Research Paper No. 090723

Energy Infrastructure for Sustained Economic Growth: Economic Assessment of a SuperGrid for California

David Roland-Holst

March, 2009

DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS
207 GIANNINI HALL
UNIVERSITY OF CALIFORNIA
BERKELEY, CA 94720
PHONE: (1) 510-643-6362
FAX: (1) 510-642-1099
http://are.berkeley.edu/~dwrh/CERES_Web/index.html

Research Papers on Energy, Resources, and Economic Sustainability

This report is part of a series of research studies into alternative energy and resource pathways for the global economy. In addition to disseminating original research findings, these studies are intended to contribute to policy dialog and public awareness about environment-economy linkages and sustainable growth. All opinions expressed here are those of the author and should not be attributed to their affiliated institutions.

Energy Infrastructure for Sustained Economic Growth: Economic Assessment of a SuperGrid for California

David Roland-Holst[1]

UC Berkeley

1 Introduction

Significant parts of California's energy infrastructure are older than the IBM PC and blind to the information revolution. What the state needs today is an Integrated Energy Infrastructure (IEI) that illuminates people as well as light bulbs. Today's energy use supports not just machines, but a web of knowledge and media content with critical requirements for detailed resolution and continuity. Some enclave sectors, like information and communication technologies (ICT or IT) enterprises, media networks, universities, hospitals, and financial institutions have developed standalone infrastructure to meet these needs. The state will never fulfill its innovation potential until these resources are integrated and more accessible to all enterprises and households.

One of the most important commitments needed in this context is to develop a state-wide "SuperGrid", a flagship infrastructure project that integrates electric power and information technology for knowledge-intensive economic development. Like a TVA for the Digital Age, this mega-project would provide strong early employment stimulus, new markets for innovators, and sustained long-term productivity benefits.

[1] Contact: Department of Agricultural and Resource Economics, UC Berkeley: dwrh@are.berkeley.edu.

In a time when the need for energy innovation is so acute, the federal government also happens to be looking for the next big thing in public works commitments (after TVA, interstates, internet). IEI is it. With its private technology leadership and forward-looking utility sector, California can define global standards for public/private partnership in energy infrastructure. Both state and federal governments are intensively debating incentives related to innovation, diffusion and adoption of new energy technologies, but the history of wind tax credits and other targeted incentives is ambiguous. Infrastructure provides the basis for all innovators, while markets are relatively adept at rewarding innovations that excel.

For rapid deployment of large-scale public spending and job creation, building the SuperGrid is a more attractive option, with a prototype in California for what would ultimately be a national system. This is better than picking winners in the underlying technologies. In the same spirit, governments build highways while companies design/build/market cars, governments build dams while developers lay out subdivisions and governments manage RF spectrum (e.g. telecom and internet infrastructure) while companies vie for the best software designs and media content.

The benefits of a megaproject approach to the grid are many. Firstly, in recessionary times there will be an early harvest of employment-intensive infrastructure development. Second, a big push will reduce transaction costs for capturing the strong complementarities that exist across an energy triangle of utilities-technologists-endusers, accelerating technology innovation, diffusion, and adoption. Finally, as California's modern history has demonstrated conclusively, superior economic growth, both in terms of rising incomes and quality of life, is intimately linked to knowledge-intensity. Just as California's UC, CSU, and Community College systems were among the most successful experiments in the history of public education, so diffusion of information technology could support the state's next great learning revolution and its many productivity dividends.

This report provides an overview of system options available for a complete, end to end redevelopment of California's electric power grid, along with a forward looking economic assessment of the expected benefits. In particular, we examine in the next section the overall technical aspects of Smart Grid design and propose five generic grid schema that should be considered for statewide deployment. These technology options are then synthesized with an economic projection framework to assess the many direct and indirect contributions that a new grid will make to California's short, medium, and long term economic growth. Three generic economic impact components are assessed in following sections:

1. Grid development (1-5 years) – This component covers the construction phase of the project will implicate planning, construction and related infrastructure industries.

2. Grid participation (medium and long run) – This component assesses the direct benefits of grid participation for established users (efficiency gains) and new participants, including emerging actors in the energy and technology sectors

3. Productivity growth (long run) – Modern energy infrastructure will support new technologies for efficiency, information, communication, and transport that will enhance productivity across the California economy and its relationship to the national and global economies. This component will estimate these benefits, arguably the largest and most important to sustaining the state's overall employment and income growth

Generally speaking, our results suggest that California has a strong economic interest in a bold commitment to the distribution component of its sustainable energy future. This commitment will require very significant financial and institutional resources, with the latter particularly focused on legacy patterns of administration, regulation and property rights. Our economic assessment makes clear, however, that the economic benefits would be large enough to justify bond finance for the larger initial public commitments needed, while the vast scope of benefits suggest that the long term interests of the general population must prevail over narrower short term interests. In both contexts, public agency and advocacy will be needed to secure the state's progress to a higher long term growth and sustained prosperity.

2 The Smart Grid Imperative

For modern societies, electricity is an indispensable economic asset. In the United States, electricity comprised 10% of total energy consumption in 1940's and electricity comprises over 40% of total energy consumption today. Coupled with the increasing demand for electricity is an increasing awareness of outdated, inefficient infrastructure. Power outages or blackouts affecting 50,000 or more U.S. customers have more than doubled from 41 cases in the period 1991–1995 to 92 cases in 2001–2005.[2] Vintage electric grids raise concerns for its reliability, capacity, and security.

An electricity grid is a conglomerate of multiple networks, power generating entities and power operators. So far, U.S. electricity grids remain complex conglomerates that are mostly under manual control and coordination. Alternatively, a smart grid features automation, interactivity, and connectivity between suppliers, thus heightening long distance transmission, local distribution, and other tasks. Modernizing the power infrastructure is imperative in order to meet growing electricity demand with greater efficiency, security, reliability and lower cost than major grids in place. According to a study by the U.S. Department of Energy (DEQ), modern, smart grid capabilities could save the nation a calculated $46 billion to $117 billion over the next 20 years.[3]

With shifting economic conditions and demands, three salient needs for energy provision emerge:

1. Residential and industrial electric power needs for a growing economy
2. Capacity to integrate extensive and diverse renewable energy sources
3. Capacity for continuous reliability and high resolution support of more extensive and intensive IT diffusion

While the adjustment costs seem high to stakeholders in the short-term, these costs are outweighed by many indirect and medium- and long-term benefits. That is, conversion costs are fixed, but the benefits will compound with time.

The Energy Independence and Security Act of 2007 had described the smart grid concept as, "a modernization of the Nation's electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet future

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[2] Amin and Stringer. 2008. "Electric Power Grid: Today and Tomorrow." *Materials Research Society Bulletin* 33: 399-411.

[3] Kannberg, L.D. et al. 2003. "GridWise TM: The Benefits of a Transformed Energy System." Pacific Northwest National Laboratory. URL: http://arxiv.org/ftp/nlin/papers/0409/0409035.pdf

demand growth."[4] Among the important characteristics identified for a national smart grid are the following:

1. "Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.
2. Dynamic optimization of grid operations and resources, with full cyber-security.
3. Deployment and integration of distributed resources and generation, including renewable resources.
4. Development and incorporation of demand response, demand-side resources, and energy-efficiency resources.
5. Deployment of ''smart'' technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation.
6. Integration of ''smart'' appliances and consumer devices.
7. Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning.
8. Provision to consumers of timely information and control options.
9. Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.
10. Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services."[5]

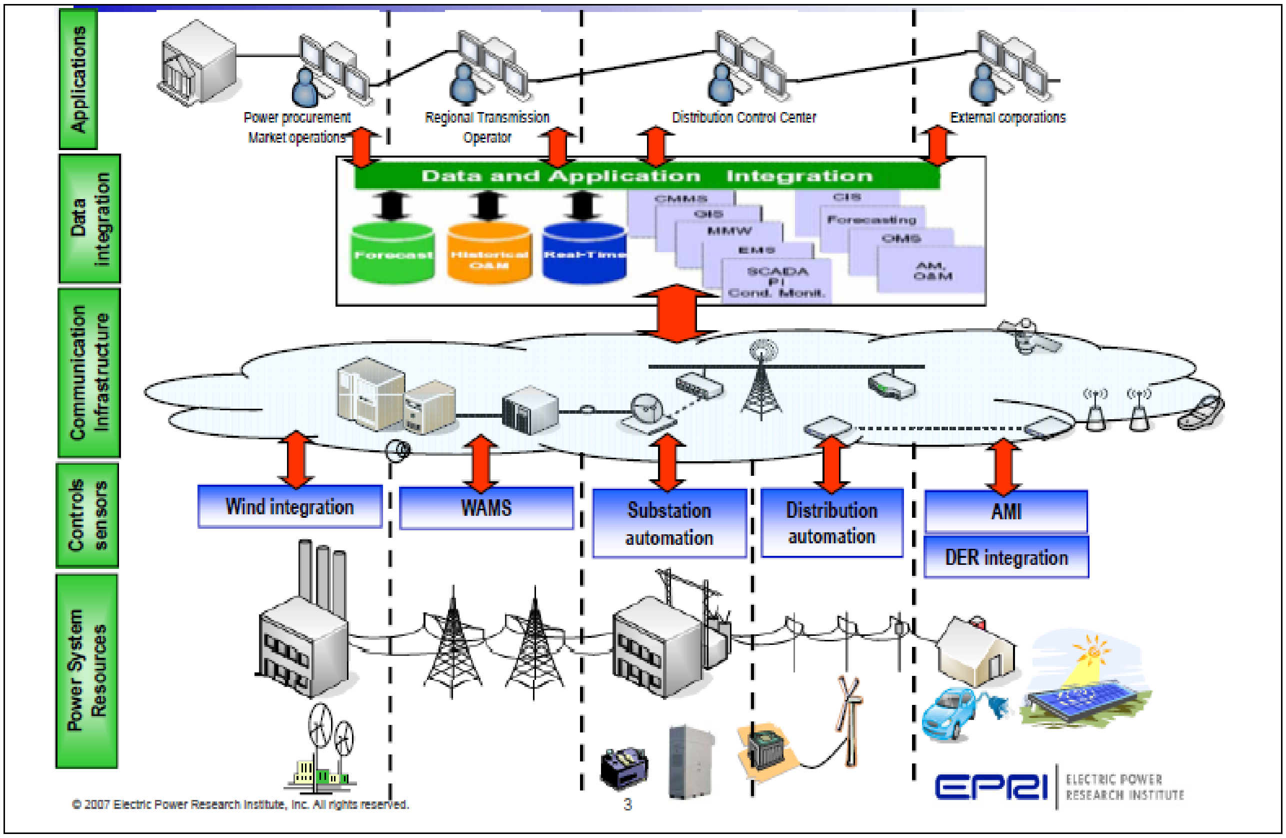
2.1 Background and Prototypes

Electricity is supplied by flow of power through a grid network, which actually refers to three distinct systems. Traditionally, this has been a one-way flow from generators to transmission lines to distribution networks and substations. Upgrading 20th century power grids with digital technology will allow for two-way communication, transparency, and coordination. With this "smart" technology, the electricity grids will save energy, reduce cost, and improve reliability. Whereas traditional power grids issue electricity

[4] Energy Independence and Security Act. 2007. Title XIII.
[5] EISA. 2007. Title XIII.

from a few central power generators to a large number of users, smart grids have the capability to route power to end-users from diverse suppliers. For solar, wind, and geothermal power, which emanate from non-urban areas and are less consistent sources of energy, smart grids can accommodate this additional power through better, more reliable controls. Smart-grid technologies use two-way information to optimize the flow of electricity – much as computers and routers do to manage the flow of bits on the Internet.

