tr>
<th>EXISTING GRID</th>
<th>SMART GRID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-mechanical</td>
<td>Digital</td>
</tr>
<tr>
<td>One-Way Communication</td>
<td>Two-Way Communication</td>
</tr>
<tr>
<td>Centralized Generation</td>
<td>Centralized &amp; Distributed Generation</td>
</tr>
<tr>
<td>Hierarchical</td>
<td>Network</td>
</tr>
<tr>
<td>Few Sensors</td>
<td>Sensors Throughout</td>
</tr>
<tr>
<td>Blind</td>
<td>Self-Monitoring</td>
</tr>
<tr>
<td>Manual Restoration</td>
<td>Self-Healing</td>
</tr>
<tr>
<td>Failures and Blackouts</td>
<td>Adaptive and Islanding</td>
</tr>
<tr>
<td>Manual Check/Test</td>
<td>Remote Check/Test</td>
</tr>
<tr>
<td>Limited Control</td>
<td>Pervasive Control</td>
</tr>
<tr>
<td>Few Customer Choices</td>
<td>Many Customer Choices</td>
</tr>
</tbody>
</table>

It is common to refer to the existing grid as being "Radial" in design, meaning that energy is supplied in one direct to the end user. Below we see a representation of a network where power can may flow dynamically in many directions. The ability to supply or draw power at any point is a key characteristic of the Smart Grid.

Figure 3 – Physical Topology Comparison between Existing & Future Grids (4)

Web 2.0 vs Grid 2.0

One of the common themes throughout is the concept of interactive participation by all parties. This is similar to the "Web 2.0" concept, which is commonly associated with web applications which facilitate interactive information sharing, interoperability, user-centered design, and collaboration on the World Wide Web.

In the same manner that "Web 2.0" applications allow users to interact with each other as contributors, a "Grid 2.0" allows users to actively participate in how they consume energy. For example, users could actively decide when to use more or less energy (i.e., washing/drying clothes) based on the market price of energy.
Table 5 – Analogies between Web & Grid 2.0

<table>
<thead>
<tr>
<th>WEB 2.0</th>
<th>GRID 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two way flow of information</td>
<td>Two way flow of energy</td>
</tr>
<tr>
<td>Interactive participation in social websites</td>
<td>Interactive participation in energy markets</td>
</tr>
</tbody>
</table>

In so far as the Web/Grid 2.0 analogy applies to social interactivity and software, the parallel is valid. However one distinction between the two is that the Web 2.0 movement doesn't necessarily imply a change in the physical architecture of network cables, while a Grid 2.0 implies a different physical topology.

**SMART IS: A Control System?**

What does it mean to be "Smart"? Frequently we associate smart with the ability to assess a situation, make decisions, and react. Following are the basic functions performed by any control system:

1. **Sense** a specific set of parameters
2. **Communicate/transmit** that information
3. **Decide** proper action based on assimilating data
4. **Actuate** accordingly

We can now map these functions to various components of a Smart Grid.

Table 6 - Typical Control System Components mapped to Smart Grid "Assets" (4)

<table>
<thead>
<tr>
<th>CONTROL SYSTEM 'FUNCTION'</th>
<th>SAMPLE 'ASSETS' WHICH DELIVERS THAT FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition Sensor system</td>
<td>Current transformer (CT), voltage transformer (VT), phasor measurement unit (PMU), smart meter, temperature, pressure, acoustic, and so on</td>
</tr>
<tr>
<td>Communication infrastructure</td>
<td>Power line carrier (PLC), wireless radio, advanced metering infrastructure (AMI), home area network (HAN), fiber-optic networks</td>
</tr>
<tr>
<td>Control algorithms (applications)</td>
<td>Wide-area monitoring and control; microgrid management; distribution load balancing and reconfiguration; demand response; optimal power flow (OPF); voltage and var optimization (VVO); fault detection, identification, and recovery (FDIR); automatic generation control (AGC); inter area oscillation damping; system integrity protection scheme (SIPS); and so on</td>
</tr>
<tr>
<td>Actuator system/physical system</td>
<td>HVDC, FACTS, DG, energy storage systems, reclosers, automatic switches, breakers, switchable shunts, on-load tap changers, hybrid transformers, and so on</td>
</tr>
</tbody>
</table>

As we will come to understand, while this is a helpful characterization, 'Automated Response' is only one aspect of the framework we will ultimately create surrounding the Smart Grid Architecture.
NETL's Five Smart Grid Key Technology Areas

With our initial objective of understanding stakeholder needs, it is also helpful to consider the NETL's Five Smart Grid Key Technology Areas.

INTEGRATED COMMUNICATIONS – Currently, little to no communications takes place between components, meters, operators or homeowners, especially on the distribution system. It will ultimately be necessary to create a new communication infrastructure, integrated or wholly separate from the existing World Wide Web, which is resilient from attack and highly reliable. Later we will refer to this as the nervous system of the smart grid.

SENSING & MEASUREMENTS – As presented in the control system analogy, it is vital to have an accurate reading of system parameter state in order to make decisions. For example, phasor measurement or customer consumption information would be made available to network operators.

ADVANCED COMPONENTS – These are the physical assets of the smart grid itself, including energy storage technologies, devices which allow for routing of power among transmission networks (FACTS), high voltage DC transmission devices, advanced meters, etc.

ADVANCED CONTROL (& PROTECTION) METHODS – These are the 'brains' of the systems, generally implying advanced software which can take input from the sensors and decide how the grid should react. Some decisions will be made from a central source, some automatically. For example, an monitoring algorithm might change breaker tripping set points depending system current flow or outdoor temperature.

IMPROVED INTERFACES & DECISION SUPPORT – While a the Smart Grid will have the capability of taking action on its own, ultimately decision making authority must reside with operators at the various network operation centers. Appropriately modeling, displaying and interacting with this information is vital.

Table 7 – Mapping of NETL Key Technology Areas to Control System Functions (5)

<table>
<thead>
<tr>
<th>NETL TECHNOLOGY AREA</th>
<th>CONTROL SYSTEM FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Communications</td>
<td>Communication Infrastructure</td>
</tr>
<tr>
<td>Sensing &amp; Measurements</td>
<td>Condition Sensor system</td>
</tr>
<tr>
<td>Advanced Components</td>
<td>Actuator system/physical system</td>
</tr>
<tr>
<td>Advanced Control Methods</td>
<td>Control algorithms (Software applications)</td>
</tr>
<tr>
<td>Decision Support</td>
<td></td>
</tr>
</tbody>
</table>
As before, while this is essential and helpful, it leaves the System Architect looking for more complete and comprehensive information. As such, we start our System Architecting Process.

**SMART GRID BENEFICIARIES & STAKEHOLDERS (STEPS 1 & 2)**

As part of the architecting process, we must clearly identify beneficiaries and stakeholders.

We should differentiate from the beneficiaries of a "Grid" and a "Smart Grid". While similar, we ignore some of the inherent and basic smart grid objectives and focus on specific differentiating needs of an improved grid.

**CUSTOMERS / RATEPAYERS** – In considering our primary value statement *(transmit electricity)*, the customer (residential, commercial or industrial) is the primary recipient of this basic service. Primary benefits include:

- Use of electricity
- Reduced electricity bills from changes in rates and services offered by the utility
- Reduced damages / costs from power interruptions (reliability) or quality

**GRID OWNER/OPERATORS & GENERATORS** – In typical unregulated markets, grid owners collect and distribute the energy, while 'generators' supply/sell electricity into the wholesale market. Both parties benefit from smart grid systems in many ways, namely economically. Specific benefits will be discussed.

**SOCIETY** – 'Society' refers to those who benefit from various externalities of Smart Grid systems (i.e., effects on the public or society at large). Benefits in this context would be reductions of negative effects of power generation such as pollutant emissions. Interestingly, positive externalities are more difficult to identify, such as indirect macroeconomic benefits of job creation.

**OTHER STAKEHOLDERS** – Stakeholders are generally those who do not directly benefit from system, but do have influence over the process. There are many stakeholders, each with more or less influence over Smart Grid evolution. Examples include:

- System Operators (could also be classified as beneficiaries)
- Regulators / Public Service Commissions
- Professional & Standards Organizations (IEEE, EPRI, GridWise Alliance, etc.)
- US Government
- Environmental Organizations
NETL published the "Seven Primary Characteristics of the Smart Grid" which have been widely accepted by the community. We shall use this to further assist in establishing a mutually exclusive succinct list of benefits/values.

In our context, we shall define a characteristic as something which is an outcome of the Smart Grid mix of systems. In other words, these are generic outcomes or items enabled by a next generation grid. These characteristics are similar to benefits, but as we shall see, are not specific enough to be useful on our way to determining statements of function.

Our objectives in the table below are as follows:
- Present the 7 principle Characteristics / Outcomes, as proposed by NETL
- Highlight a method for arriving at common and fundamental benefits
- Link sample assets to benefits & outcomes

**Table 8 – Seven Smart Grid "Outcomes"**

<table>
<thead>
<tr>
<th>Smart Grid desired OUTCOME (Items enabled by the SG)</th>
<th>Enabling Characteristics</th>
<th>GENERAL Benefit</th>
<th>SPECIFIC Benefit</th>
<th>Sample &quot;ASSETS&quot; or products ultimately produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Enables informed participation by customers</td>
<td>- Customers have access to information &amp; control options, &amp; can engage in energy markets - Operators can manage peak load through prices</td>
<td>- Electricity cost savings to customers - Better asset utilization</td>
<td>- Flatter load curve - Dynamic pricing - Lower total consumption</td>
<td>On-line buy/sell systems (like E-Bay), energy monitors, AM</td>
</tr>
<tr>
<td>2. Accommodates all generation &amp; storage options</td>
<td>- Seamlessly integrate all types and sizes of electrical generation and storage systems - Provides &quot;plug &amp; play&quot; convenience - Allows for smaller disturbed sources – shifting to a more decentralized model - Large power plants continue to play a major role</td>
<td>- Reduced GHG emissions - Reduced NOx, SOx, PM - Solid &amp; hazardous waste reduction - Reduced water consumption - Reduced land use</td>
<td>- Flatter load curve - Renewable Energy usage offsetting fossil fuels - Operation of generators more efficiently (timed use of storage)</td>
<td>Solar PV, Wind turbines, Compressed Air Storage - Reduced oil consumption - Offsetting gasoline vehicle usage</td>
</tr>
<tr>
<td>Smart Grid desired OUTCOME (Items enabled by the SG)</td>
<td>Enabling Characteristics</td>
<td>GENERAL Benefit</td>
<td>SPECIFIC Benefit</td>
<td>Sample &quot;ASSETS&quot; or products ultimately produced</td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>--------------------------</td>
<td>-----------------</td>
<td>------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>3. Enables new &amp; improved products, services &amp; markets</td>
<td>- Links buyers &amp; sellers - Links customer to RTO - Provides for consistent market operation across regions</td>
<td>- Reduced T&amp;D losses</td>
<td>- Improved network efficiency from time shifting energy to reduce strain. - Reduced cost of interruptions</td>
<td>Software to change control schemes when a feeder becomes a producer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Fewer sustained or major outages (through islanding)</td>
<td></td>
<td>Microgrid control systems and software</td>
</tr>
<tr>
<td>4. Provides power quality for the range of needs in the 21st century economy</td>
<td>- Monitors, diagnoses and responds to PQ issues - Supplies various grades of power quality at different pricing levels - Greatly reduces consumer losses due to PQ ($25B/year) - Quality Control for the grid</td>
<td>- Lower electricity cost / asset utilization - Capital / O&amp;M savings - Reduced oil consumption - [Much more]</td>
<td>- Flatter load curve - Dynamic pricing - Lower total consumption - Deferred investments - Reduced meter reading - [Much more]</td>
<td>PHEV &amp; V2G, Brokers, integrators, aggregators, etc., New commercial goods &amp; services</td>
</tr>
<tr>
<td>5. Optimizes asset utilization and operating efficiency</td>
<td>Operational: - Improved load factors &amp; lower losses - Integrated outage mgt. Asset Mgt: - Build only what's needed - Improved maint. practices - Improved resource mgt - More power, same equip Reduced O&amp;M</td>
<td>- Reduced costs of power interruptions</td>
<td>- Fewer sustained outages - Fewer major outages</td>
<td>Power quality meters, AMI, regulating equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Reduced costs from better power quality</td>
<td>- Fewer monetary outages - Fewer sever sags and swells - Lower harmonic distortion</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Electricity cost savings - Reduced T&amp;D Losses</td>
<td>- Flatter load curve, dynamic pricing, lower energy cost - Optimized network efficiency</td>
<td>Smart meters, DR control systems, current/power measuring devices.</td>
</tr>
</tbody>
</table>
Smarter Grid desired OUTCOME (Items enabled by the SG)

<table>
<thead>
<tr>
<th>Enabling Characteristics</th>
<th>GENERAL Benefit</th>
<th>SPECIFIC Benefit</th>
<th>Sample &quot;ASSETS&quot; or products ultimately produced</th>
</tr>
</thead>
</table>
| 6. Addresses disturbances through automated prevention, containment & restoration | - Performs continuous self-assessments  
- Detects, analyzes, responds to, and restores grid components or network sections  
- Handles problems too large or too fast-moving for human intervention  
- Self heals - acts as the grid's "immune system"  
- Supports grid reliability, security, and power quality | - Reduced cost of power interruptions  
- Reduced damage from wide-scale blackouts | - Fewer sustained outages  
- Shorter outages  
- Fewer major outages  
- Reduced blackouts | Measuring devices (ammeters, voltmeters), software algorithms, advanced reclosers / breakers, microgrid equipment. |
| 7. Operates resiliently against all hazards | - System-wide solution to physical and cyber security  
- Reduces threat, vulnerability, consequences  
- Deters, detects, mitigates, responds, and restores  
- Decentralization and self-healing enabled | - Reduced cost of power interruptions  
- Reduced damage from wide-scale blackouts | - Fewer sustained outages  
- Shorter outages  
- Fewer major outages  
- Reduced blackouts | Secure communications & networking equipment, (similar to #6) |

Key observations:
- General and specific benefits frequently overlap → As such, we shall explore alternative methods to categorize the benefits
- Ultimately our goal is to produce 'Assets' which can be used and sold on the marketplace. The same assets can deliver many benefits, and are often repeated under multiple categories.

In conclusion, the Seven Characteristics of the Smart Grid are very useful when seeking a summary of what a next generation grid (Smart Grid) will accomplish, but may not be specific enough in determining specific statements of function.

SMART GRID BENEFITS & VALUES DEFINED (STEPS 3 COTD.)

Thanks to the excellent work of the Electric Power Research Institute (EPRI), in their paper A Methodological Approach for Estimating the Benefits and Costs of Smart Grid Demonstration Projects, they propose a succinct list of Smart Grid benefits. In essence, they have performed a vital role of the system architect in trying to minimize ambiguity through the assimilation of the many needs of beneficiaries and stakeholders in this domain.
'Source of Benefit' = Specific Benefits from Subsystems (1st layer of decomposition)

It is important to observe that the table includes both 'General' and 'Specific' benefit categories. As previously described, for complex systems it is vital to describe the benefit using language specific to the layer of decomposition one level beneath our current level. This is vital because it allows the system architect to ultimately assign statements of function applicable to subsystems or components which reside at that level.

For example, it is not as helpful to simply define your benefit as 'cheap electricity' only. Instead, we put the benefit in terms applicable to the first layer of decomposition:

- Flatter load curve (using engineering terms specific to the operation of the whole product system or the grid)
- Lower overall consumption (refers to a benefit derived from a variety of potential subsystems, including efficient appliances, demand response systems, etc.)
- Dynamic pricing (refers to the benefit gained from subsystems which enable real-time pricing models)

Benefit = Value at Cost

Recall from our Architecture Fundamentals section, that a benefit is defined as value at cost. The inclusion of cost is vital because, in order to ultimately quantify the net benefit gained, an objective parameter (such as number of hours voltage is out of range) is necessary. Subsequently we can convert this measurable metric into a cash value. In this table EPRI therefore also proposes the objective metrics by which each of these benefits can ultimately be quantified.

Benefits Summary Table

Below is a summary table of benefits. Note that the benefits have been organized by mutually exclusive categories to assist in ensuring completeness. We observe, however, that while the 'whole product system' benefits may be different, the same benefits may be repeated at the first layer of decomposition. In other words, the benefits of subsystems often contribute to multiple overall system benefits. This underscores the challenges of the System Architect in trying to drive out ambiguity and converge on optimal system and subsystem designs.

Sample statements of function or assets are highlighted below in blue.
Table 9 – Smart Grid Benefits

<table>
<thead>
<tr>
<th>Benefit Category</th>
<th>Whole Product System Benefit</th>
<th>Source of Benefits / Specific Benefits from Subsystems</th>
<th>Measurable Parameters Related to Benefits</th>
</tr>
</thead>
</table>
| Economic         | Reduced generation costs from improved asset utilization (something the grid can control) | • Flatter load curve - From load shifted to off-peak periods, e.g., from consumer behavior and signals  
• Dynamic pricing and/or lower electricity rates (reflecting reduced generation costs with flatter load curve)  
• Lower total electricity consumption | • Generation costs (that reflect optimized generator operation)  
• Deferred Centralized Generation Capacity Investments  
• Reduced ancillary service costs |
|                  | Electricity cost savings – Lower electricity cost to consumers | • Hourly load data, by customer  
• Monthly electricity cost, by customer  
• Tariff description, by customer  
• Demographic and other information affecting demand  
• For firms, square footage and SIC code  
• Types of smart appliances in use |
| T&D capital savings | • Deferred transmission and distribution capacity investments  
• Reduced equipment failures | • Deferred T&D Investments |
| T&D O&M savings | • Reduced O&M operations costs  
• Reduced meter reading cost | • Activity-based O&M costs  
• Equipment failure incidents |
| Reduced transmission congestion costs | • Increased transmission transfer capability without building additional transmission capacity | • Actual real-time capability of key transmission lines |
| Reduced T&D losses | • Optimized T&D network efficiency  
• Generation closer to load - From distributed generation (DG) | • T&D system losses (MWh)  
• % of MWh served by DG |
<p>| Theft reduction | • Reduced electricity theft | • Estimated T&amp;D system losses from theft (MWh) |</p>
<table>
<thead>
<tr>
<th>Benefit Category</th>
<th>Whole Product System Benefit</th>
<th>Source of Benefits / Specific Benefits from Subsystems</th>
<th>Measurable Parameters Related to Benefits</th>
</tr>
</thead>
</table>
| Reliability & Power Quality | Reduced cost of power interruptions | • Fewer sustained outages  
• Shorter outages (reduced duration)  
• Fewer major outages | • SAIFI  
• SAIDI or CAIDI |
|  | Reduced costs from better power quality | • Fewer momentary outages  
• Fewer severe sages and swells  
• Lower harmonic distortion | • MAIFI |
| Environmental | Reduced damages as a result of lower GHG/carbon emissions | From each mechanism below:  
• Lower electricity consumption  
  - From Intelligent appliances  
• Lower T&D losses, from  
  - Optimized T&D network  
  - Generation closer to load (DG)  
• Lower emissions from generation, from  
  - Combined heat & power (CHP)  
  - Renewable energy (RE)  
  - Operating generators more efficiently  
  - Avoiding additional generator dispatch with demand response | • Reduced CO2 emissions  
• Reduced Sox, NOx and PM emissions  
- Hourly consumption by fuel type, compared to baseline/control group  
- % of MWH served by DG  
- T&D system losses (MWh)  
- MW of CHP installed  
- % of MWH served by RE  
- % of feeder peak load served by RE  
- Average heat rate of supply (or similar information) |
|  | Reduced damages as a result of lower SOx, NOx, and PM emissions |  |  |
| Other environmental benefits  
(Not in EPRI report) |  | • Solid & hazardous waste reduction  
• Reduced water consumption  
• Reduced land use | • Avoided water use from existing plant  
• Avoided area to build equivalent plant  
• Avoided quantity of hazardous waste which would have been otherwise been created |
To whom is the benefit delivered? Who Benefits?

