Energy and CO_2 Benefits of the Smart Grid

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The Smart Grid: An Estimation of the Energy and CO_2 Benefits

Revision 1

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Acronyms and Abbreviations

AC	alternating current
AEO	Annual Energy Outlook
AFDD	automated fault detection and diagnostics
AMI	advanced metering infrastructure
ANSI	American National Standards Institute
BPA	Bonneville Power Administration
Btu	British thermal unit(s)
CFC	chlorofluorocarbon
CT	combustion turbine
CVR	conservation voltage reduction
CVRf	conservation voltage reduction savings factor
DC	direct current
DEGI	dispatchable emergency generator initiatives
DOE	U.S. Department of Energy
EAC	Electricity Advisory Committee
ECAR	East Central Area Reliability Coordinating Agreement
EEI	Edison Electric Institute
EIA	U.S. Energy Information Administration
EISA	Energy Independence and Security Act
EMCS	energy management and control systems
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
ESPC	Energy Savings Performance Contract
ESPP	Energy-Smart Pricing Plan
EV	electric vehicle
FEMP	Federal Energy Management Program
FERC	Federal Energy Regulatory Commission
GFA	Grid Friendly™ appliance
GHG	greenhouse gas
GREET	greenhouse gases, regulated emissions, and energy use in transportation
GW	gigawatt, one billion watts of generating capacity
HCFC	hydro-chlorofluorocarbon
HEV	hybrid electric vehicle
HVAC	heating, ventilating, and air conditioning

ICT	information and control technologies
IM	interval meters
IPMVP	International Performance Measurement & Verification Protocol
ISO	Independent System Operations
kW	kilowatt(s)
kWh	kilowatt hour(s)
LC/S	load curtailment/shifting
LDV	light-duty vehicle
LoanSTAR	Loans to Save Taxes and Resources
m	meter(s)
m^2	square meter(s)
MMT	million metric tonnes
M&V	measurement & verification
MW	megawatt(s)
MWh	megawatt hour(s)
NERC	North American Electric Reliability Corporation
NHTS	National Household Travel Survey
NYSERDA	New York State Energy Research and Development Authority
OE	Office of Electricity Delivery and Energy Reliability
ORNL	Oak Ridge National Laboratory
PDRE	permanent demand reduction efforts
PHEV	plug-in hybrid electric vehicle
PLRP	Peak Load Reduction Program
PNNL	Pacific Northwest National Laboratory
PRISM	Princeton Scorekeeping Method
PV	photovoltaic
RECAP	Regional Capacity Planning
RPS	renewable portfolio standard
RTO	Regional Transmission Organization
SCADA	supervisory control and data acquisition
SUV	Sport Utility Vehicle
T&D	transmission and distribution
TWh	terawatt hour(s)
VAR	volt-ampere reactive
VMT	vehicle-mile(s) traveled

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1.0 Introduction

The U.S. Department of Energy (DOE), Office of Electricity Delivery and Energy Reliability's (OE's) mission is "…to lead national efforts to modernize the electric grid; enhance security and reliability of the energy infrastructure; and facilitate recovery from disruptions to energy supply." One key element of OE's strategy for modernizing the electric grid (http://www.oe.energy.gov/1165.htm) is to take advantage of the potential for information technology to change the operational and control strategies it uses to help keep electricity affordable by improving the cost-effectiveness of grid infrastructure investments and increasing the reliability of electricity supply and delivery to customers. OE has played a leading role in identifying this opportunity, which has come to be known generically as the "smart grid," by articulating its benefits to industry, policy makers, customers, and other stakeholders, by advancing key technologies and funding field demonstrations to prove its performance advantages (http://www.oe.energy.gov/smartgrid.htm).

As part of its efforts to quantify benefits from the smart grid, OE's Smart Grid Research and Development Program tasked Pacific Northwest National Laboratory (PNNL) to develop an estimate of the potential energy and carbon benefits that will result from deployment of the smart grid. The goals of this project are to:

- Define the mechanisms by which the smart grid can contribute to energy efficiency and the integration of renewable generation to provide carbon benefits to the United States.
- Quantify, to the extent possible, those benefits and contributions in terms of reductions in electricity consumption and CO_2 emissions.

This report articulates nine mechanisms by which the smart grid can reduce energy use and carbon impacts associated with generating and delivering electricity. To the extent possible, it presents quantitative estimates of potential impacts for each of the mechanisms through a detailed search of published results and by conducting simple analyses of the potential effects. This report does not attempt to justify the cost effectiveness of the smart grid, which to date has been based primarily upon the twin pillars of cost-effective operation and improved reliability. Rather, it attempts to quantify the *additional* benefits inherent in the smart grid's potential contribution to the nation's goal of mitigating climate change by reducing the carbon footprint of the electric power system.

OE's smart grid effort, formally established by the Energy Independence and Security Act (EISA) of 2007, is characterized by the 10 points shown in the text box (EISA 2007). The electricity and CO_2 reductions that may be obtained by implementing smart grid technologies estimated in this report will help identify the benefits associated with goals 3, 4, 7, and 8. In addition, the assessment provides a number of recommendations and issues to consider in the formulation and conduct of OE's research program that addresses: 1) ***technology development*** to modernize the delivery of electricity, 2) ***policy coordination and implementation*** to facilitate electricity system modernization, and 3) the ability for stakeholders to prepare for and respond to ***electricity supply disruptions***.

Energy Independence and Security Act of 2007
Sec. 1301. Policy on Modernization of Electricity Grid

… support the modernization of the Nation's electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet future demand growth and to achieve each of the following, which together characterize a smart grid:

(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.

Related assessments by the Electric Power Research Institute (EPRI) and The Climate Group, and an article in *The Electricity Journal*, also examined the electricity and CO_2 benefits that may result from implementation of the smart grid (EPRI 2008; GeSI 2008; Hledik 2009). These assessments also provide first-order estimates of the energy and carbon benefits for the emerging smart grid area and provide useful comparative benchmarks for this effort.

The report is organized into five sections. Section 2.0 provides an overview of the current electrical grid and a definition of the smart grid with its costs and benefits. Section 3.0 presents the assessment methodology, summarizes each mechanism and the results of its assessment, and Section 4.0 compares the results from EPRI and The Climate Group studies, and *The Electricity Journal* article. Further details of the assessments for the mechanism are provided in Attachments 1 and 2. The last section (Section 1.0) provides recommendations on mechanisms and benefits that deserve further exploration.