Figure 1: The Smart Grid, underlying component technologies and architecture

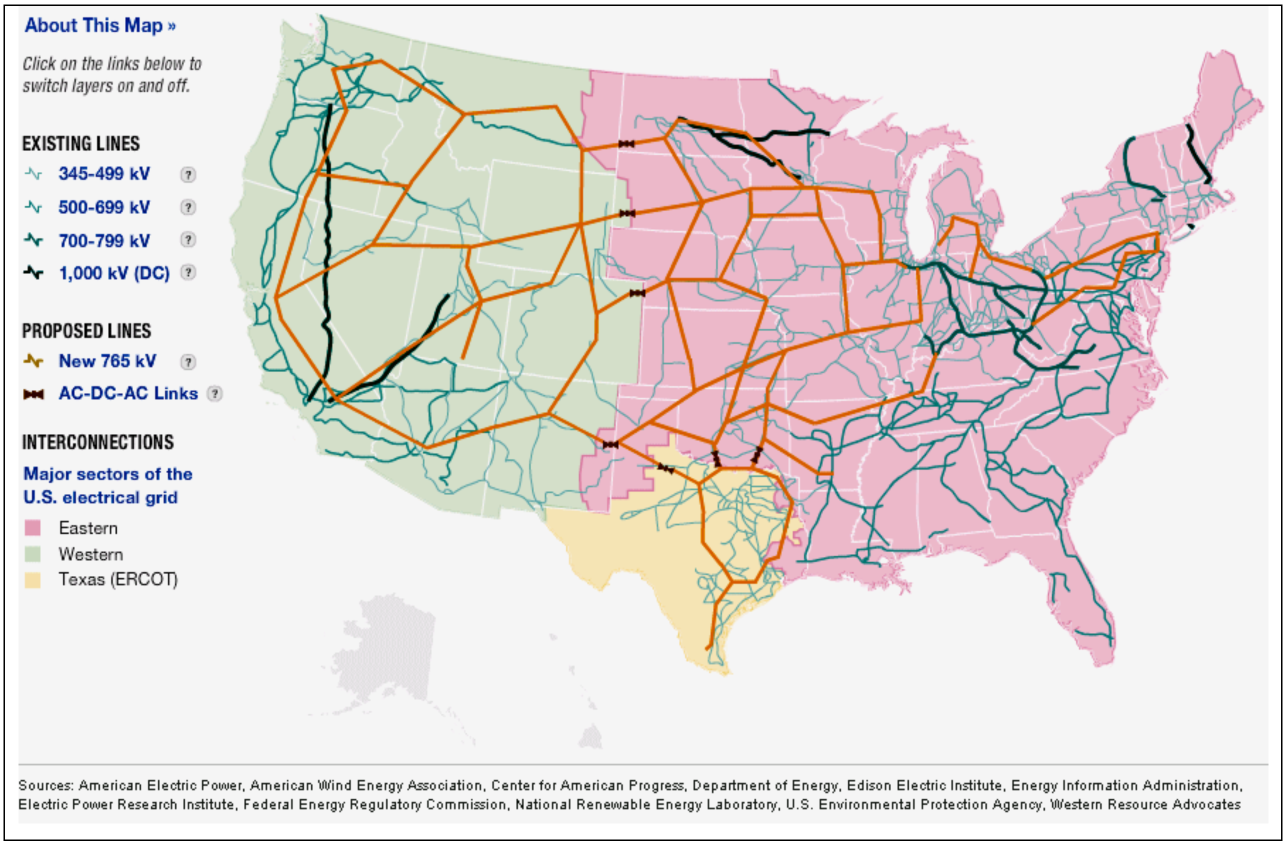


Source: Electric Power Research Institute, Inc.

Prototypes and developmental projects have been underway in Italy, UK, South Korea, and in parts of the U.S. In 2005, the Italian Telegestore project was the earliest commercial scale use of smart grid technology and remains the largest smart grid system. It cost € 2.1 billion and saves about € 500 million per year. Since 2003, the city of Austin, Texas has been working on building a “mesh network” to replace it a third of its manual meters with smart devices. Austin currently manages 200,000 devices real-time (smart meters, smart thermostats, and sensors across its service area), and expects to be supporting 500,000 devices real-time in 2009 servicing 1 million consumers and 43,000 businesses.[6] Meanwhile, in August 2008, Boulder, Colorado completed the first phase of its smart grid project. It plans to use the smart meter as a gateway to the home automation network (HAN) that controls smart sockets and devices.[7]

Currently, electricity transmission is primarily circulated within ten grid regions of the U.S. In Figure 2, proposed lines for 765 kV lines and AC-DC converters will integrate the Western, Eastern, and Texas Interconnect regions. National integration will rebuff power distribution and its sources of generation (as shown on the NPR website with variations of the bottom map configuring in solar, wind, and power plants).

Figure 2: Map of Transmission Grid Areas in the U.S.



Source: NPR. 2009.
URL: http://www.npr.org/news/graphics/2009/apr/electric-grid/

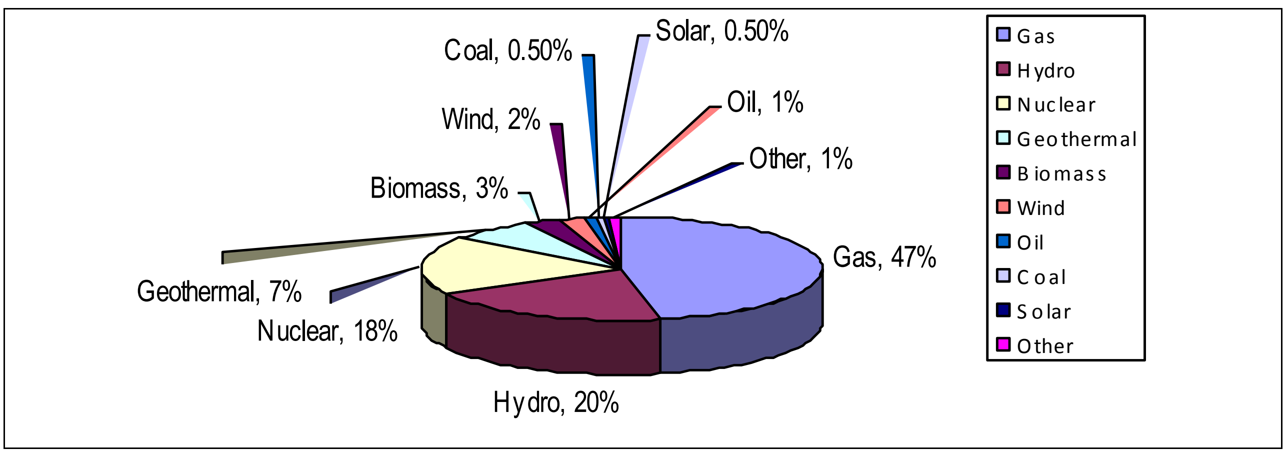
[6] "Building for the future: Interview with Andres Carvallo, CIO — Austin Energy Utility". *Next Generation Power and Energy* (GDS Publishing Ltd.) (244). http://nextgenpe.com/currentissue/article.asp?art=273073&issue=244. Retrieved on 2008-11-26.
[7] Betsy Loeff (2008-03). "AMI Anatomy: Core Technologies in Advanced Metering". *Ultrimetrics Newsletter* (Automatic Meter Reading Association (Utilimetrics)). http://www.utilimetrics.org/newsletter/index.cfm?fuseaction=Newsletter.showIssuetoPrint&Issue_ID=68. Retrieved on 2008-11-26.

2.2 Smart Grid in the California Context

While the U.S. has struggled with balancing energy supply and demand, California has been recognized as a leader in energy management with its ambitious energy efficiency efforts since the 1970's. Nonetheless, California's grid has been subjected to stress with total electricity demand increasing at an annual average rate of 2% in recent years despite relatively flat per capita electricity consumption levels. As a result, the regional grid has already undergone many incremental enhancements and a more integrated system or smart grid is urgently needed to meet future demand. Specifically, California needs a fully integrated system that possesses dynamic new customer system applications, system automation and control and siting of renewable resources.[8]

These components are not only necessary for California's growing economy and expanding population, but also particularly for actualizing ambitious state environmental goals like the Renewable Portfolio Standards and AB32 emission reduction goals. For instance, energy efficiency, demand response and renewable and distributed generation all lead in the state's loading priority order, but barriers such as limited transmission capacity could limit these resources in the absence of a smart grid. The urgency for a smart grid in California is compounded by expected growth in peak demand. Developing and investing in energy infrastructure for a smart grid now can help California to maintain cost-effective energy policy priorities and to cater to growing populations and changing climate patterns.

Figure 3: California's Energy Mix



Source: NPR. 2009.

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[8] California Energy Commission, 2008, "Integrating New and Emerging Technologies into the California Smart Grid Infrastructure." PIER Final Project Report CEC-500-2008-047.