In answering the question, "Why do we need a Smart Grid?", it is important to be able to specifically replay, "Because here is how you benefit." The table below helps clarify this.

Recall that this could also be considered the outcome of a Beneficiary/Stakeholder needs analysis. And from those needs, we derive the benefits below. As previously defined, there are four categories of benefits, including Economic, Reliability, Environmental and Societal. We acknowledge that there may be many other items which could be added to this table, but these were determined to be the primary benefits for this analysis.

Table 10 – Value Delivery to Whom

<table>
<thead>
<tr>
<th>Primary (Direct) Beneficiary</th>
<th>Stakeholder Needs! (\rightarrow) Delivered Benefit</th>
</tr>
</thead>
</table>
| Utility                     | • Optimized Generator Operation – Reduced generation costs  
                              | • Deferred Centralized Generation Capacity Investments  
                              | • Reduced Ancillary Service Cost  
                              | • Reduced Congestion Cost  
                              | • Deferred Transmission Capacity Investments  
                              | • Deferred Distribution Capacity Investments  
                              | • Reduced Equipment Failures  
                              | • Reduced Distribution Operations Cost  
                              | • Reduced Distribution Equipment & Maintenance Cost  
                              | • Reduced Meter Reading cost  
                              | • Reduced Electricity Theft  
                              | • Reduced Electricity Losses  
                              | • Reduced Restoration Cost  
                              | • Reduced CO2 Emissions  
                              | • Reduced SOx, NOx and PM-10 emissions  
                              | • Reduced Wide Scale Blackouts  |
| Consumers                   | • Reduced Electricity Cost to Consumers  
                              | • Reduced Sustained Outages  
                              | • Reduced Major Outages  
                              | • Reduced Momentary Outages  
                              | • Reduced Sags & Swells  |
| Society in General          | • Reduced CO2 Emissions  
                              | • Reduced SOx, NOx and PM-10 emissions  
                              | • Solid & hazardous waste reduction  
                              | • Reduced water consumption  
                              | • Reduced land use  
                              | • Reduced Oil Usage  
                              | • Reduced Wide Scale Blackouts  |
Other Societal Benefits. *Job Creation*

Enterprise and Societal Context

For very large and complex systems (such as the Grid), it may be difficult to know which benefits should be included or omitted, notably as they pertain to society at large. Society has many needs which could be addressed and have influence over Smart Grid design.

For example: ECONOMIC (category) → More domestic jobs (Whole product benefit) → Local resources and labor utilized in manufacturing equipment (Subsystem?)

Recall that our objective is ultimately to design specific pieces of equipment (determine form) which accomplish these objectives / deliver this value. While the value gained from domestic job growth should be considered in evaluating a new product (or demonstration project), its specific influence over the design process (which is important to us at this stage) is debatable. We acknowledge, however, that in certain instances this may have significant influence. The System Architect should evaluate these things as necessary.

Figure 5 – System Architecture in Enterprise & Societal Context (2)
REVIEW: Function → Concept & Form

Now that we have a specific list of benefits (at a sufficient level of abstraction/decomposition), we can now seek solution neutral statements of function which deliver the values we specified.

Recall:
- Function = Process + Operand
- "Operand" is the thing which undergoes transformation to deliver value

The statements are 'solution neutral' such that they do not encumber the creative process of assigning deriving the appropriate concept and form.

Basic Smart Grid 'Control & Operations' Functions

Using knowledge of existing grid subsystems and technologies, it is possible to compile a relatively comprehensive list of subsystem functions which can deliver the values we require. The list below, also compiled by the EPRI Cost Benefit Analysis Team, outlines various Smart Grid functions.

Additionally I have highlighted various potential 'Assets' in the table which represent the output mapping of function and form.

In summary, each statement could represent the primary function of a supporting subsystem. The net benefit of these subsystems, working together, contributes to the primary value related function of delivering energy to the consumer. Each of these could be accomplished through various forms (physical, software or process), yet to be determined by the "Subsystem" Architect.
<table>
<thead>
<tr>
<th>Function</th>
<th>Technical Overview</th>
<th>Sample Assets / Enabling Equipment</th>
<th>Expected Benefits from Function</th>
</tr>
</thead>
</table>
| Fault Current Limiting | Limitation of short circuits and fault currents can be to safe levels at generator outputs. | Fault Current Limiters (FCL's) | • Deferred Transmission Capacity Investments  
• Reduced Equipment Failures |
| Wide Area Monitoring, Visualization and Control | The ability to monitor transmission system conditions at control centers over large regions (multiple states) and display this information in ways that human operators can accurately interpret and act upon. | phasor measurement units (PMU’s), data concentrators, and advanced software | • Optimized Generator Operation  
• Reduced Ancillary Service Cost  
• Reduced Congestion Cost  
• Deferred Transmission Capacity Investments  
• Reduced Major Outages  
• Reduced Wide-scale Blackouts |
| Dynamic Capability Rating (AKA, Ampacity Determination) | Real time adjustment in feeder max current capability based on actual environmental conditions. | sensors, information processing and communications | • Reduced Congestion Cost  
• Deferred Transmission Capacity Investments  
• Deferred Distribution Capacity Investments  
• Reduced Equipment Failures  
• Reduced Wide-Scale Blackouts |
| Flow Control | By increasing or decreasing the impedance of a line or transformer (resistance and reactance), routing of power flow can be changed. | Phase angle regulating transformers (PARs) or Flexible AC Transmission System (FACTS) devices. Solutions are being explored using superconducting cables or very low impedance (VL) cable with a phase angle regulator | • Reduced Congestion Cost  
• Deferred Transmission Capacity Investments  
• Reduced CO2 Emissions  
• Reduced SOx, NOx and PM-10 Emissions. |
<table>
<thead>
<tr>
<th>Function</th>
<th>Technical Overview</th>
<th>Sample Assets / Enabling Equipment</th>
<th>Expected Benefits from Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive Protection (AKA, Adaptive Fault Protection)</td>
<td>Adaptive protection means that relay settings and protection schemes on feeders can be changed in response to changing system conditions.</td>
<td>Set points adjustment for the relays and switching devices would be done by algorithms running within software programs and systems.</td>
<td>• Reduced Sustained Outages&lt;br&gt;• Reduced Restoration Costs</td>
</tr>
<tr>
<td>Automated Feeder Switching (AKA, Automated Feeder Switch Actuation)</td>
<td>Automatic Feeder Switching makes it possible to operate distribution switches autonomously in response to local events, or remotely in response to operator commands or a central control system. This function is accomplished through the automatic isolation and reconfiguration of faulted segments of distribution feeders preventing “truck rolls”.</td>
<td>sensors, controls, switches, and communications systems</td>
<td>• Reduced Distribution Operations Cost&lt;br&gt;• Reduced Sustained Outages&lt;br&gt;• Reduced Restoration Cost&lt;br&gt;• Reduced CO2 Emissions&lt;br&gt;• Reduced SOx, NOx and PM-10 Emissions&lt;br&gt;• Reduced Oil Usage</td>
</tr>
<tr>
<td>Automated Islanding and Reconnection (AKA, Enabling “Islanding”)</td>
<td>A microgrid is an integrated energy system consisting of interconnected loads and distributed energy resources which, as an integrated system, can operate in parallel with the grid or as an island. This disconnection and reconnection of the microgrid and the interconnected electric grid would be done automatically as needed based on grid conditions.</td>
<td>Islanding is enabled through various sensors, controls, switches, and communications systems, inverters, controllers and distributed energy resources</td>
<td>• Reduced Sustained Outages&lt;br&gt;• Reduced Major Outages</td>
</tr>
<tr>
<td>Automated Voltage and VAR Control</td>
<td>Automated voltage and VAR control is performed through devices that can increase or lower voltage and can be switched or adjusted to keep the voltage in a required range. This function is the result of coordinated operation of reactive power resources such as capacitor banks, voltage regulators, transformer load-tap changers, storage and distributed generation (DG) with sensors, controls, and communications systems.</td>
<td>Control systems could determine when to operate these devices (i.e., generator voltage regulators), and do so automatically.</td>
<td>• Reduced Ancillary Service Cost&lt;br&gt;• Reduced Distribution Operations Cost&lt;br&gt;• Reduced Electricity Losses&lt;br&gt;• Reduced CO2 Emissions&lt;br&gt;• Reduced SOx, NOx and PM-10 Emissions</td>
</tr>
<tr>
<td>Function</td>
<td>Technical Overview</td>
<td>Sample Assets / Enabling Equipment</td>
<td>Expected Benefits from Function</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>-------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Diagnosis & Notification of Equipment Condition | This function is the on-line monitoring and analysis of equipment, its performance and operating environment to detect abnormal conditions (e.g., high number of equipment operations, temperature, gas production or vibration). | **SCADA systems including sensing / monitoring devices, communications networks and analysis software** | • Reduced Equipment Failures  
• Reduced Distribution Equipment Maintenance Cost  
• Reduced Sustained Outages  
• Reduced Restoration Costs  
• Reduced Oil Usage |
| Enhanced Fault Protection           | Enhanced protection could detect faults that are hard to locate, and clear them without reclosing which can damage equipment over time. These systems could better detect high impedance faults. | **High resolution sensors, algorithms detecting fault signatures, high speed digital communications and computing, line differential protection, adaptive relaying and System Integrity Protection systems (SIPS).** | • Reduced Equipment Failures  
• Reduced Sustained Outages  
• Reduced Restoration Cost  
• Reduced Momentary Outages  
• Reduced Sages and Swells  
• Reduced Wide-scale Blackouts |
| Real-Time Load Measurement & Management | Monitoring the energy use of customer loads over the course of the day. These same devices can be used to help customers respond to pricing signals so that system load can be managed as a resource. | **Smart meters and appliance controllers, Advanced Metering Infrastructure (AMI) systems (smart meters, two-way communications) and embedded appliance controllers, real-time price signals, time-of-use (TOU) rates, and service options** | • Reduced Ancillary Service Cost  
• Deferred Distribution Capacity Investment  
• Reduced Meter Reading Cost  
• Reduced Electricity Theft  
• Reduced Electricity Losses  
• Reduced Sustained Outages  
• Reduced Major Outages  
• Reduced CO2 Emissions  
• Reduced SOx, NOx and PM-10 emissions  
• Reduced Oil Usage |
| Real-Time Load Transfer             | Circuits may be switched and electrical feeds rerouted to make the distribution more efficient or more reliable. | **Control systems, actuating equipment, etc.** | • Deferred Distribution Capacity Investments  
• Reduced Electricity Losses  
• Reduced Major Outages |
<table>
<thead>
<tr>
<th>Function</th>
<th>Technical Overview</th>
<th>Sample Assets / Enabling Equipment</th>
<th>Expected Benefits from Function</th>
</tr>
</thead>
</table>
| Customer Electricity Use       | Enables customers to observe their consumption patterns and modify them according   | sensing and reporting equipment, interactive software, appliances which respond to signals, an on-line | • Deferred Centralized Generation Capacity Investments  
| Optimization                   | to their explicit or implicit objectives.                                           | marketplace, etc                                                                                   | • Deferred Transmission Capacity Investments  
|                                |                                                                                    |                                                                                                    | • Deferred Distribution Capacity Investments  
|                                |                                                                                    |                                                                                                    | • Reduced Electricity Losses  
|                                |                                                                                    |                                                                                                    | • Reduced Electricity Cost  
|                                |                                                                                    |                                                                                                    | • Reduced CO2 Emissions  
|                                |                                                                                    |                                                                                                    | • Reduced SOx, NOx and PM-10 emissions |
**Distributed Energy Resource’ Functions**

A common trait in the table above is that the functions outlined only pertain to the grid transmission and consumption portion of the network, and leave out what we shall separately classify as "Energy Resources". Although the EPRI COST BENEFIT ANALYSIS Group decided to create this separate category, they are still functions as defined in the System Architecture framework.

Below we describe these functions.

**Table 12 – Distributed Energy Resource Functions (6)**

<table>
<thead>
<tr>
<th>Function</th>
<th>Technical Overview</th>
<th>Sample Assets / Enabling Equipment</th>
<th>Expected Benefits from Function</th>
</tr>
</thead>
</table>
| Distributed Generation    | Refers to energy sources which are (a) comparably smaller than initially planned centralized sources of power, (b) interconnects to distribution feeders or behind customer meters. | Biomass (solid), Biomass (gaseous), Geothermal, Natural Gas, PV, Wind, Diesel – Power generation systems. | • Deferred Centralized Generation Capacity Investments  
  • Reduced Ancillary Service Cost  
  • Reduced Congestion Cost  
  • Deferred Transmission Capacity Investments  
  • Deferred Distribution Capacity Investments  
  • Reduced Electricity Losses  
  • Reduced Electricity Cost  
  • Reduced Sustained Outages  
  • Reduced CO2 Emissions  
  • Reduced SOx, NOx and PM-10 emissions |
| Stationary Electricity Storage | Electricity can be stored as chemical or mechanical energy and used later by consumers, grid owners & operators. In distributed applications, energy storage technologies most likely utilize inverter-based electrical interfaces that can produce real and reactive power. Depending on the capacity and stored energy of these devices, they can provide economic, reliability, and environmental benefits. | Pumped Hydro, Compressed Air Energy Systems (CAES), Batteries (Lead, Flow, Li-Ion, etc) | • Optimized Generator Operation  
  • Deferred Centralized Generation Capacity Investments  
  • Reduced Ancillary Service Cost  
  • Reduced Congestion Cost  
  • Deferred Transmission Capacity Investments  
  • Deferred Distribution Capacity Investments  
  • Reduced Electricity Losses  
  • Reduced Sustained Outages  
  • Reduced Momentary Outages  
  • Reduced Sags & Swells  
  • Reduced CO2 Emissions  
  • Reduced SOx, NOx and PM-10 emissions |
The batteries in plug-in electric vehicles (PEVs) can be portrayed as non-stationary energy storage devices. As such, they are similar to stationary energy storage devices and support economic, reliability and environmental benefits. By increasing vehicle fuel efficiency, they also support Reduced Oil Usage, an Energy Security Benefit. It is important to consider specific benefits gained from the Distributed Energy Resources separately. The following table of benefits is proposed by the EPRI COST BENEFIT ANALYSIS team:

### Table 13 – Distributed Energy Resource Benefits Summary

<table>
<thead>
<tr>
<th>Resource Type</th>
<th>Externally Delivered Benefits</th>
<th>Economic</th>
<th>Environmental</th>
<th>Energy Security (Oil or NG offset?)</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renewable Resource</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomass (solid)</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
<td>Maybe</td>
<td>Yes</td>
</tr>
<tr>
<td>Biomass (gaseous)</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
<td>Maybe</td>
<td>Yes</td>
</tr>
<tr>
<td>PV</td>
<td>No &amp; Yes (Varies based on region)</td>
<td>Yes</td>
<td>Maybe</td>
<td>No &amp; Yes (Varies based on conditions)</td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>No &amp; Yes (Varies based on region)</td>
<td>Yes</td>
<td>Maybe</td>
<td>No &amp; Yes (Varies based on conditions)</td>
<td></td>
</tr>
<tr>
<td>Micro CHP</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
<td>Maybe</td>
<td></td>
</tr>
<tr>
<td>Geothermal</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Hydro (mini, micro)</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td><strong>Non-Renewable</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Yes</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td><strong>Storage &amp; Other Resources?</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stationary Storage</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Electric Vehicles</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Nuclear?</td>
<td>Maybe</td>
<td>Maybe</td>
<td>Maybe</td>
<td>Maybe</td>
<td></td>
</tr>
</tbody>
</table>
In practicality, as with any highly complex system, it is a highly iterative process of mapping functions to benefits, and vice versa. Below is a summary of this mapping, as supplied by the EPRI team.

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Functions</th>
<th>Energy Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved Asset Utilization</td>
<td>Optimized Generator Operation</td>
<td>Reduced Electricity Cost</td>
</tr>
<tr>
<td></td>
<td>Deferred Generation Capacity Investments</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Reduced Ancillary Service Cost</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Reduced Congestion Cost</td>
<td>*</td>
</tr>
<tr>
<td>T&amp;D Capital Savings</td>
<td>Deferred Transmission Capacity Investments</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Deferred Distribution Capacity Investments</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Reduced Equipment Failures</td>
<td>*</td>
</tr>
<tr>
<td>T&amp;D O&amp;M Savings</td>
<td>Reduced Distribution Equipment Maintenance Cost</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Reduced Distribution Operations Cost</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Reduced Meter Reading Cost</td>
<td>*</td>
</tr>
<tr>
<td>Theft Reduction</td>
<td>Reduced Electricity Theft</td>
<td>*</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>Reduced Electricity Losses</td>
<td>*</td>
</tr>
<tr>
<td>Electricity Cost Savings</td>
<td>Reduced Electricity Cost</td>
<td>*</td>
</tr>
<tr>
<td>Reliability</td>
<td>Reduced Sustained Outages</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Reduced Major Outages</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Reduced Restoration Cost</td>
<td>*</td>
</tr>
<tr>
<td>Power Quality</td>
<td>Reduced Momentary Outages</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Reduced Sag and Swells</td>
<td>*</td>
</tr>
<tr>
<td>Environmental</td>
<td>Reduced CO₂ Emissions</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Reduced SO₂, N₂O, and PM-10 Emissions</td>
<td>*</td>
</tr>
<tr>
<td>Security</td>
<td>Reduced Oil Usage (not monetized)</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Reduced Widespread Blackouts</td>
<td>*</td>
</tr>
</tbody>
</table>

This function/benefit mapping table provides a basic first layer decomposition of grid 2.0, the summarized essence of our next generation 'smart grid'.
Where we've come?