2.0 Smart Grid – What it Is, What it Does, and Who it Benefits

A basic perspective of this analysis is that, over the next 20 years, smart grid technology will become pervasive in the United States because of the cost efficiencies it provides for the electric power system, and that it could be leveraged to provided additional benefits of reduced energy consumption and carbon emissions. Therefore, it is important to understand the kinds of assets involved in a smart grid and how they are functionally engaged to provide cost efficiencies. This sets the context for why a smart grid is likely to be deployed and what assets it is likely to contain that can be leveraged for these additional environmental benefits. The discussion in this section attempts to outline this perspective.

Electricity has historically been generated at central station power plants and distributed to customers, as shown in Figure 2.1. In 2007, an estimated 995 GW of generating capacity delivered 4.2 GWh to 142 million customers (DOE/EIA 2009) over approximately 158,000 miles of transmission line >230 kV (DOE 2002). Estimates of distribution lines are in the range of 1 million miles. The voltage is stepped-up from large central generating stations for transmission through 10,287 transmission stations, stepped-down for utility distribution in 2,178 distribution substations (DOE/OE 2006), may be further stepped-down at points along the utility distribution lines (feeders), and again at pad- and pole-mounted transformers to provide low-voltage service to one or a several customers.

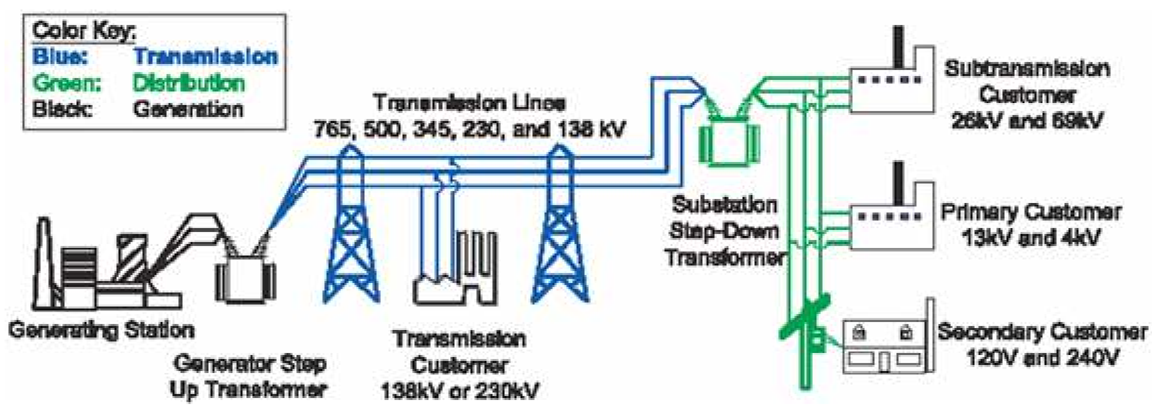


Figure 2.1. Today's Electricity Delivery System (Source: DOE/FEMP [2009], Electricity 101 at http://www.oe.energy.gov/information_center/electricity101.htm)

The delivery of electricity typically utilizes a supervisory control and data acquisition system (SCADA) that provides monitoring and control from generation through the step-down substation to detect the need for an increase/reduction in generating resources, and to respond to system instabilities. Key limitations of SCADA systems are the following:

- limited bandwidths and relatively slow data transmission rates that often require several seconds or more to respond to an alarm or system change
- limited or no visibility in the distribution network below the substation.

The coming evolution in the delivery of electricity is the smart grid, which is the application of information technology that enables more visibility and control of both the existing grid infrastructure and new grid assets, such as customer demand response and distributed energy resources consisting of small generators and electricity storage devices. The smart grid's much higher fidelity control is provided through high-speed, two-way communication, sensing, and real-time coordination of all assets down to the customer meter and the end-use devices. Thus the smart grid is not characterized by a single technology or a device, but instead is a vision for a distributed, internet-like system that will:

- provide better control of existing grid infrastructure assets
- provide additional functionality and benefits from existing assets
- integrate new (often small, widely distributed) assets into the existing operational paradigm
- engage these new assets to provide entirely new benefits to the grid.

The next immediate developments in SCADA technology for utilities are to increase bandwidth and begin to measure and control assets below the substation level, at which time the system will begin to become part of a distributed control system (Boyer 2007)—and a key part of the smart grid.

This vision is perhaps best described by a set of essential characteristics, or outcomes (see box).

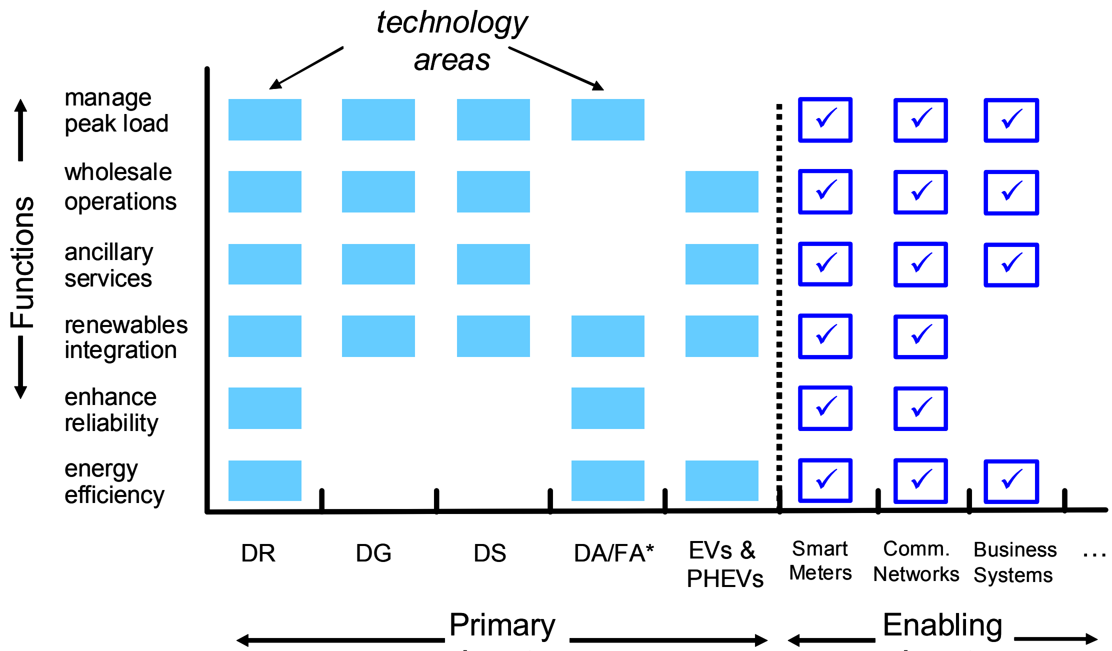
> "The smart grid isn't a thing but rather a vision… It must be more reliable...more secure...more economic…more efficient…more environmentally friendly…(and) It must be safer. A "smart grid" can be (characterized as) a "transactive" agent…(that) will:
>
> - Enable active participation by consumers…
> - Accommodate all generation and storage options...
> - Enable new products, services, and markets…
> - Provide power quality for the digital economy...
> - Optimize asset utilization and operate efficiently…
> - Anticipate and respond to system disturbances (self-heal).
> - Operate resiliently against attack and natural disaster.
>
> Achieving the vision is dependent upon participant circumstances and involves:
>
> - Empowering consumers by giving them the information and education they need to effectively utilize the new options provided by the smart grid…
> - Improved reliability and "self-healing" of the distribution system…
> - Integration of the transmission and distribution systems to enable improved overall grid operations and reduced transmission congestion…
> - Integration of the grid intelligence acquired to achieving with new and existing asset management applications…
>
> Source: Smart Grid News, April 22, 2009. *What is the smart grid?*