Table 1: Transmission Interconnections and Imports

Region	Import Capability (MW)
Pacific Northwest	
▪ AC Intertie	4,800
▪ DC Intertie	3,100
Utah	1,920
Desert Southwest	
▪ Northern System	4,727
▪ Southern System	2,823
Mexico – Baja Region	800
	18,170

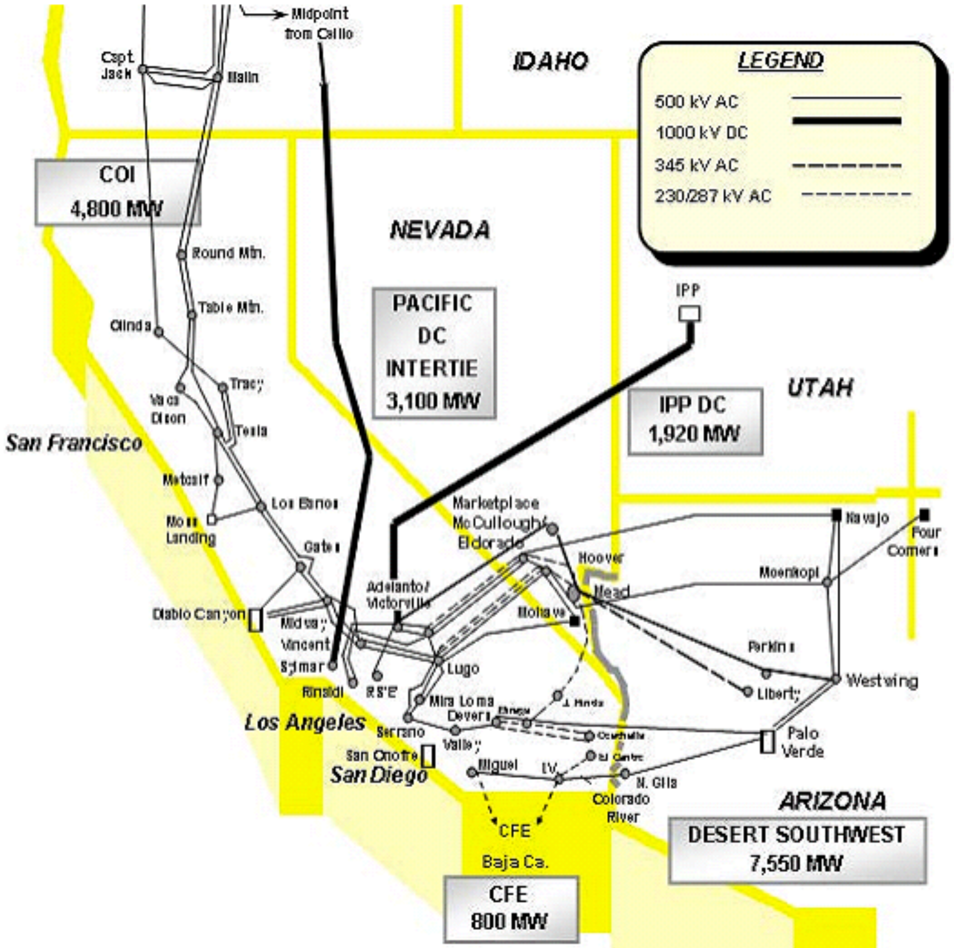
Source: Electric Power Group, LLC. 2003. URL: http://certs.lbl.gov/pdf/ca-grid-plan.pdf

Currently, electricity for the state of California is primarily supplied by gas at 47%, hydropower at 20%, and nuclear power at 18%. By 2016, however, a doctoral student at Stanford University estimates that, "with minimal upgrades to the transmission infrastructure…at least 70% of total projected California generation on a summer day in 2016 could be generated by renewable sources."

In planning for California's smart grid, both the California Public Utilities Commission (CPUC) and the California Energy Commission have taken important steps in recent years. First, the California Energy Commission has identified important short- and long-term priorities.[9] Short-term priorities focus on integrating renewable resources and storage options under an open architecture while strengthening the automation, protection and operation of the power system. Other short-term priorities include refining and expanding existing efforts of promoting active customer participation through advanced metering infrastructure and communications technology. Long-term strategies, on the other hand, will focus on harmonizing the grid's interfaces between state-level system operators, the Western Electricity Coordinating Council, independently-owned utilities, third-party generators and other service providers. Second, the CPUC have approved several utility-run advanced metering pilot projects and initiated a rulemaking to begin exploring policies, standards and protocols to guide the development of a smart grid and facilitate integration of new technologies and coordinate existing projects amongst the investor-owned utilities.[10] In 2009, workshops and symposiums on smart grid technologies have been held to update different stakeholders on existing technology trends.

[9] CEC. 2008.
[10] CPUC. URL: http://www.cpuc.ca.gov/PUC/energy/smartgrid.htm

Figure 4: Map of Transmission Grids in California



Source: Electric Power Group, LLC. 2003. URL: http://certs.lbl.gov/pdf/ca-grid-plan.pdf

Figure 5. Average power generation by source on July 2016 day - High-Renewable Penetration Case

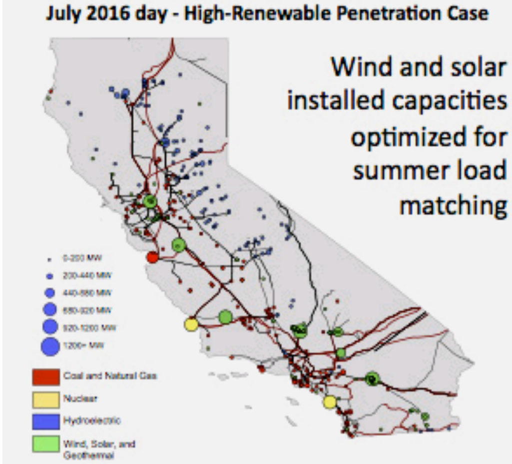
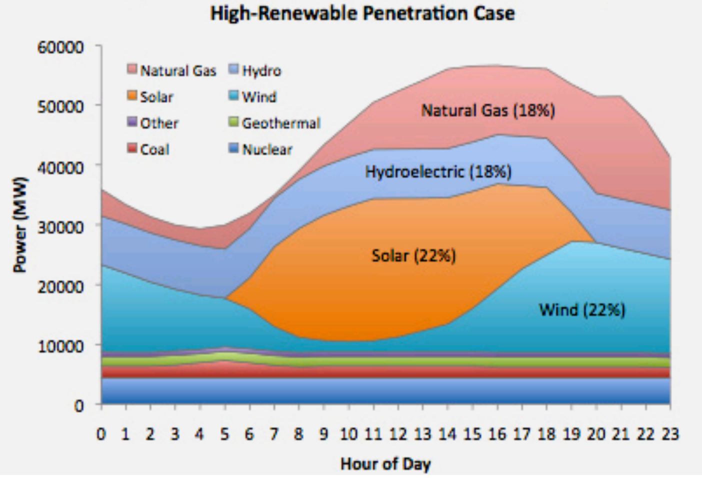


Figure 6. California power generation on July 2016 Day High-Renewable Penetration Case



Source: Elaine Hart, Stanford University.

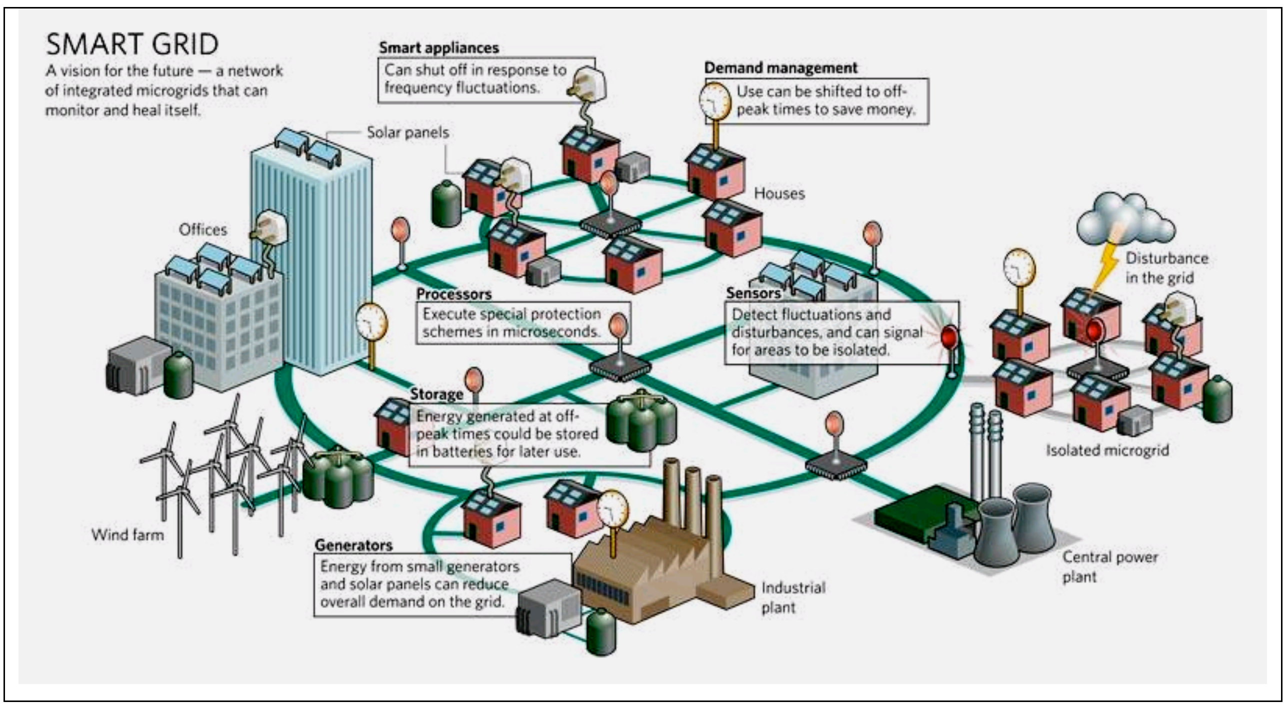
2.3 Key Technology Options

In order to meet its energy and environmental goals, California's smart grid needs to:

- Provide high quality power through a secure system
- Accommodate greater renewable and distributed generation capacities
- Have self-healing abilities through sensors and automated controls, and
- Enable greater customer participation in improving efficiency of electricity use and reduce peak load.