Using our System Architecture terminology, we have thus far completed a first layer decomposition of the Smart Grid as a precursor to assigning form to function, etc. Returning to simplified procedure outlined previously, relative to the whole product system only, what have we completed?

We've defined primary beneficiary and stakeholder needs (steps 1 & 2), outlined succinct & specific statement of benefit or value (step 3), and arrived at various solution neutral statement of function (step 5). Notably we have not prioritized the benefits, considered subsystem concepts or form or iterated to converge on design, or repeated for various subsystems. This, of course, is just the beginning of the architecting process.

Selecting Your System Boundaries & Layer of Abstraction

One of the System Architect's critical decisions will be to determine the boundaries of their product. This decision will be influenced by many contextual factors such as:

- You or your company's level of expertise
- You or your company's circle of influence in the domain
- What you believe derives enough benefit to those willing to purchase your product
- The social, political and economic situation in your domain
- Your available resource mix

In other words, you could decide to pursue a relatively narrow scope and work on begin the architecting process on that piece. For example:

- Based on the knowledge, background and specialty of my company, we might decide to focus specifically on designing 'Flow Control' devices and systems. As such, then begin the system architecting process to achieve 'Flow Control', complete with first, second and third layer decompositions, considering balances and tradeoffs, and so forth.
- Or I might decide to stay at a higher level of decomposition and specialize in Smart Grid network planning, whereby the exact details and decompositions of various 'Flow Control' devices are not of interest to me. Instead I might use modeling software and determine the optimal mix of renewable supply (based on local conditions) and baseloading supplies to match projected demand. In this case, considering existing infrastructure will be critical to my architecting process.

In all cases, each may have wholly different outcomes based on the context of your project.
Summarizing Next Steps

Now that we've..
- characterized this seemingly impossibly complex system of systems (our existing grid),
- linked specific benefits to potential functions of a next generation grid (Smart Grid),
- AND have a principle based framework continuing System Architecting process..

Our objectives are to..
- consider the political, social and economic context of a region or potential product under your influence
- determine at what level of decomposition you wish to create a service or product which serves a function above
- prioritize relevant benefits and derive products or services which meet those needs
- consider various concepts which could accomplish your task
- commence the creative process of assigning form to function

Now, let the creative and challenging architecting process begin! While it may seem that much is accomplished, of course, we have merely begun to characterize the 'big picture' problem as a precursor to the infinite amount of work left to be done as we redesign and rebuild this massive infrastructure.
Part IV. Grid Infrastructure Transformation – Beyond 2.0

Practical considerations after passing Grid 2.0
Grid 2.0 is just the beginning
Review of existing 'technology strategies'
Assessment of existing projects

INTRODUCTION

Without a doubt, we are at the beginning of this journey, but much work has been done and is already underway. Our mission now is to set challenging yet realistic targets, manage expectations, and follow through.

Technical Emphasis vs Political / Economic

As we shall see, in this section (Part IV) we will define 'optimal' grid architecture as that which provides the most benefit to the most beneficiaries. We assert that such designs will be based first in technical/engineering considerations before political/economic considerations.

No doubt, transforming and operating this future grid will be a very expensive endeavor. Determining how much it will cost and who is going to pay for it are crucial political / economic issues. While our focus in this section is primarily on what to build, we also highlight important regulatory, political and economic factors such as incentives and market regulation.

Part IV therefore is therefore divided into the following major sections:

1. UNDERSTANDING INFLUENCES – First we seek to understand the primary influences which will dictate how the grid transforms or evolves over the coming decades.
2. GRID VISIONS – It is likely that the grid will change along a predictable pathway, which we outline. We also present some of the alternative perspectives on grid evolution.
3. COMMUNICATIONS & MEASUREMENT – The first step in grid evolution is to build and operate a robust communications and measurement system. This is the 'nervous system' of our Smart Grid.
4. GRID ELEMENTS & CHARACTERISTICS – The grid of the future will have many different types of generation sources and load types, each with varying characteristics; here we review each.
5. OPERATIONS & CONTROL – Managing the operation of such a wide variety of grid resources will be very challenging. In this section we outline the primary considerations.
6. PORTFOLIO MODELING – A robust modeling tool will be necessary to test various grid operating scenarios. Here we outline desired parameters of this tool.
7. DEMONSTRATION PROJECTS – Last we highlight ongoing Smart Grid demonstration projects and outline what questions should be asked to assess their architectures.
By the end of Section III we had outlined the primary benefits and desired functions of the Smart Grid. Relative to the System Architecture process, our next general steps are to prioritize benefits, examine the influences and try to determine what and how to deliver it.

However, when transforming a major infrastructure which permeates nearly every aspect of society, it is not enough to just understand our primary desired benefits; we must also consider all the other factors which will influence the final design and implementation process.

Immediately, many natural questions may be asked:
- What exactly will dictate the final architecture which emerges in each region?
- What are the primary defining factors which will influence transformation direction? Which factors carry the most weight?
- Will we need to lobby for/or against regulation?
- How much is it all going to cost? Who is going to pay for it?

Given all these influences, how do we determine 'optimal' architecture?! We must begin by reexamining key influence categories and trying to put them in the context of major infrastructure transformation.

Many ("Upstream") Influence Categories

Previously we described the concept of "upstream influences" as those influences which the architect has not direct control over or those requirements which are inherent in the problem statement. In the case of a major infrastructure, such as the grid, we cannot solely focus on those benefits related to value delivery (as we did in Section III). Now we must consider the wide array of influence categories and how they might impact final product. The outline below is presented to paint a broad picture of some of the potential influence questions and categories.

REGULATORY/ECONOMIC Influences
- What level of unbundling exists in the existing utilities in the region? How will they change?
- How shall T&D infrastructure changes be funded? (Ratepayers?)
- How will new generation sources be funded? (Through distributors? Tariffs? Tax incentives? Markets?)
- Which standards are competing and which will ultimately dominate?

MARKETPLACE Influences (whose going to invest in technology and why..)
- Who is going to invest and why? Will any major dominant players emerge?
- Which products were backed by the most influential entity?
- How will the wholesale & retail markets evolve to accommodate next generation?
POLITICAL Influences
- What is the current economic state of the region? (Recession/Expansion)
- What is the leaning (conservative/liberal) of the law making body?
- What is the attitude (conservative/liberal) of the Regulatory Commission?

RESOURCE Influences
- Are there existing resources in the region? (Coal/NG)
- What are the most abundant renewable resources in the region? (Wind, Solar, Tidal..)

INFRASTRUCTURE Influences
- What is the architecture of the existing network?
- Can the existing network be upgraded or must it be rebuilt?

TECHNOLOGY Influences
- Which technology provides the best value? (*Not always the one which wins out selected)
- Which technology requires the greatest fundamental change in design or operation?
- Have any major technologies been introduce in the marketplace? (Energy Storage)

We can see that the 'transitory pathway' of each local grid network will be highly dependent on regional influences. Many influences are difficult to predict (especially political, regulatory and market) and their role will result in a wide variation in possible outcomes.

*Grid Infrastructure Transformation – 12 Global Dimensions*

*Infrastructure Transformation "In-Context"

Summarized below are 12 key regulatory and political dimensions which must also be analyzed, outside of the 'value related' influences outlined in Part III. A complete outline of each of the dimensions below is presented in the Appendix. (Note: These are the questions final project questions asked MIT's Engineering Economics in the Electric Power Sector, taught by Professor Ignacio Perez.)

Table 14 – Twelve Dimensions to Grid Transformation (3)

<table>
<thead>
<tr>
<th>Dimension Title</th>
<th>Description</th>
<th>Key Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Energy legislation or reform</td>
<td>Restructuring or liberalization of the system may be necessary.</td>
<td>What is the process of reform? What unbundling is necessary for wholesale or retail markets?</td>
</tr>
<tr>
<td>2. Markets vs governments</td>
<td>Each will play an important role in the transformation process; maintaining balance is critical.</td>
<td>What are the best mechanisms for setting far reaching goals? What is the role of each in setting short and long term goals? Describe tradeoffs between tariff &amp; market based (renewable energy credits) incentives.</td>
</tr>
<tr>
<td>Dimension Title</td>
<td>Description</td>
<td>Key Questions</td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>3. Renewable generation</td>
<td>Achieving penetration of renewables will require a paradigm shift in electricity market operations &amp; management and renunciation schemes.</td>
<td>What is the most adequate regulatory instrument to achieve high penetration? How must wholesale market rules change? Who pays for program administration?</td>
</tr>
<tr>
<td>4. Distribution activity</td>
<td>Renunciation of distributors is frequently tied to energy sold, not O&amp;M costs. Costs of renewable interconnection must offset.</td>
<td>Is decoupling of the retail &amp; distribution activity necessary or possible? What are the alternatives given the existing situation? How are interconnection costs covered?</td>
</tr>
<tr>
<td>5. Transmission</td>
<td>Upgrades or reconfiguration may be necessary to get renewable energy generation to demand centers.</td>
<td>Is the current transmission upgrade regulation scheme adequate for major changes? Should planning be centralized or decentralized? Performance based?</td>
</tr>
<tr>
<td>6. Locational signals for RE generation entries</td>
<td>Location based pricing is common for renunciation existing generation.</td>
<td>What economic and regulatory signals should be used for perspective new investors? Should location based pricing be applicable?</td>
</tr>
<tr>
<td>7. Generation adequacy</td>
<td>With a wide variety of variable energy sources in a portfolio, incentivizing &amp; obtaining the optimal mix of technologies is critical.</td>
<td>What schemes exist to promote investment in renewables? What is the role of forward capacity mechanisms (market auctions)? Should demand response or PHEV's be regulated?</td>
</tr>
<tr>
<td>8. Market power mitigation</td>
<td>With the mass introduction of new generation, regulatory measures should ensure prevent exercise or abuse of market power.</td>
<td>Is current market balanced? What rules should be established to ensure a balanced renewables generation market?</td>
</tr>
<tr>
<td>9. Wholesale market design with intermittent, uncontrolled supply</td>
<td>Markets must be redesigned to handle the intermittency of renewable energy generation. Also they should ensure all generation types are fairly compensated.</td>
<td>Adjusted rules for day-ahead markets? Congestion management? Transaction types? Setting of market prices? Determining operational reserves? Should intermittent generation be charged differently?</td>
</tr>
<tr>
<td>10. Retail market design</td>
<td>Incentivizing energy efficiency (and reducing demand) is a vital objective. Real-time-pricing has been suggested, but present prices too low to have an effect.</td>
<td>How is the current retail market structured? How might it be adjusted to incentivize energy efficiency? What regulatory instruments could be used to achieve this?</td>
</tr>
<tr>
<td>11. Universal electricity access</td>
<td>Distributed renewable energy resources can play an important role in rural electrification.</td>
<td>How should restructuring or liberalization support? Should mandatory renewable energy targets be put in place? What are alternative means of promotion?</td>
</tr>
<tr>
<td>Dimension Title</td>
<td>Description</td>
<td>Key Questions</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>12. CO2 markets &amp; prices</td>
<td>Regulation &amp; penalties for CO2 emissions will play an important role. &quot;Carbon Tax&quot; and &quot;Cap &amp; Trade&quot; schemes have been proposed.</td>
<td>What is the optimal solution? Should the consumer carry these costs? Should generators be given allowances? What is the role of renewable energy credits (REC's)?</td>
</tr>
</tbody>
</table>

**NATURAL Laws vs POLITICAL Influences on Design**

Role of Politics in Design Process (Especially Infrastructure Transformation)
Dealing with Political, Economic & Regulatory Influences
Inherent Uncertainty vs Optimal Design
A hierarchy of influences
Managing Inherent Uncertainty → A design requirement

How then do we know what we are looking for? What design conditions should we incorporate and which should we ignore? How do we define hypothetically 'optimal' architectures which we should lobby for?

In determining an 'optimal' architecture, natural laws, by definition, take precedent over human influences. As an architect, one of our greatest challenges will be managing the balance between natural and political influences.

Stated simply, if the local region has a lot of sun, but no wind, it may not be logical to support legislation which significantly favors large wind farms over the solar systems. Of course, it's rarely a simple tradeoff between one obvious condition and the other, but with a tentatively 'optimal' technology mix in mind we know how to set regulation to support and fund that architecture.

We define 'Optimal' architectures as that which provides the most benefit to the most beneficiaries, and is generally the result of optimizing based natural engineering principles first, followed by political or economic influences.

To the greatest extent, especially with the electricity grid, he/she must 'design in' flexibility to accommodate a wide range of options. However, some items will be completely unpredictable and are fundamentally impacting on system design. In which cases, we may be required to engage directly in the political process lobbying for regulation which support the desired Architecture.

**SHIP EXAMPLE** – Returning to the ship example, the Coast Guard might regulate that an oil tanker have a "double-hull" (concentric internal and external shells). However, a double-hull might not be the best or 'optimal' design to contain oil. (For example, an alternative 'mid-tank' design has been proposed.) In fact, the optimal design might be far worse than the regulated one. We acknowledge that the ship still floats and will get the passenger from point A to B, but the design is sub-optimal.

**GRID EXAMPLE** – Consider that a certain region has incredible geo-thermal resources, but horrible wind reserves. It would make sense to pass legislation which incentivizes geo-thermal, but instead wind incentives are passed. This is an obvious case, but the point is the same. We need to ensure that optimal architecture drives political regulation, and not the reverse.
Of course, it will not always be this clear. Consider Germany who has some of the most progressive solar legislation, despite the fact that their best solar resources are worse than our best in the United States. Especially in cases where the final legislative outcome will be unclear, it is critical that the architect understand these issues and build in the appropriate level of flexibility in their design.

**Infrastructure Transformation vs Product Development**

Based on the discussion above, we identify some important philosophical differences infrastructure transformation process (applicable here) and the product development process previously highlighted. While there are similar elements (converging on benefits, evaluating key functions, etc), there are notable differences:

**Table 15 – Product vs Infrastructure Development**

<table>
<thead>
<tr>
<th>DEVELOPMENT FACTOR</th>
<th>PRODUCT</th>
<th>INFRASTRUCTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Has a beginning and end?</td>
<td>Typically Yes</td>
<td>No ending, continuously evolving</td>
</tr>
<tr>
<td>Goals and Objectives?</td>
<td>Often clear and generally stable</td>
<td>Continually evolving</td>
</tr>
<tr>
<td>Complexity Level?</td>
<td>Simple to complex</td>
<td>Infinitely complex</td>
</tr>
<tr>
<td>Development cycle?</td>
<td>Months/years</td>
<td>Years/decades</td>
</tr>
</tbody>
</table>

**Applying System Architecture 'Benefit & Function' Framework**

Putting in context of Architectural Framework

Are any Smart Grid objectives timeless? Is there a generic list of generic objectives? Will the benefits / functions table previously described apply?

In Part III we outlined the basic design parameters (See Benefits / Functions Table) of a generic next generation grid. But are these parameters adequate for a 20 year evolution? Do they cover the wide variability of potential future possibilities? In short, yes. However, there are notable considerations..

**BENEFITS Evolution**

- Benefits will not likely change much, but stay relatively constant
- However, the relative importance of these benefits will change

For example, the value derived from the use of renewable energy (as opposed to fossil fuels) may greatly increase if (a) there was a shortage of natural gas or (b) ill environmental effects had a major impact on public opinion.

**FUNCTIONS Evolution**

- There may be many new functions which are introduced over time, each with different methods of delivering the value
  (Recall, Functions are methods of delivering value or benefit)
- The existing list is simply a snapshot of currently known Smart-Grid related top level functions
TEN, TWENTY & THIRTY YEAR GRID VISIONS

Defining the 'endgame'
What is that infrastructure evolutionary pathway?
Begin with the end in mind..!

ENVIRONMENTAL = Key Long-Term Driving Factor

So what's the point?! Why are we doing this? What are the other driving factors of this grid transformation? We return to our basic benefit categories: Economic, Reliability, Environmental & Energy Security.

I propose that the key long term driving factor has been and will be environmental. However, these environmental benefits will be driven through economic means.

There is little doubt that recent interest in this domain is as a result of society's placing a high value on energy derived from renewable sources. Over the long term, I believe that this interest and concern will continue to grow, and ultimately result in favorable regulation and favorable economic conditions for clean and renewable energy resources.

Once the cost of renewable energy resources is competitive with existing resources, the situation has fundamentally changed and our existing grid infrastructure will need to transform to accommodate these new conditions.

Economic, Reliability and Energy Security benefits are also directly related, and will also be derived from a fundamental interest in renewable energy resources.

Benefits & Functions of Distributed Resources – Revisited

Recall the functions discussion in Part III. In that table we propose both Control Functions (Table 11) and Distributed Energy Resource Functions (Table 12).

I propose that the most long term benefit to society will be derived from incorporation of renewable energy resources into the generation portfolio. However, mass introduction of renewable energy resources can only be enabled through investment of both (a) Control Functions and enabling of (b) bulk energy storage first.

In other words, as we reexamine the table below, although the benefits from PV & Wind (for example) are region dependent and debatable today, ultimately from these benefits society will gain the most long-term societal benefit.
### Table 16 – Distributed Energy Resource Benefits Summary

<table>
<thead>
<tr>
<th>Resource Type</th>
<th>Externally Delivered Benefits</th>
<th>Economic</th>
<th>Environmental</th>
<th>Energy Security (Oil or NG offset?)</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renewable Resource</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomass (solid)</td>
<td>Yes</td>
<td>Maybe</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Biomass (gaseous)</td>
<td>Yes</td>
<td>Maybe</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>PV</td>
<td>No &amp; Yes (Varies based on region)</td>
<td>Yes</td>
<td>Maybe</td>
<td>No &amp; Yes (Varies based on conditions)</td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>No &amp; Yes (Varies based on region)</td>
<td>Yes</td>
<td>Maybe</td>
<td>No &amp; Yes (Varies based on conditions)</td>
<td></td>
</tr>
<tr>
<td>Micro CHP</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
<td>May</td>
<td></td>
</tr>
<tr>
<td>Geothermal</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Hydro (mini, micro)</td>
<td>Yes</td>
<td>Maybe</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td><strong>Non-Renewable</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Yes</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td><strong>Storage &amp; Other Resources?</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stationary Storage</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Electric Vehicles</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Nuclear?</td>
<td>Maybe</td>
<td>Maybe</td>
<td>Maybe</td>
<td>Maybe</td>
<td></td>
</tr>
</tbody>
</table>

This table underscores the importance and challenge with assigning weighting factors and priorities to benefits. This table is further discussed in Part IV.