Beyond describing the smart grid as a vision, it is helpful to describe what the smart grid ***consists of*** in terms of

- the assets that would be purchased
- the functions for which they would be used, and from which benefits are derived.

This is illustrated in the matrix in Figure 2.2, with a number of key assets on the horizontal axis and broadly defined categories of major functions on the vertical axis. This illustration of the current and emerging vision for the smart grid is not intended to be definitive or comprehensive, but rather will evolve over time.

Assets are divided into primary and enabling assets. *Primary assets* are the smart grid's "prime movers," i.e., non-traditional assets that are actively controlled to effect change in the grid's operating conditions.



DR = demand response, DG = distributed generation, DS = distributed storage, DA/FA = distribution automation/feeder automation, EVs & PHEVs = electric vehicles/plug-in hybrid electric vehicles

Figure 2.2. Defining the Smart Grid in Terms of *Assets* and *Functions*

Enabling assets are the sensing, software, and information infrastructure required to coordinate the operation of the primary assets to respond to grid conditions. Although more accurately portrayed as a separate third dimension, enabling assets are shown here on the same axis for clarity.

Functions are grid operational strategies that use smart grid assets to derive cost, reliability, and efficiency or renewable energy benefits. The intersection of an asset and a function, denoted as a technology area, is the set of policies, engagement strategies, incentive mechanisms, control strategies, software applications, and capabilities of the primary and enabling assets required to accomplish a given function. The specific technology areas in Figure 2.2 illustrate the asset-function intersections and do not attempt to be definitive.

2.1 Primary Assets

The *primary assets* in Figure 2.2, broadly considered key to the smart grid, are:

- Demand response (DR) – communications and controls for end-use devices and systems to reduce (or, in special cases, increase) their demand for electricity at certain times.
- Distributed generation (DG) – small engine or turbine generator sets, wind turbines, and solar electric systems connected at the distribution level.
- Distributed storage (DS) – batteries, flywheels, super-conducting magnetic storage, and other electric and thermal storage technologies connected at the distribution level.
- Distribution/feeder automation (DA/FA) – distribution and feeder automation expand SCADA communications in substations and into the feeders with remotely actuated switches for reconfiguring

the network, advanced protective relays with dynamic and zonal control capabilities, dynamic capacitor bank controllers, and condition-based transformer-management systems (to name a few).

- Transmission wide-area visualization and control – transmission control systems that rapidly sense and respond to disturbances.
- Electric and plug-in electric hybrid vehicles (EVs/PHEVs) – the batteries in EVs represent both a new type of load that must be managed and an opportunity for them to discharge as energy storage resources to support the grid.

Demand response is intentionally defined as an asset, to differentiate the ***investment*** required for installing its control and communications capabilities from its ***use*** to achieve one or more functions. Although we recognize that the term *demand response* is often used to represent both the asset and its use for the peak load management function, this is more precisely the technology area represented by the intersection of the demand response asset and the peak load-management function. This distinction between demand response as an asset and the functions it can provide is helpful because demand response, like many other smart grid assets, can provide a number of other functional benefits ranging from ancillary services to reliability. Along with distributed generation and storage, demand response can play a key role in providing the additional ancillary services and reliability required for effectively integrating renewables. Additionally, as discussed in Section 3.0, there is potential for the control signals that support demand response to be used for conducting end-use system diagnostics and improving feedback to consumers to obtain energy efficiency.

The notion of ***active control in response to grid conditions*** is foundational to the notion of a smart grid. Most energy efficiency investments are *passive* in that they require no control at all (better insulation or air conditioner efficiency, for example). Some forms of *active* energy efficiency are controls-based (e.g., thermostat setbacks, clothes dryer humidity controls) but are not designed to be responsive to grid conditions. Hence, energy efficiency investments, while critical to obtaining efficiency and carbon savings, are not smart grid assets in this framework. However, this report does consider obtaining efficiency benefits as a functional objective for the use of smart grid assets.

Similarly, renewables themselves are not generally envisioned as a controllable smart grid asset.[1] The carbon-free energy they supply is critical to achieving the nation's carbon-management goals, however. One of the functions of a smart grid is the ability to manage the assets under its control to help integrate renewables, such as mitigating the need for additional costly ancillary services to manage their intermittency, and reducing costs for improved voltage control schemes and short-circuit protection.

[1] However, the power factor of the output from the inverters for renewable generators could be managed to meet the reactive power needs of the grid.

2.2 Enabling Assets

Investments in a number of *enabling assets* are also necessary to support the use of the primary assets for smart grid applications, hence the function of a smart grid. Among these cross-cutting technologies are:

- wide-area communications networks, servers, gateways, etc.
- smart meters–beyond what many consider as basic advanced metering infrastructure (AMI) technology, a more fully smart meter could also
  - support shorter metering intervals approaching 5 minutes or less to support provision of ancillary services and distribution capacity management (rather than the hourly interval generally considered adequate for peak load management at the bulk power systems level)
  - full two-way communications including to a home-area network to communicate to smart thermostats and appliances
  - instantaneously read voltage, current, and power factor to support distribution state estimation and optimized system volt-VAR control
  - offer remote connect/disconnect functionality for reliability and customer service applications
- local-area home, commercial building, and industrial energy management and control systems (EMCS) and networks
- consumer information interfaces and decision support tools
- utility back-office systems, including billing systems.