To achieve these goals, public investments need to focus on several key areas of technology and grid infrastructure including: modernized power system resources such as advanced conductors and electric storage to meet expanded renewable and distributed generation capacity; distributed sensors, intelligence, and smart controls for effective grid operation and responsive management; and integrated communication and data collection with dynamic customer applications.

Figure 5: Technology Structure of Smart Grid



Source: VTSEnviro Group. 2009.

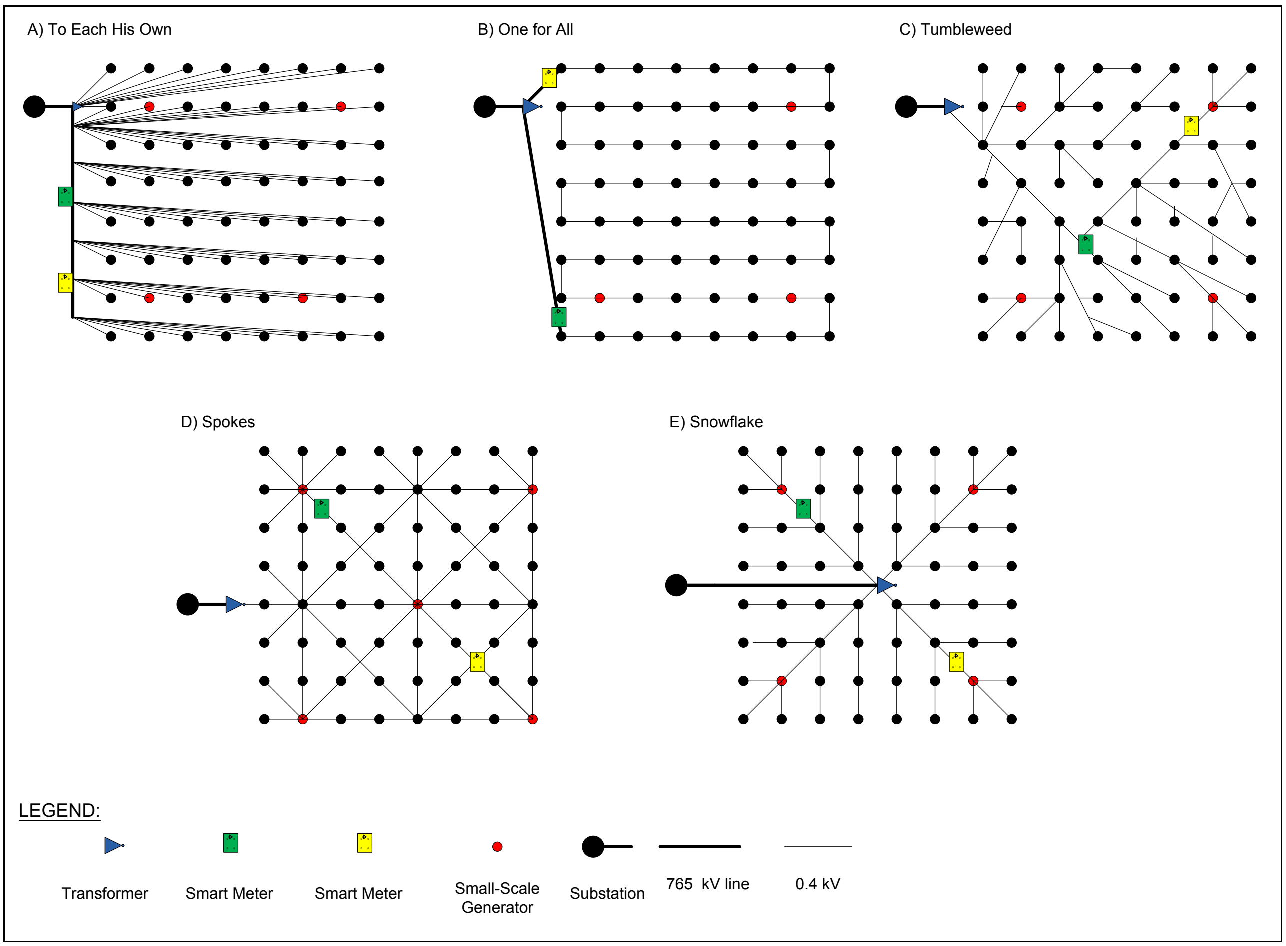
URL: http://vtsenvirogroup.files.wordpress.com/2009/05/smartgrid_454570a-6.jpg

Within each technology category, there are varying levels of existing technology options for potentially meeting the needs of California's smart grid. However, there remain notable knowledge gaps in each technology category. Examples of subcomponents in each technological area and the hierarchical structure of a possible California smart grid are illustrated in the figure below.

2.4 Grid Component Technologies

In order to compare options for distribution grids, assume that: coverage is 16 acres, involving 1 substation, 16 uniform end-users, and 4 small-scale generators (2 wind-powered, 2 solar-powered). Thicker black lines represent 765 kV transmission lines, whereas the rest of the lines represent 0.4kV leading to end-users. Each model consists of 1 transformer and 2 smart meters.

Figure 6: Types of Distribution Grids



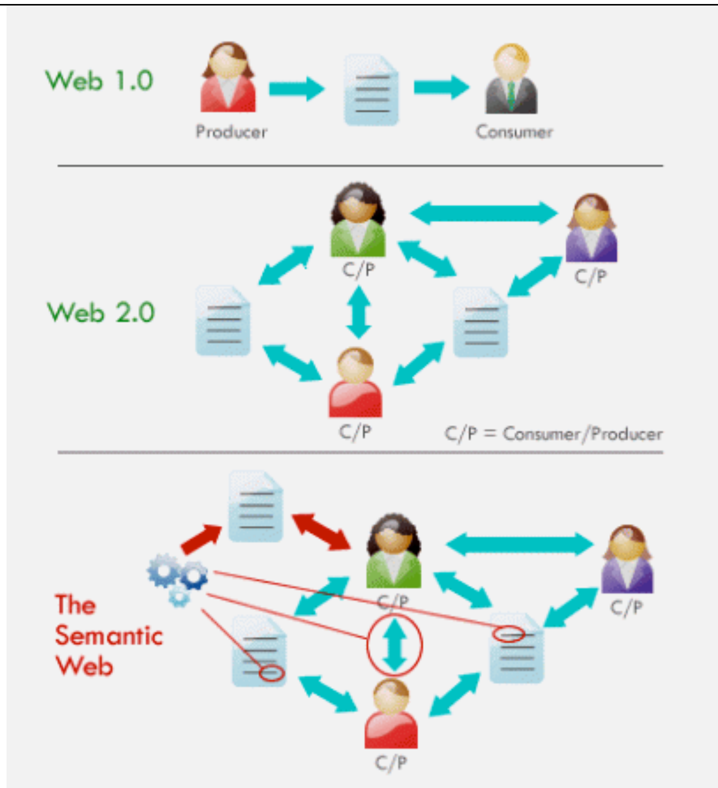
2.5 Electric Power Generation

In electricity generation, parallel lines of electricity will lose less power to heat friction. In transmission lines, parallel structure will similarly transmit energy further without losing as much to resistance as a structure of circuits in series. When distributing electricity to wholesale and end-users, transmission lines should branch off of parallel circuits and reach endpoints by various route schemes.

An integrated power grid would be most advantageous in the electricity generation and electricity transmission processes. However, it is possible that an integrated circuit for electricity distribution may be inefficient for a few salient reasons. First, an integrated distribution grid may have greater chance of overloading. Take, for example, the analogous development of the Internet network. Web 1.0 operated on a radial model with a central hub, the webmaster, who handled and routed information to end-users. Web 1.0 was prone to bottlenecks in capacity and speed. In its higher version, Web 2.0 became decentralized and end-users could access information directly, but they could interact with each other directly. A decentralized distribution grid may be as efficient a means of electricity delivery as it is an efficient means of information delivery. For one thing, end-users can tap into the electricity system with greater flexibility. This is useful as some end-users may have home power generators (e.g. windpower, solar power systems) that they are able to harvest. In the diagram below, a blogger argues that Web 1.0 was a one-way platform (in the sense that end-users could only extract), Web 2.0 was a two-way platform (in that end-users could interact, extract, contribute), and that a future Web 3.0 would be as a "smart grid" with a "web machine that learns, suggests, and anticipates what people like and would like to get." [11]

[11] Berners-Lee, Tim. "The Future of the Web as seen by its creator." URL: http://www.itworld.com/070709future

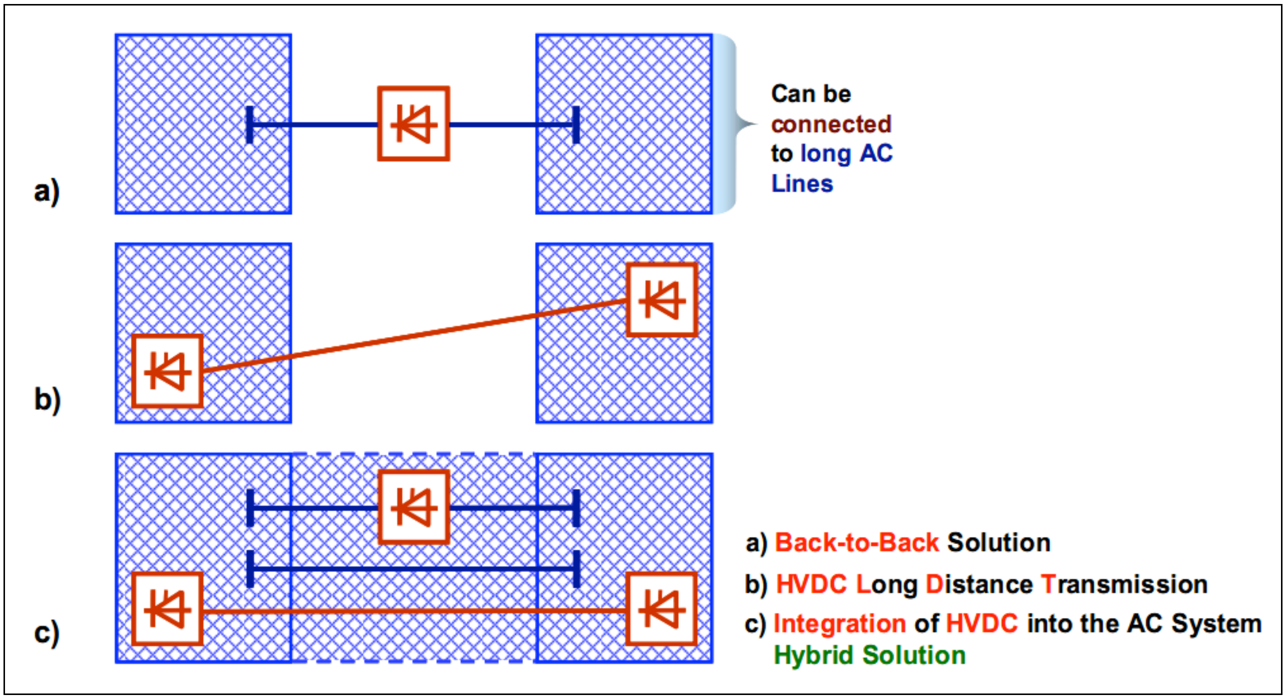
Figure 7: Evolution of Information Networks