It is expected that each of the renewable resources above will get smaller and more numerable. Historically all of the interest has been on centralized supply side investment. But with a Smart Grid infrastructure, we enable smaller distributed energy resource investment instead. Similarly, the Smart Grid enables demand side "capacity" or negative energy, which will is not included in the table above.

Note that Energy Security benefits are typically linked directly to offsetting oil consumption. Because oil is a very small proportion of fuel for power baseloading power plants, it is not considered a very significant factor. However, in the long term, as we import more natural gas reserves, this benefit will become much more significant.

**Role of Nuclear?**

While it is difficult to predict outcomes, nuclear power has a potential to play a very important role in the future electricity grid. Below we acknowledge potential influences and potential outcomes. (Note that later we will propose various methodologies for performing whole portfolio analysis, which will build on the suggestions below.):

1. **High variability nuclear used to offset high variability renewables** – In this instance, because of the unpredictable nature of wind and solar (or other renewables) a technology is need to offset "ramp" and offset supply lost (or gained) from the resource.
2. **Mass adoption of nuclear as greenhouse gas solution** – For example, as a result of our capability (or lack thereof) to supply most energy from renewable energy resources, and as the negative effects of...
burning coal or natural gas are compounded, nuclear energy will 'fill the gap' in what we need and what we can supply.

3. **Mass adoption of nuclear due to decrease in costs** – Advanced technologies may make nuclear very cost competitive, fostering support for nuclear resurges and becomes the dominant baseload energy resource.

4. **Nuclear as a distributed baseload resource** – While there are many challenges to overcome, technological advances have been posed which make smaller nuclear a potential distributed resource. (Note that CHP and geothermal have been posed as more likely distributed baseload possibilities).

I propose that there will be a synergy between combining nuclear and renewable energy resources in the future technology mix.

While it is difficult to predict final outcomes, it is likely that nuclear will play a significant role in grid transformation. Regardless of nuclear role, mass penetration of renewables poses the greatest design challenge in future transformation, and remains the focus of this analysis.

**Proposed Transformation Pathway**

*Where are we heading?*

With the ultimate objective of enabling mass introduction of renewable energy resources the following three phases are suggested:

**PHASE 1: Communication & Measurement** – As marked by many projects already underway, the first major step will be enabling the exchange of information and the establishment of a communications network. This network has been associated with the future 'nervous system' of the grid and will enable control necessary for the next phase.

**PHASE 2: Advanced Components & Dynamic control** – The next major phase will encompass a physical infrastructure transformation and initial deployment of operation schemes allowing rapid bulk energy storage, control and dispatch. Overcoming this first bulk energy 'storage/control' threshold of about 15% will be a major accomplishment.

**PHASE 3: New Energy Resources** – With appropriate control capabilities (Phase 1) and having overcome initial challenges associated with power flow dynamics (Phase 2), we will have finally enabled a situation where mass adoption of distributed generation resources is be possible. The final 'optimal' makeup of regional networks will depend highly on available resources, etc.

(See table on the next page.)
Table 17 – Grid Transformation Stages

<table>
<thead>
<tr>
<th>Timeframe</th>
<th>Phase Definition</th>
<th>Defined by.. (Key Characteristics)</th>
<th>Key Functions / Technologies</th>
<th>RE Penetration</th>
</tr>
</thead>
</table>
| 0 - 10 Year Grid| 1. Communications & Measurement       | Laying the foundation for future technologies through communications. ‘Tidying’ up our usage.       | - Energy efficiency  
- Demand Response                                                     | 5% (by capacity)                                                   |
- Islanding                                                           | 15% (by capacity)                                                  |
| 20 - 30 Year Grid| 3. Large Scale Pervasive Renewables    | Mass adoption of Renewable Energy resources enabled through Storage & fast supply & demand balancing control. | - Distributed Generation, Storage, Electric Vehicles              | 40+% (by energy) |

COMMUNICATIONS & MEASUREMENT SYSTEMS (PHASE 1)

Phase 1 Fundamentals
The Nervous System

An effective communications system is the foundation of any Smart Grid development.

Key Functions of Phase 1 (SA Review)

As we look back at the Smart Grid Control Functions previously described, two key functions represent the focal point of this phase:

<table>
<thead>
<tr>
<th>Real-Time Load Measurement &amp; Management</th>
<th>Monitoring the energy use of customer loads over the course of the day. These same devices can be used to help customers respond to pricing signals so that system load can be managed as a resource.</th>
<th>Advanced Metering Infrastructure (AMI) and embedded appliance controllers, real-time price signals, time-of-use (TOU) rates, and service options</th>
<th>(the most!) Economic, Environmental, Reliability &amp; Energy Security benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer Electricity Use Optimization</td>
<td>Enables customers to observe their consumption patterns and modify them according to their explicit or implicit objectives.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From these primary functions critical subsystems emerge.

Whole system → Critical sub-function → Define & design new sub-systems → Continue to next layer

Key concepts, methods, markets and eventually products or systems – based on these functions – are described below:
Real Time Pricing

One method of encouraging 'customer electricity use optimization' is through the use of time based pricing schemes. Several methods have been proposed:

TIME OF USE (TOU) – Refers to a tier based system where customers will pay a different rate for electricity based on time of day and time of year. Typically there are only two time blocks per day, "Peak" and "Off-Peak" which change once a year, "Summer" and "Winter" months.

CRITICAL PEAK PRICING – May be placed in effect by some retailers days where it is known that power demand may reach or exceed generation limits.

REAL TIME PRICING (RTP) – Also known as "Dynamic Pricing", links the cost of electricity to consumers to the actual retail market price of generating and delivering that energy. Prices may change on an hourly, five minute, or smaller rate.

While TOU pricing is already actively used for many retailers, enabling RTP is a key objective of the Smart Grid. Enabling RTP will be a major accomplishment in any control area and will require both (a) a significant upgrade in metering equipment and (b) creation of the market mechanisms for the retailer and the consumer to participate. Various advanced metering initiatives (described below) are being tested which would deliver this functionality.

One of the goals of the system operator must be to estimate the amount of market response which results from changing prices. These effects are further explored in the section discussing network operations.

Demand Response

Demand Response (DR) occurs when devices shut off in response to specific request by the system operator. DR is typically targeted at reducing peak demand which would otherwise have resulted in either:

1. paying a premium to startup and operate a 'peaking' (less efficient) power plant or
2. system overload or disruptions.

A resulting effect of DR is also reducing peak prices and subsequently price volatility.

DR might sometimes also be used to increase demand during periods when the cost of shutting down power plants is prohibitive. In such cases energy storage (ie Pumped Hydro) might be utilized to purchase power when the cost is low and sell that power when costs are higher.
Achieving this level of functionality requires many things, including a communications backbone, and appliances / devices programmed to respond to signals. Through DR, one of our key functions - 'real time load measurement and management' - is delivered, and is part of the major objectives of Phase 1.

Note that DR differs from Dynamic Demand, which is further described later in this paper.

**Energy Efficiency (vs Market Effects & DR)**

A third desired outcome of Phase 1 is increased use of energy efficiency methods and practices. Energy efficiency refers to the act of using less energy to provide the same level of service.

Of course, there are many things which can be done to reduce energy usage, such as: Replacing incandescent bulbs with fluorescent lights; increasing the amount of insulation in the walls and ceiling; replacing old inefficient appliances with new and efficient ones, etc.

How does the Smart Grid encourage energy efficient behavior? It is intended that through empowering the consumer with information on actual demand, real time market price, etc, a greater awareness will result in employing energy efficient methods and practices.

While each of the methods described can be used to reduce energy usage, their mechanisms are different.

### Table 18 – Methods of Reducing (or Increasing) Energy Usage

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Efficiency</td>
<td>Using less energy yet achieving the same level of service</td>
</tr>
<tr>
<td>Demand Response</td>
<td>Reduced (or increased) demand as a result of dispatched signal by operator</td>
</tr>
<tr>
<td>Market Response</td>
<td>Reduced (or increased) use of energy based on the actual market price of energy</td>
</tr>
</tbody>
</table>

**AMR / AMI / AUI**

So what methods can we employ to encourage energy efficiency? So how will RTP and DR be delivered?

Several Advance Metering Initiatives are underway, each varying in different levels of functionality. Following three different 'flavors' of advance metering are described:

Deployment methods vary, each with differing levels of functionality:

- **Advanced Metering Reading** → Wireless recording of meter values through drive by vehicle
- **Advanced Meter Infrastructure** → Incorporates two-way communications enabling Demand Side Management
- **Advanced Utility Infrastructure** → Incorporates tertiary benefits, including real time pricing

The Allegheny Power Smart Grid Initiative has characterized these items in the illustration shown.
GRID ELEMENT CHARACTERISTICS

Absolutely, one of the greatest challenges to Smart Grid development will be how to manage and control the various elements connected to the grid. At any given point in time multiple independent factors will impact the supply or demand of these elements.

For this discussion we broadly define Energy Resources as any asset (i.e., power plant or household) which supplies or demands energy. Operator Resources as those functions which the operator has control over to assist in balancing the supply and demand of energy.

In this section we shall review the characteristics of these elements and highlight the various resources available to the grid operator. With this background, in the following section we can qualitatively examine what some of the emergent and compounding impacts of this variability might be—including possible methods of how to address those effects.

**Key Energy Resource / Smart Grid Functions**

From our table of functions in Part II we identify the key Energy Supply/Demand Functions which are the focus of this section:

- Electrical Energy Generation
- Electrical Energy Storage
- Electrical Energy Use Optimization
  (Building on DR discussions in previous section.)

These functions are delivered by various energy resources in this section.

**Energy Supply / Demand Types & Characteristics**

What are the defining operating characteristics of each element connected to the grid?

Each energy resource below is can be generally described through each of the following independent characteristics. (These are the columns in the table below.)

**CONTROL TYPE**

- **Supply / Demand** – Energy resources can act as supplies, demands or both
- **Negative Demand** – A quantity of avoided demand, which otherwise would have been present
- **Dispatched** – A resource which can be controlled by a system operator (utility stimulus)
- **No Control** – Means that the system operator has no control over the demand or supply

**VARIABILITY INDEX**

- Generally refers to the maximum rate of change of power (Max ΔMW/H) the plant or resource can sustain—or might exhibit on the system and still stay in operation
- Rate of change is broken into Low, Medium and High categories
• For example, a plant with a low variability index may not respond fast enough to offset a rapid drop in power supplied by a large wind farm (discussed further in the "load balancing" or "ramp rate" discussion in the next section)

POWER VARIATION DESCRIPTION & PREDICTABILITY
• Describes the *conditions which cause a change in output power*
• Sometimes these conditions are predictable (based output temperature and follow a distinct pattern)
• By definition, items which respond to Demand Response stimuli are controllable and predictable
• Items which can be predicted have a low

CAPACITY CONSIDERATIONS
• The range shown represents the 25% and 75% values
• In some cases values have been estimated because data is unavailable or the technology is maturing or undeveloped
• Values are for the United States Electricity Grid

Table 19 - Energy Resource Characteristics (7)

<table>
<thead>
<tr>
<th>Category</th>
<th>Control Type</th>
<th>Technology / Load Type Description</th>
<th>Power Variation Description &amp; Predictability</th>
<th>Variability Index (Max ΔMW/H)</th>
<th>Average 'Per-Plant' Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Supply</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>These are the primary energy suppliers – the foundation – of grid supply. Combined, in the US this represents about 90% of our generation capacity and about 1000 GW of in 2008 (EIA). These plants are mostly fueled by (with the exception of hydro) 'non-renewable' fossil fuels (coal, NG, and oil) and nuclear fuel. These generators are broken into &quot;Baseloading&quot; which implies that they operate at a steady rate, and &quot;Peaking&quot; which are used to meet short term variable demands, typically at a higher cost.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseloading Generator (NG, Coal, Nuclear)</td>
<td>Dispatched Supply</td>
<td>Thermal / Steam</td>
<td>Runs at steady load (Often 100% or off)</td>
<td>Low</td>
<td>50 - 3000 MW</td>
</tr>
<tr>
<td>Peaking Generation</td>
<td></td>
<td>Diesel Gas Turbine</td>
<td>Ability to start/stop &amp; change load quickly</td>
<td>High</td>
<td>10 - 50 MW</td>
</tr>
<tr>
<td>Hydro (Not Pumped Storage)</td>
<td>Limited control Supply</td>
<td>Rivers or Reservoirs</td>
<td>Limited capability to withhold or 'spill' water resource</td>
<td>High</td>
<td>500 - 4000 MW</td>
</tr>
</tbody>
</table>

Additional Information
• Baseloading Ex. - In the case of a large nuclear power plant, for example, changing output power levels has a significant impact on plant conditions. In addition, rapidly changing power level causes thermal cycling of components and can significantly reduce life span.
• Hydro power is repeated in the Renewable Resource list.
A **Renewable Resource** is something that, when consumed by humans, it can be replaced by nature at or above the same rate. In other words, the resource which is consumed is supplied back by mother nature. (Note that solar, tidal, wind and hydroelectric are sometimes referred to as **Perpetual Resources**.)

Another special category is that of **Waste Stream Resources**, whereby otherwise discarded material is used to generate electricity. This may include both material waste streams (Ex, burning municipal waste or shredded tires) or thermal waste streams from a manufacturing process (Ex, Co-Generation).

**In each case, there are two basic categories of these resources:** **Dynamic Supply** resources are those which vary based on weather conditions, and cannot be controlled by the operator. It might be possible for the regulator to curtail or secure the power supply, but generally the output independent of system operator control. (Ex, Solar, Wind, Tidal)

**Baseloading Supply** resources are those that when, once operational and producing power, have limited variability, (just like baseload plants described previously). For example, sometimes it is difficult to prepare the material before injecting it into the boiler. Additionally, there are always some challenges with cycling of steam/thermal generation plants.

<table>
<thead>
<tr>
<th>Category</th>
<th>Control Type</th>
<th>Technology / Descr.</th>
<th>Predictability</th>
<th>Variability</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV</td>
<td>No Control / Dynamic Supply</td>
<td>Utility Scale</td>
<td>Centralized has greater impact</td>
<td>High</td>
<td>5 - 50 MW</td>
</tr>
<tr>
<td></td>
<td>(Without special system)</td>
<td>Comm. / Industrial / Commercial</td>
<td>Spread out across feeder mitigates impact</td>
<td>High</td>
<td>50 - 500 kW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Utility Scale</td>
<td>Centralized has greater impact</td>
<td>High</td>
<td>20 - 300 MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Community / Micro</td>
<td>Spread out across feeder mitigates impact</td>
<td>High</td>
<td>5 - 20 MW</td>
</tr>
<tr>
<td>Wind</td>
<td></td>
<td>Hydraulics / comp. air &amp; other systems proposed</td>
<td>Should be generally predictable based on sea condition</td>
<td>Med</td>
<td>1 - 20 MW</td>
</tr>
<tr>
<td>Tidal / Wave</td>
<td>Limited Control / Baseloading Supply</td>
<td>Rivers or Reservoirs, including Tidal</td>
<td>Limited capability to withhold or 'spill' water resource</td>
<td>High</td>
<td>500 - 4000 MW</td>
</tr>
<tr>
<td>Hydro</td>
<td>(Not Pumped Storage)</td>
<td>Natural heat sources in thermal cycles</td>
<td>Steady &amp; predictable supply</td>
<td>Med</td>
<td>~15 MW (Mean)</td>
</tr>
<tr>
<td>Geothermal</td>
<td></td>
<td>Incinerator / Thermal</td>
<td>Thermal plants often have limited capacity to respond change</td>
<td>Low</td>
<td>~22 MW (Mean)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fuel Cell</td>
<td>Non-Thermal pre-processing methods (Ex, Anaerobic Digester, see notes) also cannot vary quickly</td>
<td>Low</td>
<td>~3 MW (Mean)</td>
</tr>
<tr>
<td>Biomass / Waste to Energy</td>
<td></td>
<td>Other &amp; Pre-Processing Methods (See below)</td>
<td>Typically result of manuf. process or steady operation of gas turbine / generator</td>
<td>Low</td>
<td>5 - 500 kW</td>
</tr>
<tr>
<td>SOLID: Chips / husks, animal waste, etc</td>
<td>Heat Recovery Steam Generator</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GASEOUS: Processed solid waste*, Landfill / sewer gas, etc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUNI WASTE: Paper, tire chips, other bio.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micro/Mini CHP / Co-Generation</td>
<td>Heat exchanger from exhaust gases, etc.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Additional Information**

- **Waste to Energy (WtE)** is the process of creating energy in the form of electricity or heat from the incineration or other methods.
- **Incineration** & **fuel cell** methods are the most common WtE process which results in generating electricity. However, through processing the biomass first, often electricity can be created at a higher rate.
- **WtE Pre-Process Methods:** Thermal - Gasification, Thermal Depolymerization, Plasma Arc Gasification. Non-thermal – Anaerobic Digestion, Fermentation & Mechanical Biological Treatment (MBT)
Non-Responsive Demand

This category refers to demand which the system operator has no control. With the application of DR, some of this demand would be negated (see next section). Similarly, thorough the use of energy storage means, the demand could be shifted around (see storage devices).

Demand is broken up into three sectors: Residential includes typical household loads such as refrigerators and lighting. Commercial includes office spaces, retail and warehouses. Industrial refers to manufacturing plants, other utilities (water/sewer), etc.

System operators utilize Short-Term Demand Forecasting methods to predict daily system loads. Forecasting is typically done on a "day-ahead" and "half/hour-ahead" cycles. There are several Demand Forecasting methods; most are based on (a) estimating 'normal' daily demand based on historic demand and temperatures, and (b) applying correction factors to temperature sensitive loads.