Other key technical ingredients of the smart grid that are similarly cross-cutting, but are typically embedded in assets are:

- cyber-security technologies for secure communications for all levels of operation
- an interoperability framework, and associated standards and protocols that focus on communications between the various SCADA control domains inherent in the smart grid: including the Independent System Operator/Regional Transmission Organization utility, customer, and aggregator.

2.3 Functions: Operational Objectives

Functions are the benefits or applications to which smart grid assets are engaged to improve cost effectiveness, reliability, and energy efficiency of the power system. These can be summarized in broad categories corresponding to the benefits derived:

- managing peak load capacity for generation, transmission, and distribution
- reducing costs for wholesale operations
- providing enhanced reliability/adequate reliability at less cost
- providing ancillary services

- reducing the operational costs of integrating renewables
- leveraging the network for energy efficiency and carbon savings.

The first four function categories have long been considered central elements of the smart grid and are briefly described here. The last two are the fundamental subjects of this report and are discussed in Section 3.0.

Managing peak load capacity includes displacing the need for new generation, localizing this function to displace the need for new transmission, further localizing it to manage capacity to offset the need for new and upgraded distribution substations and feeders, and managing transformer loading to extend their lifetimes. About 40% of grid infrastructure costs are for generation capacity, which must be adequate to serve peak load demand while maintaining adequate reserves for forced outages and contingencies. In light of growing demand for generation worldwide, environmental constraints on new coal generation, the imposition of renewable generation portfolios by states, and rising costs for steel, concrete, and other materials, and costs for new generation capacity to meet load growth are expected to grow substantially. Another 40% of infrastructure costs are for distribution systems, so the opportunity to manage peak load demand at the substation level is an important opportunity. Peak load management from demand response, distributed storage, and optimization of distribution delivery voltages and power factors can all serve to defer investment in generation, transmission, and distribution systems. The value stream from this is derived in terms of the avoided carrying costs for investment in new capacity.

Reducing costs for wholesale operations involves lowering the demand for generation when marginal production costs are greater than revenues from retail sales, similarly minimizing purchases or maximize production when wholesale prices are high, and reducing transmission loads when and where congestion costs are high. This can be accomplished by utilizing demand response, distributed storage, and distribution voltage controls to reduce net demand.

Enhanced reliability. A smart grid can enhance reliability in two fundamental ways. It can prevent and limit blackouts with transmission wide-area control and visualization tools that enhance situational awareness and rapidly reconfigure the transmission grid to prevent or limit a blackout. At the distribution level, where the vast bulk of outages occur in terms of aggregate customer-minutes without power, outages are typically caused by events such as vehicle accidents, wind and ice storms, and animals shorting out transformers, rather than systemic failures. To remedy these outages, distribution and feeder automation assets can be used to rapidly isolate faults and then reconfigure distribution feeders through remotely actuated switches. This shortens the recovery time for nearly all customers from an hour or more to a matter of seconds. In its ultimate form, this is a stand-alone microgrid fully capable of supply its own power and managing its local distribution.

> "Through proactive grid management and automated response, the frequency and duration of power outages can be reduced, which will result in fewer anxious calls to utility call centers and improved consumer satisfaction. Remote monitoring and control devices throughout the system can create a "self-healing" grid, which can restore and prevent outages and extend the life of substation equipment and distribution assets. Through such automation, rising consumer expectations for power quality and reliability can be met in the face of growing electricity demand and an aging infrastructure and workforce."
> Source: EAC (2008).

Ancillary services. Beyond power production, many services are provided by power plants to keep the grid in a stable and reliable condition. These include the following:

- *Regulation* is supplied on a minute-by-minute basis to control the supply/demand balance by continually throttling variable-output power plants.
- *Ramping and load following* are similarly required to manage the grid when the rate of load change is high, such as the morning and late evening.
- *Spinning and non-spinning reserve* capacity is required to manage the sudden, forced-outage loss of power plants scheduled to generate electricity on a given day.
- *Reactive power* needs to be supplied by power plants to correct phase shifts between current and voltage due to system load variance.

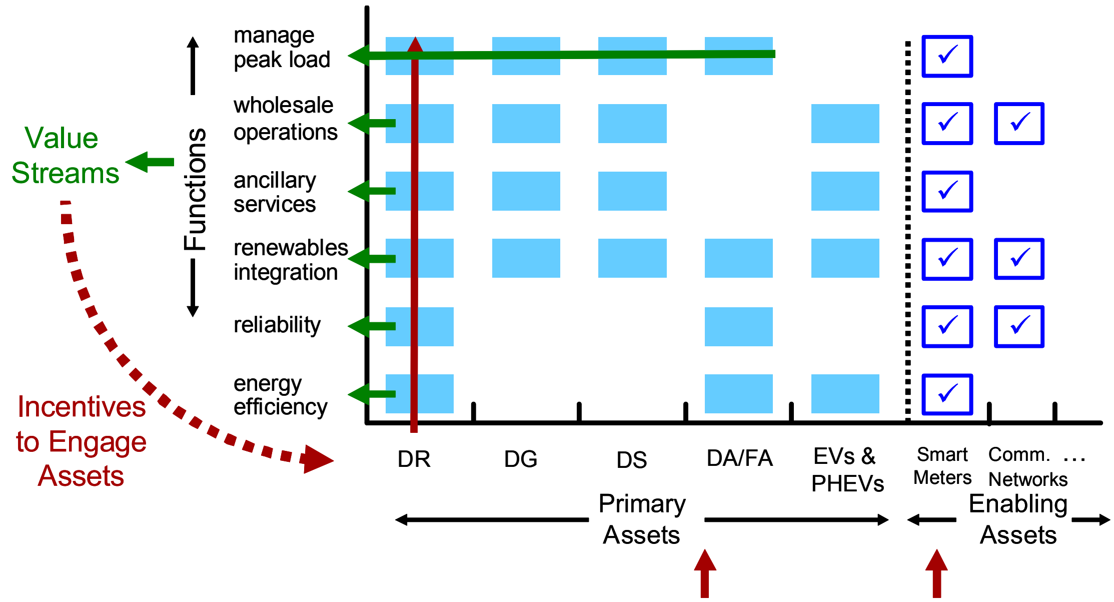
The highest cost resources in power markets that quantify such services are those for short-term regulation. Today, we turn power plants up and down continually to provide regulation, which wastes fuel and increases wear and tear on the plants. Ancillary services could be supplied by dispatching the smart grid's demand response, distributed generation, and storage assets to provide regulation and load following services, and using them in standby mode (when not otherwise engaged) to provide spinning reserves. While valuable in today's grid operations, the need for ancillary services is projected to increase as large amounts of renewable generation penetrates the grid, due to the intermittency of output from wind and solar generators.