Source: Nesta. 07/25/2007.
URL: http://blogs.nesta.org.uk/innovation/2007/07/the-future-is-s.html

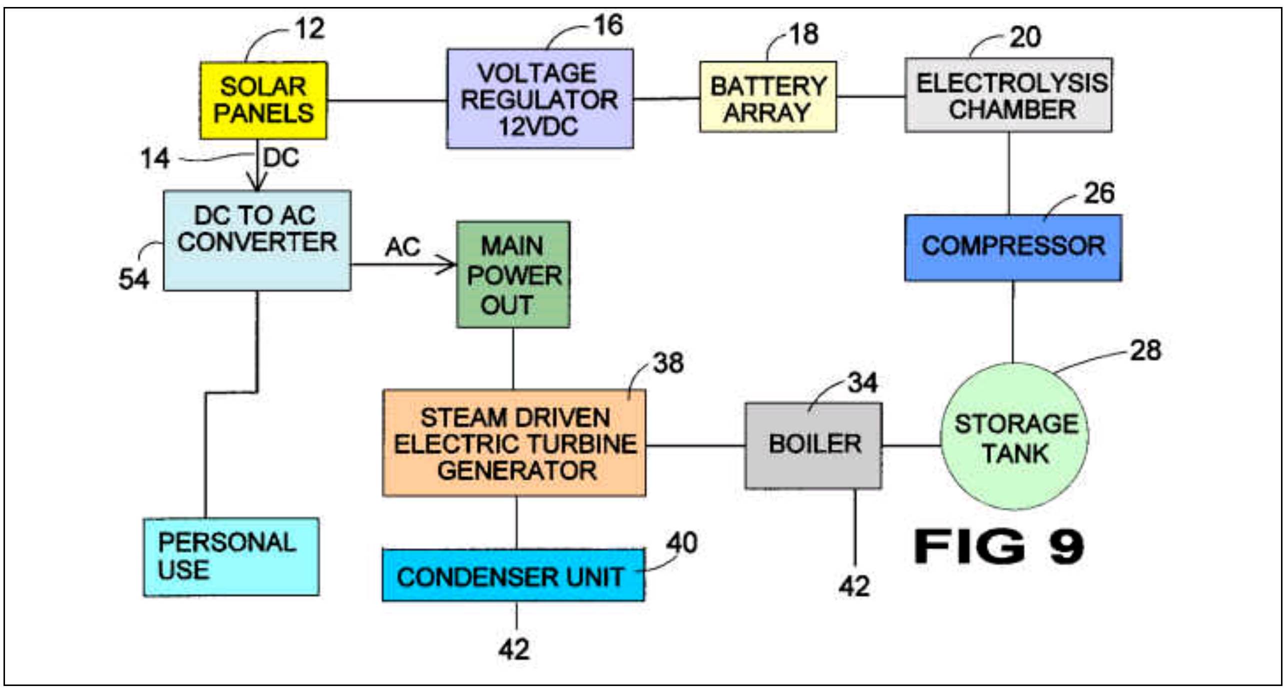
2.6 Electricity Transmission

Figure 8: Types of HVDC Transmissions



Source: Juan Miguel Pérez de Andrés, et al. 2006.

Figure 9: Types of Distribution Grids



Source: James R. Forney, 2001.

2.7 Schematic Scenarios for Electric Power Distribution

The following table sets out five proposed archetypes or generic schemes for electricity distribution:

A. To Each His Own

Each end-user has an independent connection to the substation. Such a distribution scheme would be costly and redundant in material. Users that are farther away would experience greater losses for distance across which electric power is transmitted.

B. One for All

The distribution scheme saves on material lines, but is highly inefficient since it requires a very large current to run through the entire wire. A large current would experience high losses, since a high voltage is countered by high resistance in the wire.

C. Tumbleweed

Historically, U.S. power distribution lines have followed in the radial "tree" structure.This design is the simplest and cheapest on an incremental user basis, i.e. for adding new end-users and more endpoints. However, this schema is not very effective for integrating small-scale generators, windmills, and other power systems.

D. Spokes

The substation would deliver to more localized hubs, from which electricity would flow out. In this scheme, certain hubs (colored orange in the diagram) could also be electricity generators. Thus, in this scheme, electricity is both contributed and extracted in a decentralized fashion. Such a distribution scheme would allow small-scale generators, windmills, etc. to contribute to the electricity pool and maximize the electricity harvest.

E. Snowflake

Electricity distribution is also decentralized. The substation delivers to a center point and each neighborhood or street extends from the diagonals. Small-scale generators would be optimally located along the major diagonals in order to transmit power directly to the community or substation.

Across this spectrum of design, ranging from material saving to distance saving, independent lines to integrated lines, it would seem that the Spokes (D) and Snowflake (E) schema are most efficient for integrating diverse generators and end-users, without overloading voltage across the lines. It is important to note also that the advantages of any distributional pattern should at least somewhat complement the layout of relevant cities and municipalities, since they must coexist with many other infrastructure systems.

For long-distance distribution, high-voltage direct current (HVDC, or DC) systems are less expensive and suffer lower electrical losses than alternating current (AC) systems. Because HVDC allows power transmission between unsynchronised AC distribution systems, it can help increase system stability, by preventing cascading failures propagating from one part of a wider power transmission grid to another. Yet, HVDC experience disadvantages in conversion, switching, and control. HVDC systems undergo faster technology turnover and, consequently, are less standardized than AC systems. Technical and economical advantages also diminish with the increasing size of interconnected systems, owing to load flow, oscillations and voltage quality.[12] For shorter distances, the cost of converting power from DC equipment may outweigh the other benefits of DC links. Rather, using an AC system with a transformer is efficient to step down voltages. Thus, it is recommended that a hybrid AC-DC system be implemented, wherein HVDC systems are used for power generation (for greater output) and transmission (for long-distance travel), but AC systems distribute electricity to end-users.

[12] de Andrés, et al. 2006. URL: http://www.usa.siemens.com/answers/en/_assets/Prospects_for_HVDC_Cigre_Madrid_0611_V1.pdf

Table 2: Heuristic Cost Estimates of Distribution Grid Schemes

	QUANTITY	COST EACH	A) To Each His Own	B) One for All	C) Tumbleweed	D) Spokes	E) Snowflake
Generation	**110 to 400 kV**						
Gas	47%	$9.38					
Hydro	20%	$10.53					
Nuclear	18%	$15.32					
Geothermal	7%	$10.18					
Biomass	3%	$16.49					
Wind	2%	$8.91					
Oil	1%	$8.55					
Other	1%	$9.38					
Coal	1%	$13.12					
Solar	1%	$12.65					
*AVG. COST OF POWER PER DAY *****		*$10.96*	$64,033.04	$64,033.04	$64,033.04	$64,033.04	$64,033.04
Transmission	**10 to 30 kV**						
per meter length ***		$60.76	3,381.89	5,797.52	483.13	483.13	2,898.76
Towers ***		$20,000.00	320,000.00	320,000.00	320,000.00	320,000.00	320,000.00
Transformers **		$13,019.00	13,019.00	13,019.00	13,019.00	13,019.00	13,019.00
COST OF CONSTRUCTION			$336,400.89	$338,816.52	$333,502.13	$333,502.13	$335,917.76
Distribution	**0.4 kV**						
per meter length ***		$60.76	143,370.47	34,785.12	38,306.47	45,737.15	26,957.98
CCS device *	1	$2,040.00	2,040.00	2,040.00	2,040.00	2,040.00	2,040.00
Smart Meter	2	$240.41	480.81	480.81	480.81	480.81	480.81
COST OF CONSTRUCTION			$145,891.28	$37,305.94	$40,827.28	$48,257.96	$29,478.80
TOTAL COST OF CONSTRUCTION			**$546,325.21**	**$440,155.50**	**$438,362.45**	**$445,793.13**	**$429,429.60**

**** Estimated costs for different power generation sources based on CPUC model. URL: http://www.ethree.com/cpuc_ghg_model.html

*** Estimated cost for length of transmission lines based on R.A. Lundquist's *Transmission Line Construction Methods and Costs*, with conversion to 2009 dollars.

** Estimated cost for transformer based on Copper.org. URL: http://www.copper.org/applications/electrical/energy/casestudy/study_transformer.html

* Estimated cost for Carbon Capture & Storage device from study by California regulatory agency, based on IGCC coal plant.

2.8 Advanced Power System Components

2.8.1 Conductors

With continual growth in electricity demand, demand for transmission has outpaced capacity and congestion has become a growing concern. In North America, for instance, electricity demand increased by 25% since 1990, while construction of transmission facilities actually decreased by 30%.[13] As total electricity demand continues to increase in the near future, increasing transmission capacity through improving the capacity and distance of existing lines will thus be a key aspect of the modern grid. Existing transmission lines in use have transmission losses of up to 7.5% due to heat, which can be reduced through increased voltage and decreased current.[14] The capacity of these transmission lines are also limited by temperature, as warmer lines cause sagging that can lead to major power outages and blackouts.