<table>
<thead>
<tr>
<th>Category</th>
<th>Control Type</th>
<th>Technology / Descr.</th>
<th>Predictability</th>
<th>Variability</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>No Control Demand</td>
<td>Household loads (Appliances, lighting)</td>
<td>Follows typical activity patterns, afternoon peak</td>
<td>Highly predictable based on historic data</td>
<td>2 - 5 kW</td>
</tr>
<tr>
<td>Commercial</td>
<td></td>
<td>Office Loads (HVAC, commercial lighting, computers)</td>
<td>Varies based on work times &amp; HVAC load</td>
<td></td>
<td>5 - 50 kW</td>
</tr>
<tr>
<td>Industrial</td>
<td></td>
<td>Manufacturing, municipal utilities (water sewer), etc.</td>
<td>Relatively constant depending on operations &amp; HVAC load</td>
<td></td>
<td>50 + kW</td>
</tr>
</tbody>
</table>

Additional Information
- Demand is typically predicted with a fair amount of accuracy a day ahead.
- Demand is broken up into temperature sensitive and non-temperature sensitive components. Final estimates are based on historical data and predicted hourly weather conditions.

Market Response Demand (Negawatts)

'Market Response Demand' refers to the avoided amount of demand that otherwise would have been present, as a result of a consumer responding to price variations. In other words, this is the difference between how much they would have demanded less the amount they actually demanded as a result of market effects of real time pricing. Negawatts is a term which has been used to represent this negative demand.

It is currently very difficult to predict the quantity of this demand. Estimation models will need to 'program' various customer profiles and their thresholds / responses to deviations in price.

<table>
<thead>
<tr>
<th>Category</th>
<th>Control Type</th>
<th>Technology / Descr.</th>
<th>Predictability</th>
<th>Variability</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential - MR</td>
<td>No control Demand (based on market price)</td>
<td>Homeowner response to increasing prices</td>
<td>Some to Limited (adoption curve)</td>
<td>Med High</td>
<td>(?!) Neg-kW</td>
</tr>
<tr>
<td>Comm. - MR</td>
<td></td>
<td>Business owner response to increasing prices</td>
<td>Some to Limited (adoption curve)</td>
<td>Med Low</td>
<td>(?!) Neg-kW</td>
</tr>
<tr>
<td>Industrial - MR</td>
<td></td>
<td>Manufacturing response to increasing price</td>
<td>Little or none expected</td>
<td>Low</td>
<td>(?!) Neg-kW</td>
</tr>
</tbody>
</table>

Additional Information
- Note that this effect also works in the opposite direction, whereby there is an increased demand, from normal, due to lower prices.
- Market Demand Response is enabled through a Smart Grid. Please see discussion in previous section for more basic information.

---

Dispatched Demand Response Resources (Negawatts)

Load Shedding refers to the general act of securing loads in order to avoid over powering a system. A controlled method of load shedding is known as Demand Response is negative demand dispatched by the system operator.

Typically a Demand Response Provider manages the process. The amount of demand response will vary based on many factors including the (a) type of customer and their ability to curtail demand, (b) the level of sacrifice they are willing to make, and (c) the amount of compensation they are being offered for reducing that demand.

<table>
<thead>
<tr>
<th>Category</th>
<th>Control Type</th>
<th>Technology / Descr.</th>
<th>Predictability</th>
<th>Variability</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential - DR</td>
<td>Dispatched</td>
<td>Entity response based on operator signals</td>
<td>Could be significant response, depending on adoption</td>
<td>Low - Med</td>
<td>(??) Neg-kW</td>
</tr>
<tr>
<td>Comm. - DR</td>
<td>Negative</td>
<td>Demand</td>
<td></td>
<td>Med - High</td>
<td>(??) Neg-kW</td>
</tr>
<tr>
<td>Industrial - DR</td>
<td>Dispatched</td>
<td></td>
<td></td>
<td>Low - Med</td>
<td>(??) Neg-kW</td>
</tr>
</tbody>
</table>

Additional Information
- Commonly known demand response providers include
- Market Demand Response is enabled through a Smart Grid. Please see discussion in previous section for more basic information.

Bulk Energy Storage Resources

The basic purpose of bulk energy storage in a grid system is to collect and store 'excess' energy is stored during one period, and redeliver that energy during periods when it has greater utility. There are many synergistic applications such as bulk electricity time shifting, transmission congestion reduction, reliability, power quality, and ancillary services. (8)

Bulk energy storage technologies currently in use include Pumped Hydro and underground (large scale) compressed air. Other technologies are less common or being developed, such as Surface Mounted Compressed Air Energy Storage, Flow Batteries, other advanced batteries and high speed flywheels.

"Vehicle to Grid" (V2G) enabled electric vehicles might be classified as micro- "Distributed" storage because they are (a) much smaller in individual size and (b) move from point to point throughout the day. (V2G effects are further discussed in the next section.)

<table>
<thead>
<tr>
<th>Category</th>
<th>Control Type</th>
<th>Technology / Descr.</th>
<th>Predictability</th>
<th>Variability</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Storage</td>
<td>Dispatched</td>
<td>Pumped Hydro</td>
<td>Ramp up / ramp down quickly</td>
<td>Med</td>
<td>500 - 3000 MW (est) (500 - 60k MWh)</td>
</tr>
<tr>
<td></td>
<td>- or - Quasi-</td>
<td>Comp. Air - Surface</td>
<td>Ramp up / ramp down quickly</td>
<td>Med</td>
<td>1 - 3 MW (est) (10 MWh)</td>
</tr>
<tr>
<td></td>
<td>Market</td>
<td>Comp. Air - Underground</td>
<td>ramp up / ramp down quickly</td>
<td>Med</td>
<td>3 - 50 MW (est) (30 - 200 MWh)</td>
</tr>
<tr>
<td>Market Response</td>
<td>response</td>
<td>Flow Batteries</td>
<td>Instant capacity to respond</td>
<td>High</td>
<td>1 - 3 MW (est) (10 MWh)</td>
</tr>
<tr>
<td>Arbitrage Demand</td>
<td>Demand</td>
<td>Electric Vehicles, PHEV's</td>
<td>Charge / Discharge instantly</td>
<td>High</td>
<td>0 - 10 kW (est) (8 - 16 kWh)</td>
</tr>
</tbody>
</table>

Distributed Storage (EV’s)

Additional Information
- For in-use examples of storage technologies, please see the 'Electricity Storage Association' website.
Operating/Frequency Reserves

While not a focus of this paper, it is important to understand the concepts and resources used by the system operator to maintain frequency and respond in case of a loss of power event. Each category below could refer to a technology or resource outlined already.

Operating Reserves refers to generating capacity available to a system operator within a short interval of time. Most power systems are designed such that, under normal conditions, the operating reserve is always at least the capacity of the largest generator plus a fraction of the peak load (Aka, "N-1+Margin" rules).

<table>
<thead>
<tr>
<th>Category</th>
<th>Control Type</th>
<th>Technology / Descr.</th>
<th>Predictability</th>
<th>Variability</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Response Res</td>
<td>Automatic</td>
<td>Inertia of spinning</td>
<td>On line, inherent in</td>
<td>High</td>
<td>Proportional to size of</td>
</tr>
<tr>
<td>Reserve (Regulating</td>
<td></td>
<td>machines connected</td>
<td>system operation,</td>
<td></td>
<td>generator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>to the grid.</td>
<td>available immediately</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SMALL AND</td>
<td>for 0 - 20 sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>NOT COUNTED IN O.R.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Frequency</td>
<td>Auto or</td>
<td>Flywheels, super-</td>
<td>On-line, available</td>
<td>High</td>
<td>0.1 - 3 MW (est)</td>
</tr>
<tr>
<td>Regulation Devices</td>
<td>Dispatched</td>
<td>capacitors, batteries</td>
<td>immediately for 0 - 20 sec</td>
<td></td>
<td>(0.5 MWh)</td>
</tr>
<tr>
<td>Spinning Reserve</td>
<td>Dispatched</td>
<td>Available additional</td>
<td>On-line, available</td>
<td>High</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&quot;Capacity&quot; of the</td>
<td>immediately to 10 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>generators already</td>
<td>for 1 - 10 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>on-line</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Spinning Reserve</td>
<td>Dispatched</td>
<td>Extra capacity not</td>
<td>Off-line, available</td>
<td>High</td>
<td>5 - 50 MW</td>
</tr>
<tr>
<td></td>
<td>(Once on</td>
<td>connected - &quot;Peakers&quot;,</td>
<td>within 10 min for</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>line)</td>
<td>&quot;fast start&quot; gen, Batts,</td>
<td>10 min - 1 hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pumped Hydro, CAES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replacement Reserve</td>
<td>Dispatched</td>
<td>Generators used to</td>
<td>Off-line, available</td>
<td>High</td>
<td>5 - 50 MW</td>
</tr>
<tr>
<td></td>
<td>(Once on</td>
<td>restore normal</td>
<td>within 30 min for</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>line)</td>
<td>conditions - typ gen &amp;</td>
<td>1 - 2 hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pumped Hydro</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Additional Information
- Additional requirements would be placed on these resources in the presence of high penetration of renewables.
- Significant modeling is required (see next section) to determine proper margins with renewables.
OPERATIONS & CONTROL CHALLENGES (PHASE 2)

The Brains
The Hurdle of Phase 2
Enabling Phase 3

Now that we've reviewed the general characteristics of the various grid elements (energy resources), we can discuss how they will fit and operate together.

Organized Chaos & the Role of the System Architected

In the grid of the future, many changes will be happening simultaneously:

- **Varying solar supply** → Resulting from spotty cumulous clouds on a hot summer day
- **Varying wind supply** → As the high pressure front settles for a hot muggy afternoon
- **Varying residential demand** → As appliances turn off in response to high real time prices
- **Varying storage supply** → As bulk storage operators take advantage of energy arbitrage
- **Step-change conditions!** → As a tree branch falls on a power line.

Throughout this paper we have examined the different influences on system design. In this section we focus on understanding the challenges associated with grid operation.

Mastering the operation of a grid with a high penetration of variable supplies and demands will be the defining characteristic of the second phase of grid development.

It's the role of the **System Operator** to properly maintain system function in real-time, provided the resources/tools given to them. With this perspective we can define the System Architect's role relative to operations.

It's the role of the **System Architect** to (a) consider the range of potential operating conditions (setting appropriate boundary conditions), (b) design a system which can operate throughout these conditions, and (c) provide the System Operator with the tools to properly operate within those bounds.

As we can see, the System Operator's job gets much more complicated and challenging when variable (and currently unpredictable) supplies and demands are introduced into the system. As a System Architect, we must carefully consider these effects.

Operational Objectives / Ancillary Services (3)

Ancillary Services are those activities required to guarantee security, quality and efficiency in electricity supply. The basic services provided are (a) Load Frequency Control, (b) Voltage control and (c) System Restoration which includes "Black Start" capability.
Ongoing System Operation Responsibilities:

1. Match generation and consumption across the system *(Load Frequency Control)*
   
   *(Primary control* is automatic response in generator; *Secondary control* adjusts governors per Area Control Error; *Tertiary control* is → Maintaining the lowest cost power available, through economic dispatch of generators, based on their participation in the wholesale marketplace)

2. Balance flow of current across all power lines on the network *(voltage regulation)*

3. Maintain sufficient operating reserves in case of generator loss *(N-1 Reliability)* according to State Estimation & Security Analysis → Which includes responding appropriately to system disturbances, and quickly restoring the system to proper operating conditions

Consider now a grid with a high penetration (> 15%) of variable supply and demand. We then define two related operational activities.

Additional challenges and requirements:

1. **FAST BALANCING** – Predict worst case rate of change of supply and/or demand, and ensure sufficient capacity to perform 'fast balancing' throughout those periods

2. **STORAGE MANAGEMENT** – Predict worst case supply demand disparities over daily/weekly cycles and ensure enough bulk energy storage available to maintain operation through those periods

<table>
<thead>
<tr>
<th>Table 20 – Matching Time Horizons to Operations Planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matching Supply &amp; Demand = Continuous Planning</td>
</tr>
<tr>
<td>Contingency Analysis (ie, loss of generator) = Immediate Term Planning</td>
</tr>
<tr>
<td>Fast Balancing = Short Term Variability Planning</td>
</tr>
<tr>
<td>Storage Management = Long Term Energy Supply Planning</td>
</tr>
</tbody>
</table>

**Phase 2 → Advanced Components**

*Key Operator Resource Functions & Benefits
Advanced Ancillary Services through Advanced Components*

In order to deliver the advanced level of Ancillary Services required in a grid with a high penetration of variable supply and demand (our Phase 2 grid), many new advanced components will need to be incorporated into the distribution network. To provide these services we refer back to the many functions outlined in Part III.
The functions below each represent advanced components and systems which help the network (automatically) and network-operator accomplish the operational objectives.

<table>
<thead>
<tr>
<th>Active Action by Network (automatically) or by System Operator</th>
<th>Informational to Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Flow Control</td>
<td>• Wide Area Monitoring, Visualization and Control</td>
</tr>
<tr>
<td>• Adaptive Protection (AKA, Adaptive Fault Protection)</td>
<td>• Dynamic Capability Rating (AKA, Ampacity Determination)</td>
</tr>
<tr>
<td>• Automated Islanding and Reconnection (AKA, Enabling &quot;Islanding&quot;)</td>
<td>• Enhanced Fault Protection</td>
</tr>
<tr>
<td>• Real-Time Load Transfer</td>
<td>Passive or reactionary functions</td>
</tr>
<tr>
<td>• Automated Voltage and VAR Control</td>
<td>• Fault Current Limiting</td>
</tr>
<tr>
<td>• Automated Feeder Switching (AKA, Automated Feeder Switch Actuation)</td>
<td>• Diagnosis &amp; Notification of Equipment Condition</td>
</tr>
</tbody>
</table>

While it may seem that these functions provide direct benefit only to the system operator, in each case these functions provide secondary benefits delivered back to society or the customer through greater reliability, reduced congestion costs, enabling of renewable resources, et cetera.

**Operating Reserves vs Fast Balancing 'Margins'**

*Immediate Term* Planning

First, we must draw an important distinction between two important and separate concepts.

**Operating Reserves**, typically refer to different categories of available generation supply used in response to an EMERGENCY EVENT, such as the instantaneous loss of a system generator. Strict requirements have been placed on system operators to maintain a certain amount of Operating Reserves.

**Fast Balancing (Rapid Response)**, as we shall define it, is the act of quickly responding to those effects associated with NORMAL OPERATIONS and variation of supply and demand. As such, sufficient 'Operating Margins' will need to be made available to enable the system operator to respond accordingly to the normal dynamics of supply and demand.

While "Operating Reserves" (i.e., available, standby energy) may still be used to respond to the need to perform fast balancing, the *margins* required to perform fast balancing and respond to emergency event should be kept separately. In other words, fast balancing margins are required in addition to those already required for emergencies.

\[
[Total\ Margin] = [N - 1\ Margin] + [Fast\ Balancing\ Margin]
\]
**Balancing Operations**

"Short Term" Planning

What is fast balancing? How is it accomplished?
How does it differ from Operating Reserves?

As suggested, one of the most critical functions performed by the grid operator will be "fast balancing", which the existing grid was never designed to handle.

**Fast Balancing** we define as the ability of a network to rapidly respond (ramp up or ramp down) in response to dynamic bulk power variations in order to continuously maintain the balance between supply and demand.

But what are the tools of the operator? What conditions must be matched to ensure Fast Balancing is at all times possible?

Previously in the Energy Resource Characteristics table in Part III, we described a level of Variability and Controllability for each item:

- **Variability** refers to the maximum rate of change of power imposed by, or could be sustained by a load or supply
- **Control** refers to ability a system operator has to adjust these values

Using these two independent factors, we can suggest a general categorization each of the Energy Resources:

**Table 21 – Supply / Demand Controllability vs Variability**

<table>
<thead>
<tr>
<th>FUTURE SUPPLY</th>
<th>FUTURE DEMAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>UD</td>
</tr>
<tr>
<td>US</td>
<td>UD</td>
</tr>
<tr>
<td>CS</td>
<td>CD</td>
</tr>
<tr>
<td>US = Un-controllable Supply</td>
<td>UD = Un-controllable Demand</td>
</tr>
<tr>
<td>CS = Controllable Supply</td>
<td>CD = Controllable Demand</td>
</tr>
<tr>
<td>LV = Low Variability</td>
<td>LV = Low Variability</td>
</tr>
<tr>
<td>HV = High Variability</td>
<td>HV = High Variability</td>
</tr>
</tbody>
</table>

| Solar Thermal | Solar PV |
| Biomass, EtE, etc | Wind Farm |
| Peaking Plant | Rapid Nuclear? |
| Storage | Storage |
| Typical Resi, Comm, Ind Demand | Demand Response Demand |

First we observe that the resources in the upper right quadrant represent our greatest challenges. These are items which we have no (or little) control over and can ramp very quickly. The lower right quadrant represents great assets in responding to variation. These items we have the most control over, and the greatest ability to ramp.
Focusing on the high variability items first, we shall describe two scenarios and derive the basic rules which govern the response. (Note that these same rules would apply to the LV column as well.)

RAPID LOSS OF WIND SUPPLY: While the stimulus could be in either positive or negative direction, we shall assume that there is a rapid loss in wind energy from a large off shore wind farm. First, the operator must identify the issue by noticing system frequency drop or shifting power supplies. Then, to compensate for these effects the system operator can either (a) increase the amount of supply from other generators with the same variability, or (b) decrease the demand, such as through demand response (or increase price to cause negative market response, if controllable).

In summary, the change in uncontrollable supply must be equal to the amount compensated by controllable demand controllable supply.

\[ \Delta U_{SV} \leq \Delta C_{DV} - \Delta C_{SV} \]

During actual operations, first we must continually calculate the probable minimum and maximum values of the given resource (US, CS, CD), as illustrated in the figure below. Then, given our current operating value within that band, we will ensure that there is sufficient "compensation margin" (sum of positive supply and negative, or vice versa) to compensate for the uncontrolled swing in either direction.

RAPID DECREASE IN DEMAND: In another scenario, imagine that we have a large geothermal plant supplying power into the grid. Then, due to a combination of temperature considerations and market effects, there is a relatively quick and unexpected drop in demand. As before, the grid operator must first notice by identifying an increase in grid frequency or power changing direction on certain power lines. The operator could then respond by (a) increasing demand through a demand response (increase) dispatch (or reduced market prices may mitigate effects), or (b) dispatch power to an energy storage resource.

\[ \Delta U_{LV} \leq \Delta C_{SV} - \Delta C_{LV} \]

While in practice exact mechanisms will be need to match these items, it is hoped that supply and demand items in the low variability columns (upper and lower left quadrants) can be managed in synchronous with each other. In other words, it is hoped that they do not pose as great an issue in designing systems.
Fast Balancing Design Implications

What are the design implications for the System Architect?