2.4 The Business Case for a Smart Grid

The matrix of assets and functions forms a useful basis for describing the business case for the smart grid. In essence, the business case for a smart grid weighs the capital investments in an asset or set of assets against the multiple value streams that can be derived from the applications they support (Figure 2.3). The business case is successful when the sum of the value streams derived are greater than the capital investments required, less an incentive offered to engage customer or third-party assets.

It is important to note that any given asset can support a number of functions (as illustrated with demand response), and that any given function (such as managing peak load) can be supported by a variety of assets. Therefore, smart grid assets can literally work together or compete with each other (and traditional infrastructure) to provide the necessary functions. This suggests that not only must a primary asset and its enabling assets be cost effective, it must also be ***more*** cost effective that its competitors. It also suggests, as has been pointed out by many observers, that the smart grid's ultimate configuration is necessarily path-dependent, at least to a degree, with respect to the order in which assets are deployed.

The economics of the smart grid are difficult to analyze, but the business case is gradually becoming clearer and the smart grid vision is becoming a reality. Early evidence is the passage of EISA in 2007, demonstrations that showed the viability of the smart grid concept, and Xcel Energy's initiation of Boulder, Colorado's SmartGridCity (http://smartgridcity.xcelenergy.com) project in 2007. In some utilities and states, investments in AMI and demand response assets were justified to regulators and underway before the DOE infrastructure and demonstration grant programs were announced.



DR = demand response, DG = distributed generation, DS = distributed storage, DA/FA = distribution automation/feeder automation, EVs & PHEVs = electric vehicles/plug-in hybrid electric vehicles

Figure 2.3. The Business Case: Weighing the Capital Investments for Assets vs. the Value Streams from the Functions They Support

More recently, DOE released announcements to fund modernization of grid infrastructure and conduct demonstrations as part of EISA. One of the goals of the infrastructure grants is to spur mass production and deployment so that costs at scale can be determined. The goal of the demonstration grants is to build the business case by expanding the scope of smart grid functions into unproven areas, and quantifying their benefits. Commensurate with identification and quantification of the energy and environmental benefits, efforts are also underway to improve the monetization and allocation of the economic benefits to stakeholders.

The literature describing the smart grid concept, operation, and benefits is growing. A number of documents that provide the reader a more detailed discussion of the concept and the multi-faceted benefits are:

- DOE. 2008. *The Smart Grid: An Introduction*
- Electric Advisory Committee. 2008. *Smart Grid: Enabler of the New Energy Economy*
- Pacific Northwest National Laboratory. 2007. *Pacific Northwest GridWise™ Testbed Demonstration Projects, Part I*. Olympic Peninsula Project
- EPRI. 2008. *The Green Grid: Energy Savings and Carbon Emissions Reductions Enabled by a Smart Grid*. Electric Power Research Institute, Palo Alto, California: 2008. 1016905.

This report does not attempt to monetize and include the energy and carbon-management benefits into the business case to help justify a smart grid. Rather, smart grid deployment will be justified on operational merits in its early stages, and the additional benefits treated here provide an enhancement to this value at little or no additional cost. The associated marginal costs are expected to be low, because these enhancements are primarily in the form of software applications or control algorithms, while the primary costs of smart grid are for the purchase and deployment of the assets involved. If the business case for a smart grid is ***not*** made without including the additional energy and carbon benefits, then the additional value provided by the carbon benefits can be included as the uncertainties of these benefits becomes better understood.

The goal of this report is to translate these additional benefits into reductions in energy consumption and CO_2 emissions that will accrue to customers, utilities, and society. This report and the three others reviewed provide a first-order assessment of these potential benefits from deployment of smart grid technologies. Improved understanding of these benefits will require a more significant effort to account for the displacement of generating resources by renewables, among other issues.

3.0 Mechanism Methodology and Summaries

Nine mechanisms, as shown in Table 3.1, by which a smart grid can help reduce energy consumption and carbon emissions are described in this report. Two types of impacts are analyzed: 1) ***direct reductions***, in which smart grid functions produce savings in energy and/or emissions consumed at the end-use or by reducing generation requirements, and 2) ***indirect reductions*** in which smart grid functions produce cost savings, which are subsequently reinvested in energy efficiency and/or renewable resources. As discussed earlier, no attempt has been made to quantify impacts on consumer electric bills, utility revenue requirements, or other economic considerations that are considered the fundamental benefits of a smart grid.

Indirect mechanisms do not result in energy and emission savings in and of themselves. Rather, they reduce capital and/or operational costs that can then be reinvested in the deployment of energy efficiency programs or of renewables to provide reductions. To estimate the potential value of indirect reductions and place them in context with the direct reduction estimates, we estimate the savings that would ensue from reinvesting the cost savings in the purchase of additional cost-effective energy efficiency at an average electricity cost of 8.8¢/kWh. In effect, this represents a policy decision to reinvest the savings in the purchase of additional efficiency and renewable resources.

An alternative policy decision is to "pocket" these capital and operational cost savings, in effect using them to reduce the societal cost of obtaining reductions from energy efficiency and renewables that would have been purchased anyway. One view of the consequences of such policy is that no indirect benefits would be realized. Another view is that additional deployment of such resources would naturally occur because they are effectively cheaper, and the potential indirect reductions are a way to estimate this effect. Hence, the potential value of indirect reductions is subjective and left to the reader.

Table 3.2 provides an overview of the estimated potential of a smart grid to reduce energy consumption and CO_2 emissions from the nine mechanisms examined. Each mechanism was assigned to a subject matter expert, who conducted a review of the applicable literature. The potential impacts are primarily based on the results found in the literature and the judgment of the authors regarding key assumptions, as documented in Attachments 1 and 2. Table 3.2 first lists the potential direct reductions, and then the potential indirect reductions, for each mechanism. The second column is the estimated potential to reduce the annual electricity supply in 2030 ***for a specific subsector*** of the United States (columns five and six). The third and fourth columns provide low and high ranges for the estimate. The fuel consumption of light-duty vehicles (LDVs) (for Mechanism F) has been converted to its electricity equivalent so it can be viewed on an equivalent basis with the other mechanisms. No rigorous attempt has been made to analyze the uncertainty associated with each mechanism, because the methodology used is not tailored to provide such specific estimates. Instead, likely ranges of uncertainty are provided based on the judgment of the authors, in light of the range of results found in the literature and uncertainties in key assumptions.