In light of these limitations, advanced conductors with better technical, environmental and economical performance are needed to serve as the key component of transmission and distribution system in California's smart grid. Conductors can help improve the capacity of transmission lines with higher strength-to-weight ratios. Specifically, the integration of new materials with existing components and subsystems can help produce advanced conductors with higher current-carrying capacity, lighter weight, greater durability, lower line losses and lower installation, operation and maintenance costs.[15] Existing conductors used in transmission lines are made of aluminum conductor steel reinforced material but alternative composite cable materials such as aluminum, stainless steel, various glass and carbon fibers and Kevlar 49 fibers are under development. The development and use of these high temperature superconducting materials can replace existing grid segments with enhanced capabilities that provide more flexibility, reliability and efficiency.

These improved conductors will be crucial to increasing grid capacity to accommodate more renewable and distributed power generation sources without siting more transmission lines, which is an expensive and timely process. Existing projects aim to develop conductors with five times the current capacity at current costs by 2010, and fifty times the current capacity by 2025.[16] In the advanced conductor development and commercialization process, key technical challenges that need to be addressed include

[13] DOE Office of Electricity Delivery and Energy Reliability.
[14] Amin and Stringer, 2008.
[15] U.S. Department of Energy Office of Electric Transmission and Distribution, 2004, "National Electric Delivery Technologies Roadmap: transforming the grid to revolutionize electric power in North America." Available at: http://www.netl.doe.gov/moderngrid/resources.html
[16] Amin and Stringer, 2008.

reducing manufacturing and installation costs, increasing durability and corrosion resistance, and reducing weight and line sag.[17]

Besides the adoption of more advanced conductors, replacement of existing underground conductors is also another key infrastructural need for developing the state's smart grid. Specifically, reliable diagnostic techniques based on improved models, data and sensors can help determine the conditions and remaining lifetime of existing underground conductors.[18]

2.8.2 Energy Storage

As another essential part of the smart grid, low-cost, flexible and reliable energy storage devices can play a major role in boosting the grid's utilization of greater generation, transmission and distribution capacity. Besides small- and medium-scale storage options like batteries and power supply units in distribution systems, large-scale, high technology energy storage systems can store tens to hundreds of MWh. The two main types of energy storage technologies are power systems and energy systems. Power systems provide bursts of power in short intervals to support grid functions of spinning reserve, area regulation, VAR compensation, and maintaining appropriate power quality. On the other hand, energy systems that provide longer-term storage for peak shaving, load leveling, renewable dispatch and micro-grid power management.

A primary function for power system storage is to provide system reliability, as systems like flywheel storage and super capacitor systems serve as a back-up resource for unexpected changes in power supply or demand. The two specific kinds of existing power systems that could be used in the smart grid include flywheel energy storage systems and super capacitor systems. Flywheel storage systems currently only exist on a small-scale, with U.S. capacities ranging from 5 to 100 kW. Super capacitor systems are even newer and more expensive, with only one utility-scale, 450 kW and 30-second demonstration system in use. Compared to flywheel storage, super capacitor systems have higher efficiency, faster response and longer life expectancy.[19]

Complementary to power systems are energy storage systems, which have greater advantages in applications where long-term storage is needed. Energy storage systems have diffused further into the market, with several new technologies on the order of 100s of MWh currently available and close to commercialization in the U.S. [20] These systems include zinc bromine battery, vanadium redox battery, sodium sulfur battery and compressed air energy storage systems. While zinc bromine and vanadium redox battery storage systems have already been developed as intermediate sized

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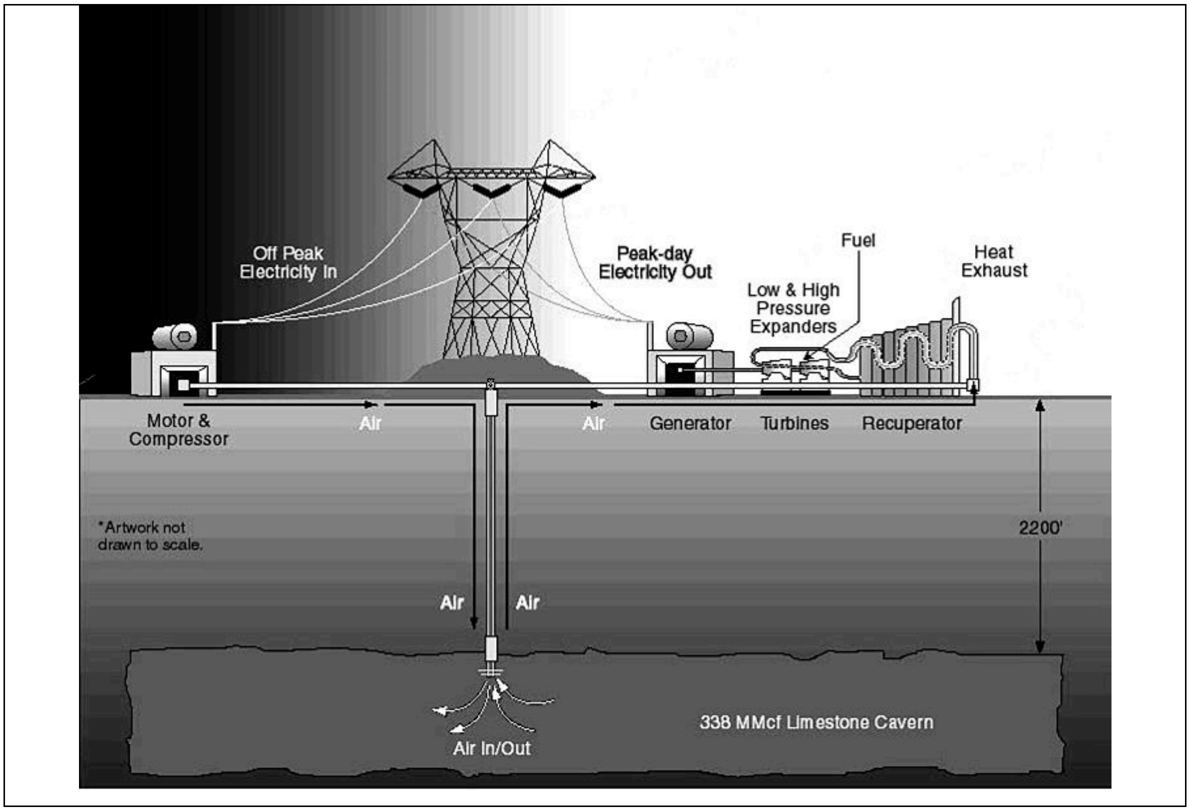
[17] U.S. DOE, 2004.
[18] CEC, 2008.
[19] CEC, 2008.
[20] CEC, 2008.

storage systems on the range of 0.5 to 5 MWh suitable for intermittent to daily cycling applications like peak shaving and substation upgrade deferral, others can play a greater role in renewable energy dispatch. In particular, sodium sulfur battery storage systems have already been fully commercialized for wind stabilization in Japan while compressed air energy storage system is an increasingly popular storage option being considered for wind generation stabilization and dispatch. [21]

Figure 10: Potential Application of Compressed Air Energy Storage System



Off-peak electricity power (e.g., generated by periods of high wind power capacity) can be used to compress air into underground air-storage system, which can later be used to feed a gas-fired turbine generator to generate electricity during period of peak demand.

Source: Sandia National Laboratory, 2001. URL: http://www.sandia.gov/media/NewsRel/NR2001/norton.htm

[21] CEC, 2008.

Regardless of their differing advantages, utility-scale energy storage systems all face similar technical and social barriers for large-scale deployment by utilities. From the technical perspective, achieving significant cost reductions while improving efficiency and performance in charging and discharging processes is an important area for further improvement. The social barriers include difficulties in garnering public and utility support for siting and permitting of the systems, interfacing with local utilities, and a general unwillingness amongst customers and utilities to try new technology options.[22] In California, sponsored demonstration projects involving these emerging energy storage technologies have helped overcome some of these deployment challenges and continued support will be key to their successful adaptation for the smart grid.

2.8.3 Advanced Grid Operation & Control Methods

As a modern grid, a significant advantage of having a smart grid in California would be its self-healing abilities through the use of advanced grid operation and control methods and power electronics. The ideal smart grid would consist of two key elements: (1) an intelligent and autonomous digital system capable of identifying surges, downed lines and outages and (2) resilient and self-healing system capable of providing instantaneous damage control.[23]

To enable real-time fault detection and system restoration, each component and connection of a substation including breakers, switches, and transformers must have an associated processor that enables communication with one another. Coupled with the use of sensors, these processors can hold permanent information on device parameters and report real-time status and analog measurements to central control computers. In essence, data is distributed throughout the system components, which act as independent agents and thus have the ability to react appropriately to disruptions without affecting the entire network.[24] For these separate components to be functional and fully integrated with one another, there first needs to be a coherent framework in the form of standardized communication architecture. This basic communication architecture is particularly important to facilitating the flow of real-time information about grid system and electricity market conditions, which in turn can help reduce grid congestion through better demand management.[25] Thus, a smart grid's advanced capabilities lies in its distributed intelligence and control system, which not only supports

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[22] National Energy Technology Laboratory, 2007. "Systems View of the Modern Grid: Accommodates All Generation and Storage Options. Available at: http://www.netl.doe.gov/moderngrid/docs/Accommodates%20All%20Generation%20and%20Storage%20Options_Final_v2_0.pdf
[23] Amin and Stringer, 2008.
[24] Amin and Stringer, 2008.
[25] DOE, 2004.

the more effective operation of the grid but also promotes deployment of new technologies and end-use applications.

Besides the communication backbone, there needs to be investment and development of a variety of distributed sensors, data acquisition devices and advanced control algorithms that connect the different components.[26] The different technology options for these components are discussed below.