Some powerful design tools will be necessary to ensure that the system contains sufficient margin to cover all these conditions. For example, it's not possible to use traditional methods to estimate supply and demand needs. In the presence of bulk high variability sources, the System Architect must carefully examine each category of supply and demand (variability, controllability, etc., as above) and ensure that they provide sufficient margins.

Moreover, this procedure assumes that you can predict, with some certainty, the bands of operation of uncontrolled demand and supply, which is complicated by the inclusion of market effects on price, etc.

The basic parameters of a modeling tool are outlined in the Portfolio Management section, which could be used to assist in 'testing out' various operating scenarios.

Bulk Storage Basic Operations Considerations

In Part III we outlined many potential applications / benefits from the use of energy storage, such as:

- **Strategic placement of storage** for reduced (a) congestion, (b) Transmission & distribution capacity costs, and (c) increase system reliability, etc.
- **Timed operation** performing 'load leveling' to (a) increase generator optimization, (b) reduce required capacity investments, etc.

Specific applications of particular interest for Phase 2 → Phase 3 transformation are:

- Renewable Energy Production Time Shifting
- Renewable Energy Production Capacity Firming

In each of these cases, our primary interest and value (including surpassing the Phase 2 hurdle of 15% renewable energy penetration) is on bulk energy storage used in 'time-shifting' purposes. In other words, we will store the energy when it is of lesser value, and dispatch that energy when it is of greater value to the system. We shall define "bulk" energy storage as those systems which provide at least greater than 500 kW of power for more than 6 minutes (0.1 hrs).

Figure 8 - Bulk Electricity Time Shifting (7)

Because there is very little precedent for the use of bulk energy storage, there are many questions which must be answered when considering daily operations:

- What level of control does the system operator have over the device?
- Can the system operator start and stop the device at will? What is the startup time?
• How much flexibility does the system operator have in ramping up / ramping down power?
• How many times can the system be cycled in a day?
• Does the system need to be fully charged (or discharged) before reversing power flow?
• How can the system operator see what the state of charge is? (Full to empty?)
• What is the variability rate?

The answer to these questions will vary greatly on the type of energy storage system being used. Each of the five technologies currently in use or being developed has notably different operating characteristics, and will provide different answers to the questions above to the system operator.

The five commonly used technologies are as follows:
1. Capacitors
2. Flywheels
3. Batteries (which includes distributed battery electric vehicles)
4. Compressed Air
5. Pumped Hydro

Given our long time horizon to Phase 2 and ultimately Phase 3, it is difficult to predict what technologies may play the greatest role in our future smart grid.

Provided all the benefits delivered by bulk energy storage, the emergence of a cost effective technology will mark the beginning of a paradigm shift in transmission and distribution system design and operation, and help usher in Phase 2 of our Smart Grid transformation.

**Bulk Storage for Renewable Electricity Time Shifting**
*Similar to Energy Arbitrage*

As described, one of the primary problems with renewable energy is that it does not coincide exactly with demand and is not controllable. Therefore, if we are ever to achieve a condition whereby 40% or more (i.e., Phase 3) of our energy is supplied by renewables, we will have to determine a way to perform bulk energy storage.

As a near term example, one type of application being developed is using compressed air to store energy from a small wind farm and subsequently dispatch that energy during periods of higher prices. We observe that, while wind might blow the strongest at night, this is the period where both (a) there is the least amount of demand and the system operator may even curtail wind turbine operation, or (b) the wholesale cost of energy is very low and the wind farm owner is not receiving great value for the energy.
In this case, either the system operator (i.e., the distribution system owner) or the wind system owner may decide at night to supply energy to the energy storage system and re-dispatch it during peak periods the next day.

**Bulk Storage for Independent Operations (Islands & Micro-grids)**

Planning for islanding operations

Long Term Planning

Daily, weekly, monthly cycles

In cases where either (a) there is or could be a lack controllable base or peaking load (such as a feeder which is designed for islanding operation), or (b) system boundaries limit the maximum amount of power which can be imported, it will be necessary to properly size storage within the grid network.

Note that storage sizing (this discussion) is treated separately from variability capacity matching (previous section). Each analysis will need to be performed to determine system design.

Calculating the amount of energy storage needed for independent operations will vary based on many factors, such as:

- What are the system boundaries and what is the maximum energy which can be supplied across those boundaries, if any. (This will be zero for microgrid operations.)
- What is the desired duration of independent operation?
- What are the best and worst case load curves (hour by hour) for all supplies and demands during the control time period?
- With what level of accuracy can supply and demand curves be predicted?

A simple case might be a feeder which is to be islanded in the event of a power outage. The amount of energy storage would be equal to the expected energy demand for the period of time you wish to supply storage, plus sufficient operating margin. In this case (a) the architect will have already sized the storage and (b) the operator must only ensure the storage is full prior to the event.

Now consider a system consisting of a varying load and a single supply and energy storage (see illustration). At all periods throughout the day the amount of energy demanded must be met by the sum of power from supply and storage. (Note, however, in this exercise our objective is to size the total energy supply, not the instantaneous demand, which must also be calculated.) During periods of excess supply energy will be stored, and vice versa. In both instances, energy going into storage and coming from storage, there will be a certain efficiency loss which must be accounted for.

$$\eta \cdot \text{Storage}_t = \text{Supply}_t - \text{Demand}_t$$
Next, we must extend our time horizon to estimate the worst case condition supply demand conditions. For example, what is the maximum amount of energy storage needed to get through the week? The month?

If the storage is appropriately sized (with margin) it will be the operator's responsibility to ensure proper reserve margin at all times, based on projected supply / demand characteristics. Depending on the amount and type of renewable energy supply, a key factor in calculating how much storage will be dependent on the weather. In other words, how long can the system be sustained during prolonged periods without wind or sun? How much energy storage is required to get through these periods?

Clearly these are simplified cases. In practice, and probabilistic analysis will be required on weather patterns, the ability to influence through market (pricing) effects and demand response, et cetera.

**V2G Operations & Management Example**

As a final illustration, consider a case of electric vehicles. The mass introduction of EV poses a whole new dimension, and complexity, for the system operator. Sample questions and considerations are as follows:

- How many vehicles are plugged in and where are they? Are they connected to a feeder which is currently being stressed?
- Of those vehicles, connected what is their capacity to supply energy? To demand energy?
- How much will it cost me (the system operator) to draw energy from this group of EV's?
- By what method am I communicating with the vehicles to send/receive information?
- What are the price points already set by the vehicle owner? Does the market price justify a charge/discharge scenario? Can I override those set-points in the event of an emergency?

It is exciting to imagine the possibilities of using EV's as a bulk energy storage method. However, the challenges for both the system architect and system operator are notable. No doubt, through proper design, they can and will be overcome.
PORTFOLIO MANAGEMENT – MODELING THE ENDFGAME (PHASE 3)

Putting it all together
Applying form to function at the whole product system level
Preparing for Phase 3
Quantitative testing of reserve 'margins'

Returning to System Architecture Fundamentals

Here is where we finally have an opportunity to apply form to function as a network designer. In this case we can examine electricity networks on the whole product system level, moving and adjusting elements to ensure proper and continuous delivery of the primary function.

Returning to our ten step process, we are now:
- Step 6. Creatively consider concepts
- Steps 7 & 8. Assigning form to function
- Steps 9 & 10. Iterate...

Basic Software Operation & Objectives

After constructing a sample network, feeder or microgrid (based on an existing or hypothetical systems), using the select elements and variables for each type of energy resource (see Energy Resource Elements Table), the user can run the model. The outputs of the model will state under which cases they are (a) exceeding a maximum market price, (b) exceeding a maximum ramp-up / ramp-down rate, or (c) exceeding the capacity of their supply, provided the constraints they have established. The operator would then iterate model inputs and boundary conditions and run the system again, ultimately converging on a potential solution for that given condition.

Over time we can evolve the software to include new functionality, including detailed examination of internal network structure.

Necessity for a Portfolio Modeling Tool

A robust tool for adequately testing and modeling the operation of the network at this level is vital. No longer can we be focused only on slight grid evolutionary steps. While there is no shortage of electrical network modeling tools on the market, it is unclear whether one is available to perform the functions as described herein.

Such a tool is important, not only because determining market effects and generator dispatch is tedious and computationally intensive, but also because the most robust and optimal system architecture cannot be determined without evaluating the characteristics at the first layer of decomposition.

Key Characteristics

In the utility industry traditionally 'Portfolio' modeling refers specifically to modeling network effects of supply side large centralized generators. In addition, most tools are intended at testing worst case conditions and provide highly accurate fault analysis results.
The modeling tool we need is notably different than most being used today. Key characteristics include:

- Models both both **supply** and **demand** side dynamics
- Instead of large and central, the model allows for **smaller** and **more distributed**
- Demand side elements respond to market price (based on inputs)
- Demand response schemes are pre-programmed based on certain conditions
- All supplies are modeled, including uncontrollable, variable and non variable **renewables**
- Supply side includes **bulk energy storage**
- Demand side includes estimated responses to retail prices

Although it may seem so, the proposed version of the software is not complicated to start. As suggested, our primary objective is to produce an hourly curve for each device showing how much energy it supplied, demanded, and what was the market price. Basic information would be supplied for each category of element, such as:

- Controllable Supply: Capacity, price curve, max variability rate
- Variable Supply (Solar Wind): User provides a simple 24 hour production curve
- Demand Response: When activates automatically based on price or margin stimulus
- Market Response: Consumption is curtailed based on preset price responses
- Storage: Either used as 'driver' (pre programmed as demand / supply) or 'buffer' (program automatically suggests how much supply is needed to maintain operation

Through examining hourly curves we can also see when/if maximum variability rates were exceeded.

Ultimately we will include 'grid dynamics' analysis tools, such as determining necessary margin sizes to account for source variability (See Grid Operations section). Other dynamics objectives include examining how might recloser setpoints need to be adjusted based on current flow.

The results of initial testing will someday inform highly granular analysis such as identifying uncontrollable dynamics or various fault conditions, but such functionality is not a near term objective with this software.

**Sample Screenshots & Further Information**

Sample symbology used in the modeling tool is shown in the Appendix.

**ANALYZING EXISTING SMART GRID DEMONSTRATION PROJECTS**

*Review of Existing Demonstrations*
*Which projects will deliver the most long term benefit to the most people?*

The primary objective below is to (a) highlight some ongoing projects, but more importantly (b) present seven key question categories, tailored on the architectural framework in this paper, for analyzing smart grid projects and architectures. This section is concluded with a couple key observations.
**Grid Demonstration Initiatives Underway (6)**

**DOE PROJECTS** – The federal government has set various Smart Grid initiatives as a national priority, as reflected in Title XIII, "Smart Grid," of the Energy Independence and Security Act of 2007 (EISA). Subsequently, the Department of Energy awarded contracts in 2008 to nine smart grid demonstration projects. These projects, summarized in the Appendix, are intended to catalyze this effort. Renewable and Distributed System Integration (RDSI), also a DOE initiative, which is enabled by Smart Grid systems, is incorporated in various projects.

**EPRI PROJECTS** - The Electric Power Research Institute (EPRI) is also leading several Smart Grid projects, which have broad goals, similar to the DOE projects.

- AEP Smart Grid Demonstration Project - "Virtual Power Plant Simulator (VPPS)"
- Con Edison Smart Grid Demonstration Project "Interoperability of Demand Response Resources"
- EDF Smart Grid Demonstration Project - "PREMIO: Distributed Energy Resources Aggregation and Management"
- FirstEnergy Smart Grid Demonstration Project - "Integrated Distributed Energy Resources (IDER) Management"

**SMART GRID CITY** – The Smart Grid City project, led by Xcel Energy, is privately funded and has some of the most aggressive penetration objectives than any other project. Notably this project is focused more on actual larger scale deployment (as opposed to just demonstration) than any others.

**Key questions to be answered**

**NOTE:** In answering the questions below it is important to acknowledge existing, greater and lesser layers of decomposition. In other words, acknowledge boundaries and state whether your answer is relative to a greater system or subsystem level.

**BENEFICIARIES & STAKEHOLDERS**

Who are the primary beneficiaries? Stakeholders? What role does each play?

**FUNCTIONS & TECHNOLOGIES**

Outline the functions performed and value delivered at the 'whole product system' and 'first layer decomposition' levels. What are the assets/technologies which deliver the value? How are they similar/different from those previously outlined?

**MAPPING FORM TO FUNCTION**

Are unique concepts used to map form and function? Is the design elegant (minimum complexity and maximum utility)?

**FOUNDATION FOR LONG TERM GROWTH? (Downstream Influences)**

In context of the three phases of Smart Grid development described previously, do the technologies being deployed or tested build a foundation for long term growth?

**DEPLOYMENT & OPERATIONS (Downstream Influences)**

Can the systems be constructed? Are the systems operable, maintainable, sustainable, reliable?
**SATISFIES UPSTREAM/DOWNSTREAM REQUIREMENTS**

Are the objectives clearly understood? Does the value delivered meet the stated objectives? Does the system meet strategic business objectives?

**OPTIMAL vs POLITICAL**

Does it seem the system appear to be designed 'optimally' (according to engineering principles first)? What appear to be suboptimal/political influences on design?

**Brief Analysis**

In a brief survey of the projects above, we observe that nearly every project (with the exception of the EPRI modeling project) falls directly in our Phase 1. **However an architectural analysis should be performed of each project, assisted by the questions derived above.**

Some common characteristics of each project include – upgraded substations, feeders and transformers, smart meters, and Web-based tools – all vital first steps to Phase 1.

These projects are absolutely vital and are laying the foundation for all future growth. We are encouraged by their progress and eager to participate in similar projects across the country.
Part V. Observations & Conclusions in Framework Application

How was applying the system architecture framework useful?
What methods or conclusions emerged which aren’t present in other literature?

The basic intent of this paper is summarized as follows:

The System Architecting process essentially provides a suggested methodology or framework for understanding or designing complex systems. This framework is based on timeless principles which have always governed the design process but may not have been explicitly acknowledged.

Our first basic goal is to present that methodology and apply it to the infinitely complex system of systems, such as the electricity grid. Having applied this framework to today’s grid, now we can use it to (a) redefine a next generation grid, (b) determine and present a pathway of transformation, (c) outline key design and operational implications on final product, and (d) outline key questions for evaluating the architecture of other grid systems.

This paper is both about both the "How?" (applying the architecture process) and the "What?" (the results of that process) of the Smart Grid. How should you evaluate and examine the Smart Grid? How can I best determine what is important? How should I participate? And also... What are the key observations? What specific conclusions can be drawn which help define system design or operation?

A few key observations are outlined below:

**#1 Defining the Smart Grid in terms of benefit & function is most helpful**

There are many methods for describing the smart grid. While there is utility in describing it in terms of output 'characteristics', for the System Architect or system designer, it is most helpful to describe it in terms of benefit and function. By doing so we are able to hone in on specific subsystem level systems or components, as opposed to generalities. By examining at a higher level of granularity we can more effectively quantify the value delivered and assign form.

By definition, if ever the problem statement is unclear, undefined, and system boundaries are unknown, this is one tool of many in the principle based System Architecture framework which you can rely on to provide direction.

**#2 Provides context to Smart Grid subsystems value delivery**

Through the application of the system architecture framework one can clearly define at what layer of decomposition a particular function or product delivers value. This provides vital context when evaluating or creating new designs.

The Grid is an infinitely complex multi layered infrastructure; understanding where your product fits into this vast domain is vital and can be accomplished with these processes.

**#3 Natural & technical influences are considered first, political & economic are layered afterward**
The System Architecture framework has provided a means for understanding and prioritizing influences in the infrastructure transformation process. Through this process we are able to first take a wide view of all the various potential impacts on design, and hone in on those specific items with \textit{should be} important in defining design. Those key influences should be based on natural / engineering influences first, followed by political or market influences.

As such, the System Architect must both understand the issues and participate in the political process to ensure desired outcomes.

\textbf{#4 Key long term benefits are social, but driven by economic means}

In evaluating the many influences on infrastructure transformation it is concluded that, while there are many benefits delivered to the consumer (i.e., cheap energy and reliability), the overall driving force will be environmental benefits delivered to society. The mechanism to deliver these benefits must be economic.

Political influences will be great and will often contradict what we seek as optimal architecture; understanding our principle based ideal solutions will be critical when lobbying for supportive regulation.

\textbf{#5 Communications are the first step to Smart Grid transformation}

Communications & Measurement development represents the Smart Grid nervous system, and is the first phase of infrastructure transformation. Key milestones will be enabling real time pricing, demand response and encouraging energy efficiency through the use of advanced metering infrastructures. All subsequent phases of development require having this strong communications backbone.

As a first step, all utilities must engage in this vital first step; all future development depends on it.

\textbf{#6 Additional operating margin is needed to accommodate uncontrolled variable resources}

Many operations functions must be introduced to overcome the 15 to 20\% penetration barrier, including ‘fast balancing’ and ‘storage management’ schemes, each in response to inherent variability of high renewable energy penetration. Overcoming these operational barriers marks Phase 2 of grid development. It is critical that we understand this dynamic effect occur long before in major market investments in this new class of non-dispatched dynamic loads.

In some markets (i.e., California) feeders are already meeting their 15 to 20\% penetration limits. Our goal is to establish clear operational guidelines today and anticipate these challenges before an event which inhibits transformation occurs.

\textbf{#7 Matching energy resources effectively is a key challenge of the System Architect}

There are many categories of energy resources (i.e., conventional supply, renewable supply, regular demand, controllable and non-controllable demand, energy storage, and energy reserves), each with very different characteristics. A key challenge for the system architect will be evaluating the complete range of operational possibilities and ensuring a portfolio mix which is optimized and ensures complete value delivery.
These observations underscore the importance of performing feeder and network wide analysis today, similar to what is being done in many of the smart grid demonstration projects. All network owner/operators should begin smart grid pilot and demonstration projects of their own.

#8 A robust system design tool is vital for the network designer

Product form can only be defined through the integration and analysis of parts at the first layer of decomposition. Due to the highly complex nature of the grid and the many dynamic conditions which take place, a robust modeling tool is necessary to adequately perform system level testing, ensuring all design parameters are met. The tools to perform this level of resolution analysis do not exist, or at least are not made available.

Our goal should be to develop and deploy a simple tool for designers and academics to experiment with.