Table 3.1. Smart Grid Mechanisms and Impacts Analyzed

Category of Smart Grid Function	Mechanism	Type of Impact Analyzed	
		Direct Reduction of Energy and CO_2 Emissions	Indirect Reduction of Energy and CO_2 Emissions
Energy Efficiency	A. Conservation Effect of Consumer Information and Feedback Systems	Conservation Effect of Consumer Feedback Based on AMI and Demand Response Controls	--
Energy Efficiency	B. Joint Marketing of Energy Efficiency and Demand Response Programs	--	Energy efficiency program cost savings from shared marketing and outreach expenses
Energy Efficiency	C. Deployment of Diagnostics in Residential and Small/ Medium Commercial Buildings	Efficiency savings from equipment performance diagnostics for heating, ventilating, and air conditioning (HVAC), and lighting	--
Energy Efficiency	D. Measurement & verification (M&V) for Energy Efficiency Programs	Efficiency from marginal energy efficiency measures that are cost effective based on more accurate M&V	Reduced costs for M&V of savings from energy efficiency programs
Energy Efficiency	E. Shifting Load to More Efficient Generation	Reduced fuel and emissions resulting from load shifting to more energy-efficient power plants using demand response and distributed storage	--
Energy Efficiency	F. Support Additional EVs and PHEVs	Reduced fuel and emissions from the additional electric-powered LDVs enabled by smart charging	--
Energy Efficiency	G. Conservation Voltage Reduction and Advanced Voltage Control	Reduced distribution losses and end-use energy consumption from optimizing distribution voltage	--
Renewables Integration	H. Support Penetration of Solar Generation (renewable portfolio standard [RPS] > 20%)	Distribution-level solar generation enabled by using advanced voltage controls and feeder automation to manage reverse power flow	--
Renewables Integration	I. Support Penetration of Renewable Wind Generation (20% RPS)	Reduced energy consumption by using demand response and distributed storage instead of power plants to supply regulation services	Reduced costs for additional generation capacity by using demand response and distributed storage instead of power plants to meet reserve requirements

Table 3.2. Potential Energy Consumption and Carbon Emissions Reductions from Smart Grid Deployment

	Reduced Energy Consumption (2030)					Electric Sector Annual Reductions (2030)			
				Baseline Electricity Consumption		Energy		Carbon Emissions	
Direct Reduction Mechanism	Est. %	Low %	High %	End-Use Sector(s)	(10^9 kWh/year)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ yearr)
A. Conservation Effect of Consumer Information and Feedback Systems	6	1	10	Residential	1722	3	155	3	92
	6	1	10	Small/Medium Commercial Buildings	854				
C. Enabling Mass Deployment of Diagnostics in Residential and Small/Medium Commercial Buildings	15	10	20	Residential (Heat Pump & Air Conditioner)	331	3	152	3	90
	20	10	30	Small/Medium Commercial Buildings (HVAC + Lighting)	510				
D. Measurement and Verification for Efficiency Programs: *Marginal Efficiency Measures Enabled by Acurate M&V*	7	5	20	Residential (Heat Pump & Air Conditioner)	331	1	59	1	35
	7	5	20	Small/Medium Commercial Buildings (HVAC + Lighting)	510				
E. Shifting Load to More Efficient Generation	0.04	0.02	0.06	Total Electric Supply	4968	0.04	2	0.03	1
F. Support Additional Electric Vehicles (EVs) / Plug-In Hybrid Electric Vehicles (PHEVs)	3	2	5	Electricity Equivalent of Light Vehicle Transportation (cars, vans, SUVs, light trucks)	5135	3	139	3	82
G. Conservation Voltage Reduction and Advanced Voltage Control	2	1	4	Total Electric Supply	4968	2	99	2	59
H. Support Penetration of Solar Generation: *Reduced Energy for Regulation (25% RPS)*	Note: Estimates for extra regulation required by solar generation are not available, but may be similar to that for wind. Therefore the savings for meeting a 20% RPS, all or in part with solar, are already included in the estimates for wind generation (Mechanism I)								
I. Support Penetration of Wind Generation: *Reduced Energy for Regulation (25% RPS)*	20	10	30	Fuel Savings for 0.1% Additional Regulation Requirement	5	0.02	1	0.02	1
Total, Direct Reductions									
without additional EVs/PHEVs						**9**	**467**	**9**	**277**
including support for additional EVs/PHEVs						**12**	**606**	**12**	**359**

Table 3.2. (contd)

Indirect Redcution Mechanism (Reinvestment of Capital Savings in Efficiency/Renewables)	Avoided Expenditure Reinvested to Save Carbon (2030): Est. %	Low %	High %	Baseline Captial Expenditure: Investment	Baseline Captial Expenditure: (10^9 $)	Savings (10^9 $)	Electric Sector Annual Reductions (2030): Energy: % of United States	Energy: (10^9 kWh/ year)	Carbon Emissions: % of United States	Carbon Emissions: (MMT/ year)
B. Joint Marketing of Efficiency and Demand Response Programs	0	0	1	10% Demand Response, Residential @ $400/kW & 8.8¢/kWh	15	0.0	0	0	0	0
	0	0	1	10% Demand Response, Small/Medium Commercial Buildings @ $300/kW & 8.8¢/kWh	6	0.0				
D. Measurement and Verification for Efficiency Programs: M&V Cost Savings for Energy Efficiency Programs	1	0	2	10% Energy Efficiency, Residential @ 8.8¢/kWh,10-Year Life	152	1.5	0.5	26	0.5	15
	1	0	2	10% Energy Efficiency, Small/Medium Commercial Buildings @ 8.8¢/kWh,10-Year Life	75	0.8				
H. Support Penetration of Solar Generation: *Distribution Voltage Controls for RPS > ~20%*	Note: Voltage control for distribution systems with solar generation above ~20% RPS becomes problematic due to reverse flow of power toward the substation. Comparative costs for voltage management alternatives are not available.									
I. Support Penetration of Wind Generation: *Reduced Reserve Capacity (25% RPS)*	2	1	3	1111 GW Total Generation Capacity @ $1000/kW	1111	22	5	253	5	150
Total, Indirect Reductions							**6**	**278**	**6**	**165**
Total, Direct and Indrect Reductions without additional EVs/PHEVs							**15**	**746**	**15**	**442**
including support for additional EVs/PHEVs							**18**	**884**	**18**	**525**

The final four columns show the corresponding potential to reduce the energy consumption and the CO_2 emissions of the ***entire electricity sector***. Columns eight and ten provide the absolute reductions and columns seven and nine provide the reductions as percentages for energy and CO_2 emissions, respectively. That is, the absolute potential reduction divided by U.S. electricity sector total generation and CO_2 emissions in 2030. This facilitates direct comparison of the magnitude of the reductions with the RPS that require certain fractions of electricity to be supplied by renewable generation (and, in some states, energy efficiency) in a decade or two.