2.8.4 Sensors and Wide Area Measurement System

As an invaluable measurement instrument and the foundation of data collection, advanced sensor technology will be crucial to the smart grid operations and control system. With the incorporation of more components and complex processes into the smart grid, advanced sensors must be able to collect more accurate real-time data on more variables from more system locations. For example, sensors need to be able to accurately detect and measure chemical species such as CO_2, NOx and SO_2, while physically able to withstand extreme temperatures and chemical environments.[27] Being small enough to be used in distributed applications throughout different power components is another important physical characteristic of sensors. Possible technology options currently being considered for advanced sensors are different fiber-optic sensors that are versatile, small and free from magnetic interference. A specific example of an advanced sensor technology is the synchrophasor measurement unit that uses synchronized satellite time clocks to determine and compare real-time voltage, current, and phase angles at any locations in the grid. These synchrophasor measurements are taken at high speeds of thirty observations per second and time-stamped according to a common reference time. With a consistent time and geographic reference system, synchrophasor measurements can provide early warnings of potential system instability, increase system loading with stability margin, improve operator response to system contingencies and promote system wide data exchanges with a standardized data format.[28]

More importantly, synchrophasor measurements can be used to support wide area measurement systems and improve the optimal use of all grid resources. A wide area measurement system gathers real-time phasor measurements to provide detailed power grid monitoring and stability control. For example, phasor measurement and backscatter sensors on the transmission grid can provide real-time information on the status of specific transmission lines through the use of communication technology like

[26] DOE, 2004.
[27] Amin and Stringer, 2008.
[28] CEC, 2008.

radio frequency identification technology.[29] These sensors detect instantaneous problems on the grid as they develop and provide utilities with the necessary information to act immediately. In the future, more advanced applications of this system can also be used across larger geographic scopes like the continent to improve system reliability and help coordinate large blocks of renewable energy from sources to loads.[30]

However, the lack of a secure communications network for data transmission, management protocols and adequate security measures poses potential problems for the wide deployment of synchrophasor in smart grids. To examine and address these limitations, the North American SynchroPhasor Initiative has been launched on the national level by the Pacific Northwest National Laboratory.[31] A wide area measurement system pilot project involving phasor measurements conducted by the energy group ABB also found that such a monitoring system can significantly improve grid optimization during periods of peak transmission while detecting critical factors that influence network stability.[32]

2.8.5 Active Distribution Management and Control

With detailed data collected through phasor measurements, computer-based algorithms that integrate sensors with distribution supervisory control and data acquisition systems (SCADA) can then provide diagnostic analysis to monitor all essential grid components on a real-time basis.[33] These control methodologies will support devices like the wide area measurement system and distribution and substation automations and help optimize grid operations and planning through integration with the asset management process. Specifically, active distribution management and control provides rapid reconfiguration of discrete components in response to changing grid conditions and allows for managed island modes of operation. In general, active distribution management and control requires many subcomponents including real-time monitoring, communication interface and information models, data processing and simulation tool requirements, and algorithms.

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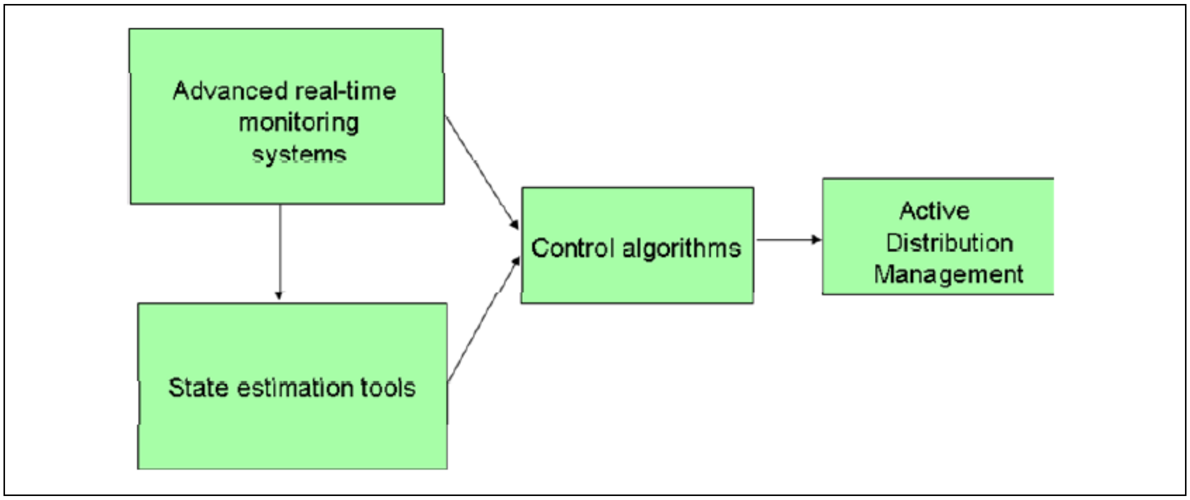
[29] Butler, F. 2009. "A Call to Order: a regulatory perspective on the smart grid." *IEEE Power & Energy Magazine* March/April 2009: 16-25.
[30] CEC, 2008.
[31] See http://www.naspi.org/
[32] ISO New England, Inc. 2009. "Overview of the Smart Grid: Policies, Initiatives and Needs." Available at: http://www.iso-ne.com/pubs/whtpprs/smart_grid_report_021709_final.pdf
[33] SAIC Smart Grid Team, 2006, "San Diego Smart Grid Final Report."

Figure 11: Components of Advanced Grid Operation and Control



Source: CEC, 2008.

Besides the previously discussed advanced monitoring and communication interface components, data processing and simulation tool requirements are also important factors for active distribution management and control. With large amounts of data collected through numerous sensors, adaptable data processing capability that can filter out key event information and support the control system's response is essential. Similarly, advanced analysis and simulation tools need to be developed to support planning, design and simulation of real-time information.

In addition to monitoring and analytical tools, multiple levels of algorithm capabilities are needed to support active distribution management and control. First, algorithms to control individual components of the grid such has capacitor banks, switchgear or distributed generators are required. Second, algorithms will need to manage assemblages of different advanced components within the same circuit by adapting to the specific circuit in each case. On the circuit level, the algorithms need to be responsive to incoming real-time data in selecting the appropriate circuit and device dispatch actions.[34] There may also be algorithms developed for higher level of supervisory control, such as at substations, but little research and development work has been done at these higher levels. In essence, these algorithms will serve as the basis for automating substation monitoring and distribution in a more efficient and optimally operated smart grid. Investment in developing more complex control algorithms at higher supervisory levels will thus be essential to a California smart gird, along with extensive field trials and testing of distribution and control systems.

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[34] CEC, 2008.

2.9 Integrated Communication: Dynamic Consumer Applications

Besides a modern underlying grid operational and control infrastructure, California's smart grid also needs an integrated communication infrastructure to enable real-time data acquisition, protection and exchange.[35] After standards are developed to govern this integrated communication infrastructure, dynamic consumer applications can be incorporated into the smart grid. Using the smart grid to provide interfaces with energy customers can help meet the state's important energy efficiency, system reliability and security and environmental (i.e., greenhouse gas reduction) goals. In particular, consumer-driven demand response applications for the future smart grid can include smart meters through an advanced metering infrastructure (AMI), home area networks and other smart devices.

2.9.1 AMI and Smart Meters

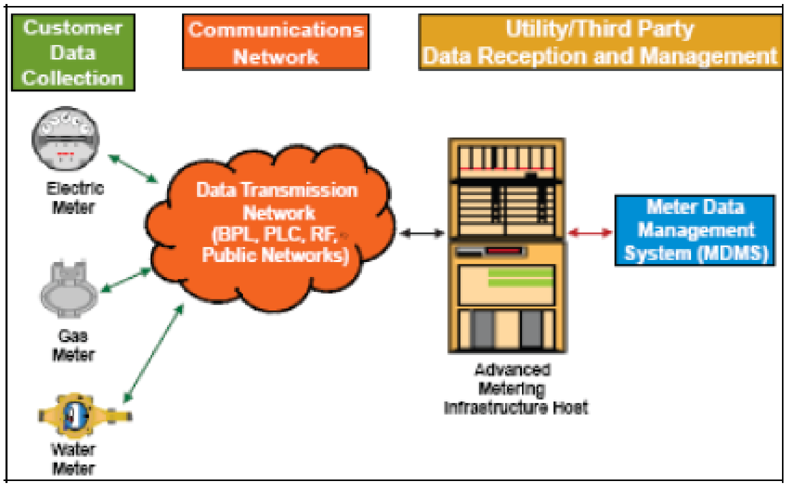
As an integral component and predecessor to smart grids, advanced metering infrastructure or AMI have become increasingly popular with the launch of several state pilot projects in the last few years. AMI refers to "the full measurement and collection system that includes smart meters at the customer site, communication networks between the customer and a service provider, and data reception and management systems that make the information available to the service provider."[36] The three different components of AMI and their interactions are illustrated in the figure below.

As seen in Figure 4, smart meters are the key tool used for customer data collection in AMI. Over the past few decades, there has been a technological shift from electromechanical meters to solid state, electronic meters that allow for more efficient and less costly remote meter reading, particularly for larger utility customers like businesses and commercial users. Unlike electromechanical meters that are much harder to retrofit and require the installation of an electronic meter module under-the-

[35] Department of Energy Office of Electricity Delivery and Energy Reliability, 2007, "A Systems View of the Modern Grid Appendix B1: Integrated Communications." Available at: http://www.netl.doe.gov/moderngrid/resources.html
[36] EPRI, *Advanced Metering Infrastructure* (Palo Alto, CA: February 2007). (EPRI-2)

glass of the older meter, solid state meters are easier to upgrade to enable communication with AMI systems.[37]

Figure 12: AMI Components



Source: FERC, 2007.

Besides the physical meters, AMI data collection also involves the use of a fixed network for remotely collecting and retrieving meter data. The existing AMI networks include broadband over power line, power line communications, fixed radio frequency networks and systems utilizing public networks such as landline, cellular or paging. The choice of one of these three communication networks has been debated extensively amongst utility decision-makers, regulators and vendors, though the latest round of AMI deployments including the recent California pilot projects have favored radio frequency networks.[38] The next technology choice in mass AMI deployment will be choosing between three competing sets of communication technologies: the current set with increased bandwidth, latency ability and IP capabilities; the emerging set in the form of 3G, General Packet Radio Service (GPRS) and WiMax technologies; and a future set based on virtual metering through internet connectivity and interfaces with the Home Area Network.[39]

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[37] Federal Energy Regulatory Commission, 2006. "Assessment of Demand Response and Advanced Metering Staff Report." Available at: http://www.ferc.gov/legal/staff-reports/demand-response.pdf
[38] Roberts, T. 2008. "Update on Advanced Metering for California's Large Utilities." Presented at CEC Workshop on Metering Infrastructure, May 27, 2008.
[39] Tai and Ogain, 2009. "Behind the Buzz: Eight Smart-Grid Trends Shaping the Industry." *IEEE Power & Energy Magazine* March/April 2009: 88-93.