For more information on the contents of this paper or on the author, please contact gregory.sachs@sloan.mit.edu.
APPENDIX 1: System Architecture Terms & Concepts

SYSTEM ARCHITECTURE GLOSSARY (2)

Principles, Processes and Tools:
Architects use principles, processes and tools. Principles are the underlying and long enduring fundamentals that are always, or almost always valid. Processes are the organization of methods and tasks to achieve a concrete end, which should be solidly grounded on principles. Processes are usually applicable. Tools are the contemporary ways to facilitate process.

Product:
A thing of value which can be delivered or transferred and has value

System:
A set of interrelated elements that perform a function, whose functionality is greater than the sum of the parts

Complex:
Having many interrelated elements and interfaces

Value:
Benefit at cost

UPSTREAM & DOWNSTREAM INFLUENCES

A primary responsibility of an architect is to sort through the many diverse, undefined, and contradictory influences on potential or existing system design. It is helpful to contextualize these influences in two categories, "Upstream" and "Downstream" influences. As suggested, this phase is embodied by steps 1 & 2 of the Architecting Process above.

Upstream influences, simply stated, are those which the architect has little direct control over. These are influences or requirements which are set by others, such as the actual needs of the primary beneficiary, codes or regulations, or other market influences.

Downstream influences are those which the architect has control of, depending on how he/she defines the product or system. In other words, the architect has the ability choose a concept and form which the operator is able to understand or utilize effectively. Another downstream influence would be ensuring the operator has the ability to replace or fix parts.

The outline below builds upon the definition above and describes various considerations and questions of an architect.
Table 22 – Upstream & Downstream Influences & Concept

SA ROLE IN DEFINING UPSTREAM & DOWNSTREAM INFLUENCES & CONCEPT

1. Interprets needs, defines objectives (=goals) and desired functions
   (Aka, "Upstream" influences – inherent outside requirements, set by others)
   a. Interpreting beneficiary and stakeholder strategies
   b. Considers competence of beneficiary and stakeholders
   c. Interpreting regulatory and other inherent system requirements
   d. Interpreting potential market influences
   e. Infusing available technologies

2. Considers the management of evolution of complexity, such that objectives are met and function is delivered
   (Aka, "Downstream" influences – considerations impactable by design, influenced by architect)
   a. Thinks holistically about product life cycle: designability, manufacturability, operability, evolutionary capability, risk management, sustainability
   b. Anticipates failure modes and plans for mitigation & recovery
   c. Defines interfaces between subsystems
   d. Configures / structures the subsystems: flexibility vs optimality, modularity vs platform, new vs legacy, vertical vs horizontal

3. Creates the concept for the system, consisting of internal function(s) and form
   (Aka, creatively considering design)
   a. Considers objectives derived from upstream and downstream influences
   b. Determines specific functional operations
   c. Proposes and develops options for form using various concepts
   d. Conducts highest level trades-offs and optimizations

Graphical Representation of Upstream and Downstream Influences (2)
DELIVERABLES OF AN ARCHITECT

The following "deliverables of an architect" are presented to further reinforce core concepts in characterizing complex systems. Under each deliverable are the questions and considerations which must be addressed in order to produce the product. As previously suggested, while an 'operations manual' may be the last thing you submit to your client, the implications of operation were considered way back in the conception stage of the project.

1. GOALS / GENERAL OBJECTIVES: Establish a clear, complete, consistent and attainable set of objectives (with emphasis on functional objectives)
   a. Who are the beneficiaries and what are their needs? Determine value related operand.
   b. Consider other stakeholder influences: strategy (values, investors), market forces, regulatory restrictions, and standards. Consider available and evolving technology impacts. (clarifying ambiguity of other upstream influences)
   c. Consider complete life cycle and usage (designability, manufacturability, operability, evolutionary capability, sustainability), mitigation of risk, and other downstream influences outlined per deliverables below
   d. Derive primary objectives of system

2. CONTEXT: Consider the broader context in which the system sits, and the whole product context
   a. Define the whole product system, product systems, and supporting systems
   b. What key considerations must be made at system boundaries and interfaces? What is shared or passed across boundaries?
   c. What is the use context?
   d. What key "down"

3. SPECIFIC FUNCTIONS / DESIGN SPECIFICATIONS: Determine a functional level description of the system, with at least two layers of decomposition
   a. Derive solution neutral statements of the value related transformation for both the whole product system and other systems.

4. CONCEPT FOR OPERATION: Select a final concept for the system
   a. What are the various methods by which the primary objectives can be accomplished? For each concept consider optimal tradeoffs between objectives, function and form.
   b. Which have we selected?
   c. What are the concepts for sub and supporting systems?

5. DESCRIPTION OF FORM / MANUFACTURING SPECIFICATIONS: Provide design drawings outlining the form of the product/system, with at least two layers of decomposition
   a. Provide documentation necessary to construct the system/product: Schematics, shop drawings, fabrication procedure, detailed specifications

6. USAGE DOCUMENTATION: A notion of the timing, operator attributes, cost, risks, and the implementation and operation plans
   a. Provide explanatory information, installation manuals, operating manuals, maintenance / troubleshooting procedures, description of emergency, contingency or stand alone operation.
**WHAT DEFINES "GOOD" ARCHITECTURE?**

What is good architecture?

- **Answer 1:** That which meets the objectives of the system; Which are based on the important needs of key stakeholders
  - Starts with resolving upstream ambiguity
  - Problem is constrained by mission and outcomes of the enterprise
- **Answer 2:** That which uses appropriate and creative concepts to meet statements of solution neutral function while providing for minimum complexity
- **Answer 3:** That which has a set of internal processes, a well structured set of instrument objects, so that the external value related function emerges (AKA, that which resolves possible inconsistencies in modularization)
  - Must carefully decompose the system and ensure soundness of architecture
  - Seeks combinations of objects and processes to meet functional requirements

Good Architecture (cotd.)

- **Upstream**
  - Satisfies customer (beneficiary) needs
  - Meets strategic business objectives
  - Incorporates appropriate technology
  - Enables effective completion in the marketplace
  - Meets or exceeds present and future regulations
- **Downstream**
  - Is operable, maintainable, sustainable, reliable
  - Can be evolved/modified as appropriate
  - Can be designed and implemented by envisioned team
  - Can be implemented with existing/planned capabilities
- **AND IS ELEGANT** (minimum complexity to maximum utility)
- **Delivers benefit at competitive cost!**
APPENDIX 2: DOE Smart Grid Project Characteristics

DOE Smart Grid Characterization Framework (9)

(Comparison table begins on next page)
The following table summarizes DOE Smart Grid project characteristics, compiled from a variety of online resources. (9)

<table>
<thead>
<tr>
<th>Lead Entity</th>
<th>Allegheny Power</th>
<th>ATK Space Systems</th>
<th>Chevron Energy Solutions</th>
<th>City of Fort Collins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sponsor</td>
<td>DOE</td>
<td>DOE</td>
<td>DOE</td>
<td>DOE</td>
</tr>
<tr>
<td>Title / Tagline</td>
<td>Advanced Utility Infrastructure (AUI) -- WV Super Circuit</td>
<td>Powering a defence company with renewables</td>
<td>CERTS Microgrid Demonstration</td>
<td>Mixed DR for peak load reduction</td>
</tr>
<tr>
<td>Tech-Smry</td>
<td>Biodiesel combustion engine, microturbine, PV, E.Storage, advanced wireless comms, dynamic feeder reconfiguration</td>
<td>Hydro turbines, CAES, solar trough &quot;booster&quot;, wind turbines, waste heat recovery</td>
<td>1.2 MW Solar energy, 1 MW fuel cell, (if wind?), energy storage and control systems on a microgrid</td>
<td>3.5 MW diverse RE integration: PV, CHP, thermal storage, FC, microturbines, PHEV, DR</td>
</tr>
<tr>
<td>Key Objective(s)</td>
<td>Improve distribution system performance, reliability, and security of electric supply</td>
<td>Reduce peak load and measurably improve power reliability</td>
<td>Achieve a 20-30 percent peak load reduction on multiple distribution feeders</td>
<td></td>
</tr>
<tr>
<td>Topology Desc.</td>
<td>West Virginia &quot;Super Circuit&quot; - Distribution Feeders</td>
<td>Building?</td>
<td>&quot;Microgrid&quot;</td>
<td>Distribution Feeders</td>
</tr>
<tr>
<td>Location</td>
<td>Morgantown, WV</td>
<td>Promontory, Utah</td>
<td>Santo Rita Jail, Alameda County, CA</td>
<td>Fort Collins, Colorado</td>
</tr>
<tr>
<td>Lead Entity</td>
<td>Illinois Institute of Technology</td>
<td>San Diego Gas and Electric</td>
<td>University of Hawaii</td>
<td>University of Nevada</td>
</tr>
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<tr>
<td>Sponsor</td>
<td>DOE</td>
<td>DOE</td>
<td>DOE</td>
<td>DOE</td>
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<tr>
<td>Title / Tagline</td>
<td>Interoperability of DR Resources</td>
<td>The Never-Failing &quot;Perfect Power&quot; Prototype</td>
<td>Beach Cities Microgrid</td>
<td>Transmission Conestion Relief</td>
</tr>
<tr>
<td>Tech-Smry</td>
<td>DR, advanced sensing, switching, feeder reconfiguration, and controls. -- AMI, intelligent &quot;PP&quot; sys controller, gas fired generators, DR controller, UPS, E.Storage.</td>
<td>DR, E.Stor, outage mgt sys, automated distribution control, AMI -- Dispatchable distribution feeder for peak load reduction and wind-farming</td>
<td>Intermittency mgt sys, DR, wind turbines, dynamic simulations modeling</td>
<td>PV, AM, &quot;in home dashboard&quot;, automated DR to consumer products, Battery E.Storage</td>
</tr>
<tr>
<td>Key Objective(s)</td>
<td>Enhanced reliability of distribution and improve operations efficiency -- Methodologies to achieve true interoperability between a delivery company and end-use retail electric customers</td>
<td>Demonstrate that cost-effective power can be delivered to consumer precisely as the consumer requires it, without failure and without increasing costs</td>
<td>Improve stability and reduce peak loads on feeders/substations -- integrating multiple distributed resources with advanced controls</td>
<td>Management of distribution system resources for improved quality and reliability, transmission congestion relief, grid support, (and transportation relief??)</td>
</tr>
<tr>
<td>Topology Desc.</td>
<td>Dense (NYC) network infrastructure</td>
<td>Distribution feeders</td>
<td>&quot;Microgrid&quot;?</td>
<td>Distribution System</td>
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<td>IIS, Chicago, IL</td>
<td>San Diego, CA</td>
<td>Las Vegas, NV</td>
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<td>Stakeholders</td>
<td>Con Edison, Verizon, Innovative Power, Infotility, Enernex</td>
<td>IIT, Exelon/ComEd, Galvin Electricity, S&amp;C</td>
<td>SDG&amp;E, Horizon Energy Group, Advanced Control systems, PNNL, Univ of San Diego, Motorola, Lockheed Martin</td>
<td>University of Nevada, Pulte Homes, Nevada Power, GE Ecomagination</td>
</tr>
</tbody>
</table>
### APPENDIX 3: Sample Symbology of Portfolio Modeling Tool

#### Grid Elements and Load Curves

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Type</th>
<th>Load Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Symbol" /></td>
<td>Baseload Generator</td>
<td><img src="image2" alt="Load Curve" /></td>
</tr>
<tr>
<td><img src="image3" alt="Symbol" /></td>
<td>Peaking Generator</td>
<td><img src="image4" alt="Load Curve" /></td>
</tr>
<tr>
<td><img src="image5" alt="Symbol" /></td>
<td>Bulk Energy Storage</td>
<td><img src="image6" alt="Load Curve" /></td>
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<tr>
<td><img src="image7" alt="Symbol" /></td>
<td>Distributed E. Storage (EV)</td>
<td><img src="image8" alt="Load Curve" /></td>
</tr>
<tr>
<td><img src="image9" alt="Symbol" /></td>
<td>Solar</td>
<td><img src="image10" alt="Load Curve" /></td>
</tr>
<tr>
<td><img src="image11" alt="Symbol" /></td>
<td>Wind</td>
<td><img src="image12" alt="Load Curve" /></td>
</tr>
<tr>
<td><img src="image13" alt="Symbol" /></td>
<td>Hydro</td>
<td><img src="image14" alt="Load Curve" /></td>
</tr>
<tr>
<td><img src="image15" alt="Symbol" /></td>
<td>Residential Demand</td>
<td><img src="image16" alt="Load Curve" /></td>
</tr>
<tr>
<td><img src="image17" alt="Symbol" /></td>
<td>Commercial Demand</td>
<td><img src="image18" alt="Load Curve" /></td>
</tr>
<tr>
<td><img src="image19" alt="Symbol" /></td>
<td>Industrial Demand</td>
<td><img src="image20" alt="Load Curve" /></td>
</tr>
</tbody>
</table>
**Necessary Complexity, "Down 2 Up 1"**

A fundamental principle of System Architecting is that in order to design a system which produces value on your existing layer (layer 1) of abstraction, you must decompose and identify all the elements at layer 2. As simple example, if you need to organize a stack of papers, you must understand the content on each page in order to put the pages in categories. We can generally refer to this as the "Down 2 up 1" principle.

**Sample Graphical Representations of Network Topologies**
APPENDIX 4: Grid Transformation – 12 Key Dimensions

Twelve Key Dimensions of Grid Transformation
Ignacio J. Pérez-Arriaga

Excerpted from final Term Paper Requirements
Engineering, Economics and Regulation of the Electric Power Sector
Spring 2010, MIT-ESD

POWER SYSTEM RESTRUCTURING GOAL:
40% of penetration of renewable electricity generation by 2030

1. **Energy legislation.** Describe the process of *restructuring and/or liberalization* that has taken place in the systems to be considered; submit an opinion about its performance. Specific to be addressed include: • Whether the process of restructuring and/or liberalization has been correctly designed and executed; • Unbundling of activities and resulting system structure; • Wholesale and retail market rules; • Potential for the abuse of market power; • Remuneration of the regulated activities and incentives for efficiency improvements; • Treatment of environmental / sustainability objectives and constraints; • Electricity prices; • Quality of service; • Security of supply; and • Transmission investment or governance of the relevant regulatory institutions. Describe the current body of legislation governing the power sector; indicate what type of changes, and at what level, will be needed to reform the current legislation of the power system of your choice.

2. **Markets versus Governments.** Describe whether it is justified for the power system in question to establish such an ambitious target for the contribution of renewables to the production of electricity? On which grounds could a mandatory target like this be established? Express your ideas about the role of markets vs governments in the regulation of the energy sector, and the electricity power sector in particular. Consider the role of both shorter-term goals (affordable prices, competitiveness, immediate security of supply) and longer-term objectives (the different dimensions of sustainability). What degrees of freedom that should be left in practice to electricity markets? Make the arguments specific for the power system in question. Discuss the role (if any) that indicative energy (and electricity) planning could play in this respect.

3. **Renewable generation.** Now choose the most adequate regulatory instrument to achieve this type of target in renewables penetration in the considered power system. What regulatory approach would serve best to meet the prescribed target with a maximum confidence and the lowest cost? Describe and justify this choice. Describe alternative choices and the reasons why for or against them. In each case, outline what necessary adaptation of the wholesale market rules might be necessary including the implications for financiability of the investments. (Are any specific support regimes necessary?) Describe the impact on the dispatch methods and market remuneration methods of other technologies (ie, existing power plants or other distributed resources). Describe who should pay for the extra costs associated with the programs which support development of renewables?

4. **Distribution.** Assuming an RPI-X method might be used for price control of the distribution network in your system: Indicate what difficulties may appear in the application of this method if a
significant fraction of the new renewable generation will be connected at distribution level. Explain how the RPI-X method could be upgraded.\(^7\) Based on this analysis, make recommendations for distribution remuneration for the system in question. Can the system in place be adapted? Be sure to consider losses and quality of service, as well as innovation incentives in the review.

5. **Transmission.** Intermittent renewable generation may be far away from the demand centers in the system of choice. This may require major reinforcements and perhaps a major reconfiguration of the transmission network. Is the existing regulation in the power system is adequate for this new situation. Examine available international experiences. You have to cover investment, access and pricing issues. Examine the trade-offs between centralized and decentralized planning approaches. Examine the possibilities of application of some kind of performance-based regulation. Make a proposal about the regulatory changes that would be necessary to implement in your system.

6. **Locational signals for new generation entries.** (This applies to future renewable generators that could be located either in transmission or distribution networks.) For both types of networks, discuss the convenience of using appropriate economic and regulatory signals for prospective new investors about the implications of their choice of siting. Be specific about the locational signals that could be used (if any) in the considered power system.

7. **Generation adequacy & capacity mechanisms.** It is believed that with a large penetration of intermittent generation, and the pressure to reduce CO2 emissions, the future optimal mix of technologies will be very different from what is now. Specifically there is concern about getting the right amount of investment, especially considering that a large fraction of the installed capacity is intermittent. Capacity mechanisms could be of help in this respect. Perform a critical evaluation of the regulatory instruments which have been adopted and/or implemented in the US (such as capacity payments or capacity markets) and elsewhere to promote adequacy in the investment of generation capacity. Describe and evaluate in detail the Forward Capacity Market in New England (or any other advanced scheme). Describe how they could be adapted to the case of large penetration of intermittent generation. Describe the potential role of demand response and other technologies such as plug-in hybrid vehicles (PHEVs). Is there a need for specific regulation of demand response and PHEVs? Are there special rules for the various types of interconnectors. Review and compare any conclusions with other meaningful international experiences. Propose optimal solutions and describe how to overcome any problems in the implementation of the method proposed and if the level of horizontal concentration in generation in your power system is high.

8. **Market power mitigation.** Is it believed that the present level of horizontal concentration in the power system is compatible with the existence of a working electricity wholesale market? Is it believed that there is any other major barrier that should be removed if a wholesale market is to function correctly, or must one be created, whatever is the case? Assume that 50% of the new intermittent generation capacity is added to the capacity of the largest generation company in the network, with the rest being evenly distributed to the remaining generation companies. Does this new situation increase the potential for the exercise of market power in your power system? Indicate (in priority order, beginning with those measures that you would recommend first) the regulatory measures that you would advise to adopt, if any, along with justification. Refer to existing regulatory approaches and

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\(^7\)Presently the UK regulatory authority OFGEM is carrying out an in-depth review of the RPI-X method, as currently applied to electricity and gas networks. Most documents of this review are available at the OFGEM website. It could be useful to examine the documentation of this project.
international experiences for the mitigation of market power in wholesale electricity markets. Describe the success or failure of the regulatory mechanisms have been proposed and implemented.