The estimates assume deployment of smart grid technologies in 100% of utility service territories in the United States. To a first order, the estimates provided can be scaled downward linearly to reflect estimate impacts for less than 100% deployment, in proportion to the percentage of the U.S. population served by a smart grid.

Each mechanism is generally described with its estimated reduction in energy consumption and CO_2 emissions in the discussion that follows. The full results of the literature review and analysis of each of the nine mechanisms is contained in Attachment 1, and the details of the calculation of the estimated reductions are contained in Attachment 2.

As might be expected, there is considerable variation in the potential of the mechanisms to reduce energy consumption and CO_2 emissions. A primary purpose of this investigation is to provide some guidance as to which mechanisms are most important. Some mechanisms were estimated to have a negligible effect; in one case, no firm evidence could be identified to justify an estimate greater than zero. While none of the direct mechanisms is more than 3% individually, they combine to form a significant contribution toward the nation's carbon management goals for its electricity sector. The total direct reduction of 12% includes an estimated reduction of 3% from eventually supplying an additional 9% of vehicle-miles traveled (VMTs) with electricity. The indirect reductions provide an additional 6%, primarily from reinvesting savings from the operational costs of integrating a portfolio of 25% renewable generation. This is based on the cost of capacity to meet the intermittency characteristic of wind resources. The combined potential of the mechanisms (18%) is substantial.

It must be noted that the range of uncertainties is high, often 50% or more of any given estimate. This is not unexpected given the exploratory nature of this analysis and the early stage of development of a smart grid. Narrowing the range of this uncertainty and refining the estimates is the focus of many of the recommendations for follow-on analysis, and is particularly important for the mechanisms that offer the most significant potential. While any given mechanism has some likelihood of providing little or no savings, the probability that this would be true for all the mechanisms is much less, in light of the wide variety of how the savings are achieved. A smart grid, although not the central means of providing the savings that energy efficiency and renewables represent, nevertheless appears to have a significant role in enhancing those savings and achieving them at less cost.

3.1 The Smart Grid and Energy Efficiency

Utilities increasingly consider energy efficiency as a "fifth fuel" because of concern about the implications of a carbon-constrained world for their business and their obligation to serve customer demand. One driver is that many utilities are having difficulty gaining approval for new base-load generation (generally coal-fired power plants) from state regulators because of projected carbon restrictions. Among many recent examples is Duke Power's commitment to purchase carbon offsets to cover the difference in carbon emissions from its proposed new coal-fired power plant as compared to a cleaner combined-cycle natural gas turbine and also retire two older dirty coal-fired power plants. This increases the attractiveness of energy efficiency, because natural gas tends to be more expensive than coal and increasingly relies on imports with consequent price volatility.

A second driver is that many states have passed or are considering passage of an RPS that sets a minimum requirement for renewable generation and, in many cases, includes energy efficiency as a means of meeting the RPS or as a separate requirement. A third driver is the probability that national cap-and-trade legislation for carbon emissions will be passed, which in effect raises electricity prices and hence makes efficiency more attractive. It may also be accompanied by a national RPS. A fourth driver is that state regulators are advancing policies to remove utility and customer disincentives to greater penetrations of energy efficiency. Related to these drivers is a growing recognition of the need to address key barriers to obtaining the large potential of the energy efficiency resource (EPA 2008; EPRI 2009; McKinsey & Company 2009).

If the increased role of renewables and energy efficiency comes to pass, as seems increasingly likely, then the United States will need to make drastic changes in everything from its vehicles, buildings, and the way in which it generates electric power. One way to think about how this will affect utilities is introduced in Figure 3.1, which shows a well-known carbon supply curve (McKinsey & Company 2007). It shows the technical potentials of various carbon reduction technologies in the United States (the width of each bar) against their equivalent cost per ton of avoided CO_2 (the height of each bar), ordered from the lowest to the highest cost.