With integrated and secure two-way communication, smart meters can help consumers monitor and adjust their energy use while collecting important data points for grid operation. AMI and its related components can also play a major role in raising consumer awareness and motivating active participation in demand response and energy efficiency initiatives in a smart grid. For example, advanced metering enables the implementation of time-based rates or real-time pricing by measuring, storing and transmitting interval usage data to the utilities. These capabilities provide consumers with a pricing signal for peak versus off-peak periods by helping them understand their hourly usage patterns and the relationship to costs.[40] Additionally, the integration of AMI with direct load control communication technology can also enhance grid system operating efficiency through remote meter reading, improved forecast as well as support utility billing, customer support and outage management applications.[41]

Table 3: Summary of California Large Utilities' AMI Projects

	Pacific Gas & Electric	**San Diego Gas & Electric**	**Southern California Edison**
Scale	5.1 million electric meters	1.4 million electric meters	5.3 million electric meters
	4.2 million gas meter modules	900,000 gas meter modules	SoCalGas MAY connect to this system
Total Costs	$1.74 billion approved	$582 million approved	$1.72 billion approved
	$467 million upgrade approved		
Deployment Timeline	2007-2012	2008-2011	2009-2012

Source: CPUC Energy Division.

In recognition of smart meters' potential, the California Public Utilities Commission have approved funding requests from three of the four major investor-owned utilities for pilot smart meter installation projects. The scope and scale of each of these three pilot projects are outlined in Table 2, above. The latest approval on September 18, 2008 was for Southern California Edison (SCE) to install over five million smart meters for

[40] FERC, 2006.
[41] Roberts, 2008.

their consumers over four years.[42] As with the previous pilots, this project is intended to collect utility data on energy savings and financial benefits associated with different demand response, load control and conservation programs enabled by AMI as well as spearhead AMI educational and awareness campaigns. However, some consumer groups have objected to the high cost of SCE's AMI deployment estimated at t $1.63 billion and the relatively lower estimated consumer benefits of $9 to $304 million.[43] Therefore, investment in AMI infrastructure has already began in California and will likely continue as planning and preparation for the state's smart grid continues.

2.9.2 Home Area Networks

Besides AMI, another important demand response customer interface under a smart grid would be a home area network, or HAN. HAN helps connect all the smart devices in a home such as appliances, thermostats, in-home displays and even plug-in hybrid electric vehicles (PHEVs) and manages the congruous operation of these devices efficiently while balancing the home's electricity supply and demand.[44] The HAN can serve as a consumer empowerment tool since the utility controls the smart meter but homeowners own and control energy use through HAN. A mature HAN as depicted in Figure 5 can connect to as many as 45 different applications.

Through a secure two-way communication with the smart meter, HAN can enable public price signaling, consumer-specific signaling, distributed generation and submetering. For instance, more readily accessible information through AMI can help integrate PHEVs into the smart grid by making real-time pricing possible and shifting consumer charging to off-peak hours.[45] This has additional benefits of reduced peak load and improved load management. HAN can also be a valuable tool for helping integrate PHEVs into consumer's energy management, where long term vehicle chargers may even be able to dictate if and when they want to use the PHEV to provide power back to the home or to the grid.

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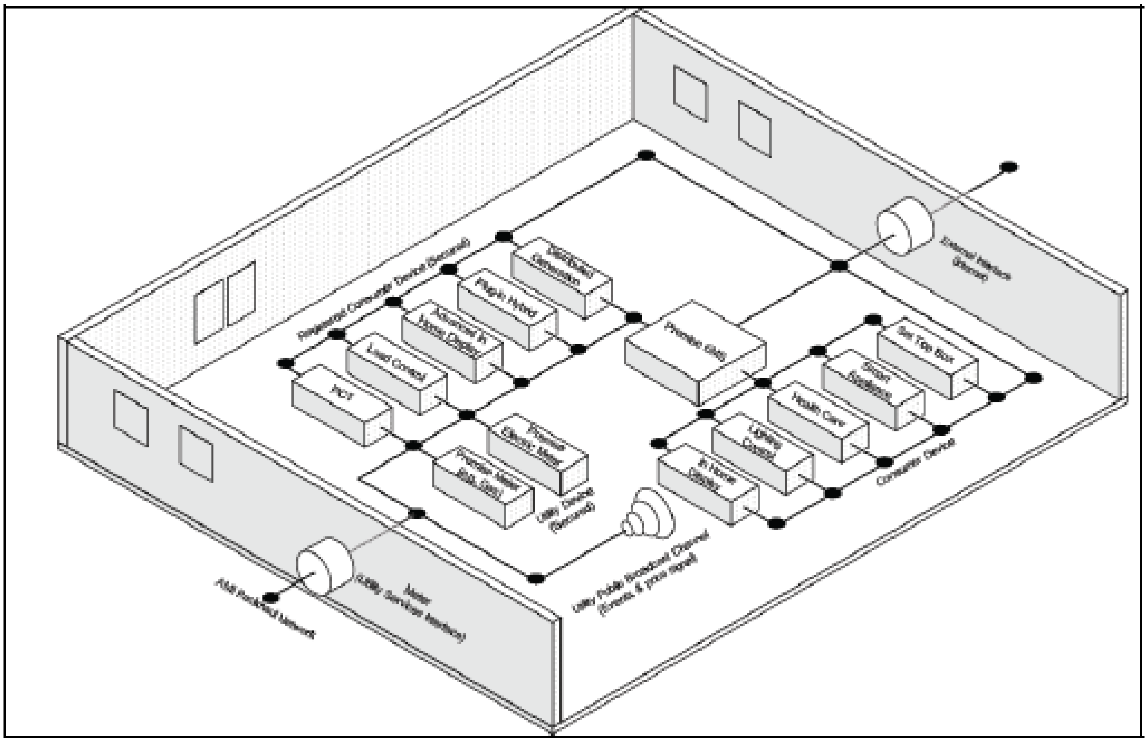
[42] See CPUC demand response website: http://www.cpuc.ca.gov/PUC/energy/Demand+Response/R0206001.htm
[43] Butler, 2009.
[44] ISO New England, 2009.
[45] CEC, 2008.

Figure 13: Diagram of a Mature Home Area Network



Source: ISO New England, 2009.

2.9.3 Smart Devices

As the most consumer-oriented application, smart devices like smart appliances and smart thermostats enable active consumer participation in the smart grid. Smart appliances are configured with a grid-friendly appliance controller that monitors voltage and shed load whenever an under-frequency event occurs. Recent field testing of smart appliances like hot water heaters and clothes dryers have shown impressive results and suggest that they can be used both autonomously and as part of a HAN.[46] As relatively new technologies, there needs to be greater consensus on standards for smart appliance interfaces.

In addition, programmable controllable thermostats can further provide information to motivate consumers to undertake more energy efficient practices. For instance, smart thermostat can be used to display information on the current price in effect as well as

[46] ISO New England, 2009.

daily bill updates. As early as 2002, Southern California Edison launched a pilot project installing 4,600 smart programmable thermostats in 2,600 smart businesses to test their potential in demand response load reduction during peak use periods. Project results have been promising, as analysis of initial load dispatch during the summer showed the initial load reduction goal could be doubled without remotely turning off the air conditioners.[47]

For all these dynamic consumer interfaces with the smart grid, a key success factor would be active consumer participation and awareness. Ultimately, HAN and smart devices can only be effective demand response and energy efficiency resources if consumers actively use them to manage their own energy use.

2.10 Conclusions

While specific aspects of California's smart grid will change as technology continues to be developed and tested and different stakeholders weigh in on relevant policies and programs, there are several prevailing technology areas and related options that will remain the basic infrastructure for a modern grid. These include the use of advanced power system materials and energy storage for utilization of more renewable and distributed power generation, integrated and automated grid operation and control methods for a real-time responsive grid system, and multifaceted communication interfaces with consumer applications to promote efficiency, demand response and system reliability.

In some technology areas such as AMI and smart devices, California has already taken the lead by supporting large utilities' ambitious smart metering and smart thermostats pilot projects. Nevertheless, the current structure of retail pricing do not appropriately reflect variations in wholesale price and thus may not adequately motivate consumers to be more active participants in the smart grid development process. In other areas like power electronics, energy storage and automation, however, the lack of research, developing and deployment and lack of public acceptance poses major technical and social barriers on both the state and national level. For grid network automation specifically, very little regulatory incentives are currently available to encourage utilities to invest in smart and flexible distribution infrastructure for automation.

The existing and emerging technology options in each of the three infrastructure areas will likely give rise to disagreement amongst different stakeholders in the road to building California's smart grid. With increasingly more technology options, standards are becoming even more crucial to facilitating interaction between different components

[47] Martinez and Russell, 2004. "Demand Response: Smart Thermostats Getting Results at SCE." *Utility Automation and T&D*.

and maintaining systems interoperability. Finally, deployment of the smart grid and its numerous interlinked components will require large investment from different players in an economically uncertain environment, which then need to be balanced with incoming benefits.

Thus, while California has made significant strides towards setting the infrastructure for a smart grid, much remains to be done before the modern grid can truly take form.

2.11 A Formidable Investment and Engineering Challenge, but Well Worth the Commitment

Electric power infrastructure for a sustainable future economy poses very substantial financial, technical, logistical, and institutional challenges. Most of the legacy grid was designed to support local electrification, appropriate for yesterday but today it presents a serious burden of fragmentation and inefficiency. The grid of the future must be integrated for efficient allocation, load/cost sharing, and continuous technology diffusion and reliability. To make this work will require determined public/private partnership, with government committing to the major component and institutional needs and facilitating the necessary private agency to populate a new system with state-of-the-art innovation from end to end. Most important at the outset will be a clear commitment device: huge initial investment and exercise of property rights.

While this will require significant financial resources, economic benefits in the future can underwrite today's public financing. Domain and property rights issues will also loom large in the foreground of such a visionary strategy, but again the enormous long term benefits to the many must be defended against narrower short term interests. The following sections of this report present economic assessments of the expected benefits of such a comprehensive new grid system for California, but they can be summarized easily. Policy makers and advocates should keep these three categories in mind as they strive to overcome the obstacles to delivering a sustainable energy future for the state's economy:

- Early harvest of employment-intensive infrastructure development
- Strong complementarities across an energy triangle of Utilities–Technology–End-users to facilitate adoption and innovation
- Long term benefits for sustainability and knowledge-intensive growth.

3 References