9. **Wholesale market design.** Examine the *rules of the wholesale* market of the power system being transformed and assess their *suitability in the context of the anticipated strong presence of intermittent generation*. Indicate the changes that should be made to establish a *level playing field* for all the different technologies. In particular the following topics will have to be contemplated: a) rules of the day-ahead market, congestion management, intra-day markets, and any markets for operation reserves or balancing markets; b) organized or over-the-counter markets for contracts; c) the formation of the electricity market prices; d) capacity mechanisms for adequacy and firmness. Carefully examine special requirements which must be placed on the *size and characteristics of operation reserves* as a result of the strong presence of intermittent generation. Analyze any special needs for operating reserves that may result from the large component of wind and solar generation in the power system, as well as the potential role that demand response may play here. *Should intermittent generation be charged* for the requirements that they might impose on the utilization of operating reserves?

10. **Retail market design.** In parallel with the deployment of renewable generation, the best immediately available approach to reduce CO2 emissions in a well developed economy is the application of measures of *energy efficiency* and savings. In the electrical power sector this could be achieved by letting the consumers experience the *hourly electricity prices* so they would try to avoid consuming at times when prices are highest. However, present electricity prices are typically too low for bringing a strong consumers’ response, in particular for the residential sector. *If the regulator*, because of sustainability-based constraints, *wants to increase the consumers’ response in order to reduce demand in the system, what kind of regulatory instruments can best be used?* Make sure that the instruments proposed apply the right incentives on the right agents. What might the role of retailers and/or distributors and/or energy service companies be in this task? Justify any choices, in particular regarding the role and the incentives for each kind of company in the context of the power system being considered.

11. **Universal electricity access.** The *level of electrification* (percentage of people with access to electricity) is low in many countries. Almost one third of mankind does not have access to modern forms of energy. Describe whether restructuring and liberalization of the power sector in these countries can be a positive /negative or neutral factor to facilitate access in those countries? Which measures are necessary to achieve the objective of *universal access to electricity*? To what extent does *climate change* play a role when addressing this issue? What *role do renewables play*? Should these countries consider also *mandatory targets* for penetration of renewable energy sources for electricity production? Are there any *alternative means for promotion of renewables* in developing countries? Which are most practical for the given situation?

12. **CO2 markets and prices.** Assume that the power system being transformed is part of an *emission trading scheme of the cap-and-trade type* (such as in the EU or in the US Northeastern region under the Regional Greenhouse Gas Initiative, RGGI). Then answer the following questions: • Should the *market price of electricity* internalize the price of the CO2 emission allowances? • If the electricity market price increases because of the influence of the price of CO2 emissions, do you think that it is adequate that power plants that do not have CO2 emissions (such as renewables, hydro or nuclear) should have their revenues also increased? • Presently in the EU the power plants with CO2 emissions are given for free an amount of emission allowances that more or less compensates the amount that they would have to buy in order to have emissions in the future that are similar to the emissions that they had in the past.
This has been also contemplated (partly, at least) in some of the bills that have been proposed in the US. Is this regulation correct? • If a volume of emissions is given for free to each power plant, as indicated in the preceding bullet, do you think that this has an impact on the merit order in the dispatch of the different generation technologies in the electricity market? • In the present EU regulatory scheme for emission trading, an old or inefficient generation plant will stop receiving emission rights at the time the plant retires from the market and decides to stop activities for ever. Is this a correct regulation? Justify answers.
APPENDIX 5: Alternate Smart Grid Characterization Models

"A VISION OF SMART TRANSMISSION GRIDS"

IEEE Whitepaper - "A VISION OF SMART TRANSMISSION GRIDS", 2009

AUTHORS: Zhenhua Jiang, Senior Member, IEEE, Fangxing Li, Senior Member, IEEE, Wei Qiao, Member, IEEE, Hongbin, Sun, Member, IEEE, Hui Wan, Member, IEEE, Jianhui Wang, Member, IEEE, Yan Xia, Member, IEEE, Zhao, Xu, Member, IEEE, Pei Zhang, Senior Member, IEEE

Table of Smart Grid characterization & categories

<table>
<thead>
<tr>
<th>A Vision of Smart Transmission Grids</th>
<th>Framework &amp; Characteristics of Smart Transmission Grids</th>
<th>Enabling Technologies</th>
</tr>
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<tbody>
<tr>
<td>• Environmental Challenges</td>
<td>1. Digitalization</td>
<td>1. New materials and alternative clean energy resources</td>
</tr>
<tr>
<td>• Market / Customer Needs</td>
<td>2. Flexibility</td>
<td>2. Advanced Power electronics and devices</td>
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<tr>
<td>• Infrastructure Challenges</td>
<td>3. Intelligence</td>
<td>3. Sensing and measurement</td>
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<td></td>
<td>5. Sustainability</td>
<td>5. Advanced computing and control methodologies</td>
</tr>
<tr>
<td></td>
<td>6. Customization</td>
<td>6. Mature power market regulation and policies</td>
</tr>
</tbody>
</table>

SG Control Centers
1. Monitoring / Visualization
2. Analytical Capability
3. Controllability
4. Interactions with Electricity Market

Smart Transmission Networks
1. High-Efficiency and High-Quality Transmission Networks
2. Flexible Controllability, Improved Transmission Reliability and Asset Utilization through the Use of Advanced Power Electronics
3. Self-Healing and Robust Electricity Transmission
4. Advanced Transmission Facility Maintenance
5. Extreme Event Facility Hardening System

Smart Substations
1. Smart Sensing & Measurement
2. Communications
3. Autonomous Control and Adaptive Protection
4. Data Management and Visualization
5. Monitoring and Alarming
6. Diagnosis and Prognosis
7. Advanced Interfaces with Distributed Resources
8. Real-Time Modeling

(Accompanying Graphic on next page)
Fig. 1. Vision of a smart transmission grid
"THE PATH OF THE SMART GRID"
By Hassan Farhangi

Excerpted Graphic Representations:

**Figure 3.** Basic smart grid ingredients (source: GridWise Alliance).

**Figure 4.** Smart grid pyramid (source: BC Hydro).
Table of Functions, Full Descriptions

**Full Descriptions of Proposed Smart Grid Functions**

Excerpted From:
Methodological Approach for Estimating the Benefits and Costs of Smart Grid Demonstration Projects, Electric Power Research Institute, January 2010

**Key:**

<table>
<thead>
<tr>
<th>Operand</th>
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<tr>
<td>Process</td>
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<td>Definition</td>
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<td>Assets/Technologies</td>
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<table>
<thead>
<tr>
<th>Function</th>
<th>Technical Overview</th>
<th>Expected Benefits from Function</th>
</tr>
</thead>
</table>
| **Fault Current Limiting** | Very high currents due to short circuits can cause severe mechanical stress on T&D equipment, resulting in failure or damage over time. These high fault currents can be limited to safe levels by inserting an electrical resistance into the circuit between the sources of the fault current and the equipment that must be protected. Fault Current Limiters (FCL's) are commonly available at this time but are expected to be available in the commercial marketplace soon. | • Deferred Transmission Capacity Investments  
• Reduced Equipment Failures |
| **Wide Area Monitoring, Visualization and Control** | Wide area monitoring (WAM) is the ability to monitor transmission system conditions over large regions (multiple states) and display this information in ways that human operators can accurately interpret and act upon. Technologies such as phasor measurement units (PMU’s), data concentrators, and advanced software are used to provide a real-time operating picture of the bulk transmission system. This information will be available in grid control centers to help operators observe, analyze, and operate the system more precisely and reliably. | • Optimized Generator Operation  
• Reduced Ancillary Service Cost  
• Reduced Congestion Cost  
• Deferred Transmission Capacity Investments  
• Reduced Major Outages  
• Reduced Wide-scale Blackouts |
| **Dynamic Capability Rating** (AKA, Ampacity Determination) | Capability ratings for power lines and equipment are typically based on thermal limits. Because of the inherent electrical resistance of normal conductor, the more current they carry, the hotter they become. Ratings on equipment (like transformers) are limited by the amount of heat that can be tolerated before damage or degradation occurs. Ratings on transmission lines are typically based on how low the conductor sags due to heating. Some transmission lines are stability limited, and are not operated up to their thermal limits. Since ambient conditions, such as air temperature, wind speed, and moisture affect heat rejection from equipment, they can significantly affect the true power handling capability of lines and equipment. Utilities typically assign ratings to lines and equipment to account for seasonal changes, and also emergency conditions. These ratings are based on manufacturer specifications, utility standards, and operating experience. Although these ratings schedules attempt to account for changes in... | • Reduced Congestion Cost  
• Deferred Transmission Capacity Investments  
• Deferred Distribution Capacity Investments  
• Reduced Equipment Failures  
• Reduced Wide-Scale Blackouts |
<table>
<thead>
<tr>
<th>Function</th>
<th>Technical Overview</th>
<th>Expected Benefits from Function</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ambient conditions, they cannot account for the actual conditions in which system elements are operating at any point in time. For much of the time, these ratings may be conservative and may limit loading unnecessarily.</td>
<td><a href="#">Reduced Congestion Cost</a> • <a href="#">Deferred Transmission Capacity Investments</a> • <a href="#">Reduced CO2 Emissions</a> • <a href="#">Reduced SOx, NOx and PM-10 Emissions</a></td>
</tr>
<tr>
<td>Dynamic Capacity Rating</td>
<td>Dynamic Capability Rating utilizes sensors, information processing and communications to give grid operators a clearer picture of the true capability of network elements in real time through adjusting feeder rating capacity in real-time, based on actual conditions. In cool or windy conditions, this could allow a grid operator to load a transmission line beyond its basic rating without overheating. In extremely hot weather, this could prevent a transformer from being loaded to the point of winding damage or failure.</td>
<td></td>
</tr>
<tr>
<td>Flow Control</td>
<td>In AC power systems, the impedance of lines and transformers determines how power flows from generators to load. As electricity follows &quot;the path of least resistance&quot;, it does not necessarily go where engineers and grid operators would prefer. By increasing or decreasing the impedance of a line or transformer (resistance and reactance), routing of power flow can be changed. Today, flow control can be done with phase angle regulating transformers (PARs) or Flexible AC Transmission System (FACTS) devices. However, these solutions are often expensive, and they are not widely applied. New technologies such as superconducting cables hold promise due to their very low impedance, and could be used in combination with other devices to regulate power flow over critical areas of the system. For example, American Superconductor envisions pairing a very low impedance (VLI) cable with a phase angle regulator. Using the two together you can control the combination of a very low impedance with a controllable impedance. The cable by itself cannot do flow control, it can only reduce the impedance.</td>
<td>• <a href="#">Reduced Sustained Outages</a> • <a href="#">Reduced Restoration Costs</a></td>
</tr>
<tr>
<td>Adaptive Protection (AKA, Adaptive Fault Protection)</td>
<td>Detecting and clearing electrical faults (short circuits) is critically important for ensuring public safety, preserving property, and minimizing damage to the electrical system itself. Faults are detected using protective relays that monitor current and voltage and send signals to circuit breakers or switches when conditions exceed set points. (Fuses are also used on distribution feeders, and sometimes as backup for circuit breakers to protect equipment such as large transformers.) Electric power systems are protected by complex systems of relays and switching devices whose settings and operation is carefully designed and coordinated by engineers as part of initial system implementation. Protection schemes are designed to provide reliable fault clearing under expected conditions, and are not frequently changed. Adaptive protection means that relay settings and protection schemes can be changed in response to changing system conditions. For example, a distribution feeder might be designed with relays set to trip if the current flowing from the substation exceeds a predetermined level. If</td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td>Technical Overview</td>
<td>Expected Benefits from Function</td>
</tr>
<tr>
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</tr>
</tbody>
</table>
| Automated Feeder Switching (AKA, Automated Feeder Switch Actuation) | Utilities design distribution feeders with switches so that portions of the feeder can be disconnected to isolate faults, or de-energized for maintenance. In most cases, these switches are manually operated, and require a service worker to travel to the switch location, coordinate switching orders with a dispatcher, and then physically operate the switch. **Automatic Feeder Switching makes it possible to operate distribution switches autonomously in response to local events, or remotely in response to operator commands or a central control system.** Automatic Feeder Switching does not prevent outages; it simply reduces the scope of outage impacts in the longer term. This function is accomplished through the **automatic isolation and reconfiguration of faulted segments of distribution feeders** via sensors, controls, switches, and communications systems. Automatic Feeder Switching can reduce or eliminate the need for a human operator or field crew for operating distribution switches. This saves time, reduces labor cost, and eliminates "truck rolls". | * Reduced Distribution Operations Cost  
* Reduced Sustained Outages  
* Reduced Restoration Cost  
* Reduced CO2 Emissions  
* Reduced SOx, NOx and PM-10 Emissions  
* Reduced Oil Usage |
| Automated Islanding and Reconnection (AKA, Enabling "Islanding") | A microgrid is an integrated energy system consisting of interconnected loads and distributed energy resources which, as an integrated system, can operate in parallel with the grid or as an island. This disconnection and reconnection of the microgrid and the interconnected electric grid would be done automatically as needed based on grid conditions. Islanding would be enabled through various sensors, controls, switches, and communications systems, inverters, controllers and distributed energy resources. | * Reduced Sustained Outages  
* Reduced Major Outages |
| Automated Voltage and VAR Control | **Automatic voltage and VAR control is performed through devices that can increase or lower voltage and can be switched or adjusted to keep the voltage in a required range. Control systems** could determine when to operate these devices (i.e., generator voltage regulators), and do so automatically. This function is the result of **coordinated operation of reactive power resources** such as capacitor banks, voltage regulators, transformer load-tap changers, storage and distributed generation (DG) with sensors, controls, and communications systems. These devices could operate autonomously in response to local events or in response to signals from a central control system. | * Reduced Ancillary Service Cost  
* Reduced Distribution Operations Cost  
* Reduced Electricity Losses  
* Reduced CO2 Emissions  
* Reduced SOx, NOx and PM-10 Emissions |
<table>
<thead>
<tr>
<th>Function</th>
<th>Technical Overview</th>
<th>Expected Benefits from Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnosis &amp; Notification of</td>
<td>By better managing voltage and VAR resources, the transmission and distribution network can be optimized for electrical efficiency (lower losses), and can allow utilities to reduce load through &quot;energy conservation voltage reduction&quot; while maintaining adequate service voltage. These load reductions will contribute to the amount of generation required. It should be noted that these might not be accomplished independent of other upgrades previously mentioned, or at least their impact may be reduced if this is undertaken after the other investments.</td>
<td>Reduced Equipment Failures</td>
</tr>
<tr>
<td>Equipment Condition</td>
<td>Some equipment such as transformers and circuit breakers are critical to providing electric service to customers. Utilities test and maintain this equipment periodically in an effort to ensure that it operates reliably over a long service life. Because of the large amount of equipment, and the labor intensity of taking measurements and analyzing results, testing and maintenance can be very expensive, and may fail to identify critical equipment conditions before they lead to failure.</td>
<td>Reduced Distribution Equipment</td>
</tr>
<tr>
<td></td>
<td>This function is the on-line monitoring and analysis of equipment, its performance and operating environment to detect abnormal conditions (e.g., high number of equipment operations, temperature, gas production or vibration). As a result, the function enables the equipment to automatically notify asset managers and operations to respond to a condition that increases a probability of equipment failure. This would be enabled through SCADA systems including sensing / monitoring devices, communications networks and analysis software.</td>
<td>Maintenance Cost</td>
</tr>
<tr>
<td></td>
<td>Particularly, distribution protective devices rely on high fault currents to cause them to be activated. Some faults (like a line lying on the ground) may not cause sufficient fault current to cause the protective relay to sense the fault quickly. Another problem is that multiple relays may sense the same fault and operate and all to try and clear it (which generally results in variable results). Enhanced protection could detect faults that are hard to locate, and clear them without reclosing which can damage equipment over time. Enhanced fault detection with higher precision and greater discrimination of fault location and type with coordinated measurement among multiple devices could detect and isolate faults without full-power re-closing, reducing the frequency of through-fault currents. Using high resolution sensors and fault signatures, these systems could better detect high impedance faults.</td>
<td>Reduced Sustained Outages</td>
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<td>Transmission protective systems are more complex than those used for distribution. High speed digital communications and computing will enable more sophisticated transmission protection schemes, such as line differential protection, adaptive relaying and System Integrity Protection systems (SIPS).</td>
<td>Reduced Restoration Costs</td>
</tr>
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<td>Real-Time Load Measurement Devices such as smart meters and appliance controllers can monitor the energy use of customer loads over the course of the day. These same</td>
<td>Reduced Ancillary Service Cost</td>
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<td>Deferred Distribution</td>
</tr>
<tr>
<td>Function</td>
<td>Technical Overview</td>
<td>Expected Benefits from Function</td>
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</table>
| & Management                   | devices can be used to help customers respond to pricing signals so that system load can be managed as a resource. Real-time measurement of customer consumption and management of load through Advanced Metering Infrastructure (AMI) systems (smart meters, two-way communications) and embedded appliance controllers may help customers make informed energy use decisions via real-time price signals, time-of-use (TOU) rates, and service options. | Capacity Investment  
  • Reduced Meter Reading Cost  
  • Reduced Electricity Theft  
  • Reduced Electricity Losses  
  • Reduced Sustained Outages  
  • Reduced Major Outages  
  • Reduced CO2 Emissions  
  • Reduced SOx, NOx and PM-10 emissions  
  • Reduced Oil Usage |
| Real-Time Load Transfer        | In places that may have more than one distribution feeder in the area, circuits may be switched and electrical feeds rerouted to make the distribution more efficient or more reliable. This function allows for real-time feeder reconfiguration and optimization to relieve load on equipment, improved asset utilization, improved distribution system efficiency, and enhanced system reliability. This is accomplished using control systems, actuating equipment, etc. | • Deferred Distribution Capacity Investments  
  • Reduced Electricity Losses  
  • Reduced Major Outages |
| Customer Electricity Use Optimization | A key characteristic of the modern grid is that it motivates and includes the customer. This function enables customers to observe their consumption patterns and modify them according to their explicit or implicit objectives. These could include minimizing cost, maximizing reliability, or purchasing renewable energy, among others. Potential assets which would deliver this benefit include sensing and reporting equipment, interactive software, appliances which respond to signals, an on-line marketplace, etc. | • Deferred Centralized Generation Capacity Investments  
  • Deferred Transmission Capacity Investments  
  • Deferred Distribution Capacity Investments  
  • Reduced Electricity Losses  
  • Reduced Electricity Cost  
  • Reduced CO2 Emissions  
  • Reduced SOx, NOx and PM-10 emissions |