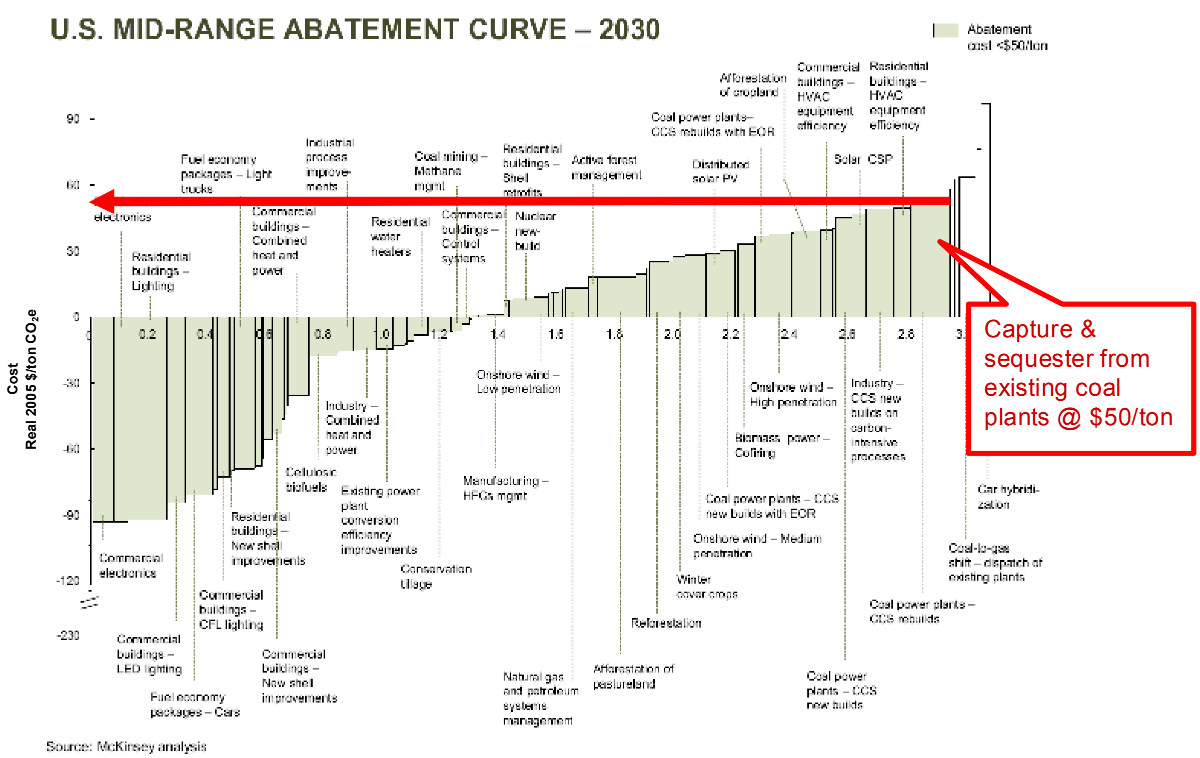


Figure 3.1. Carbon Cost Abatement Curve. Source: McKinsey & Company (2007)

It is striking to note that nearly one half the CO_2 reductions, mostly from efficiency measures, could be achieved at ***negative*** cost. That is, the energy savings ***alone*** more than pay for the cost of the efficiency measure over its lifetime. This illustrates one of the key barriers: energy efficiency investments, largely left to the consumer, lags considerably below those that are cost effective. In economic terms, consumers apparently discount efficiency investments or, equivalently, have very short payback requirements.

If carbon capture and sequestration from coal-fired power plants becomes a viable option in the future, it has been suggested that it may cost approximately \$50/ton CO_2. Assuming there is no shortage and ready access to sequestration sites, this may become the "limiting option" and effectively places a cap on carbon prices. This translates to a doubling of wholesale power costs from coal (currently approximately 5¢/kWh), which would render all the carbon reduction measures in Figure 3.1 to the left of carbon sequestration (the shaded "bars") as cost effective.

This suggests that massive energy efficiency and renewables programs are likely in the future, at a scale beyond what was generally imagined just a few years ago. Utilities have both the motive and the means to deploy energy efficiency on a massive scale, because they have good access to capital at more attractive rates than consumers, and are in the business of making large infrastructure investments that earn steady, but modest long-term rates of return. That they can gain carbon credits and meet RPS requirements through energy efficiency investments further increases their motivation. Properly incentivized, accelerated deployment of utility-funded energy efficiency programs could have a major role in reducing CO_2 emissions.

It is against this backdrop that we examine the role of a smart grid. Although none of the cost-effective carbon reductions from improved energy efficiency in Figure 3.1 explicitly ***require*** a smart grid, a smart grid may facilitate deployment of efficiency measures. This is particularly true for some of those in the middle and second half of the curve that are marginally cost effective today or will require a price on carbon to become cost effective. Several of these are the subject of subsequent discussions of the mechanisms in this report. The following subsections summarize the mechanisms that relate to energy efficiency.

3.1.1 Conservation Effect of Consumer Information and Feedback Systems

Many demand response projects have reported some customer energy savings, typically a few percentage points, in addition to their primary objective of reducing peak loads. While some energy savings can be attributed to physical effects of reducing load during peak load times, the primary basis for the savings is likely to be the effect of feedback provided to consumers on their usage patterns as part of these programs. This mechanism is summarized here, with detail on the literature review and conclusions provided in Attachment 1.

It is worth noting that demand response is fundamentally a curtailment behavior, and so has more in common with energy ***conservation*** than energy ***efficiency***. Although sometimes used to indicate both, energy efficiency more properly describes obtaining the same service or amenity from a device for less energy input (i.e., a more efficient lighting source or air conditioner), whereas energy conservation means doing without the device's service or amenity. In this respect demand response and conservation are similar, although they occur over different time scales. Demand response for managing peak loads involves, at most, 100 or so hours a year, and seldom more than a few consecutive hours. Demand response used to provide ancillary services involves time periods of a few minutes. Any associated loss of amenity is occasional and short term, and in some cases negligible. When the objective is to save energy, conservation must affect a large fraction of the hours the device is used, and the loss of amenity is more or less continual.

Demand response itself can reduce energy consumption because controlling an end-use to lower peak load demand shifts the load to other times, or in some cases actually eliminates some consumption. A prime example of the latter is lighting—dimming lights on peak load also saves energy. Other mechanisms are more subtle, second-order effects. For example, deferring air-conditioning loads until later in the evening allows the air conditioner to run when it is cooler outside, hence, when it operates more efficiently. Counteracting this effect, control strategies that pre-heat or pre-cool in advance of peak load demand periods can result in slightly higher overall energy use. Controls that cycle water heaters off effectively reduce the water temperature somewhat, and can produce substantial savings if hot water is used during those times.[1]

Most of the large end uses, aside from lighting and electronics, are fundamentally controlled by a thermostat (heating, air conditioning, water heating, refrigeration, and drying). So, to a first order, deferring energy input into a device simply results in an equal amount of energy input later to heat the device back up or cool it back down to its original temperature. It is this eventual restoration of service that distinguishes demand response from conservation, and the reason the latter can produce large energy savings when the former typically does not.

Although there may be some physical explanation for the energy savings reported by demand response programs, we believe the primary contribution comes from heightened awareness of energy use on the part of the participants. This awareness can come simply from the decision to participate, but demand response programs usually offer formal feedback mechanisms to the consumer, based on the AMI interval consumption data that shows patterns of usage over the day and week. In some cases, these feedback mechanisms are supplemented by web-based portals or in-home displays that deliver the information and may include a breakdown of consumption by end use.

The focus of our analysis of this mechanism is to determine the potential benefits of leveraging these smart grid assets to provide detailed and timely energy feedback and a variety of usage information. Fundamentally, the objective of feedback is to overcome the issue of ***energy invisibility***, which refers to the gradual de-coupling of overt human behavior from energy use, reflected by the historical transition from chopping wood for fuel, to shoveling coal for a furnace, to gas and electric power delivered seamlessly and automatically on demand.

To do this, we examined the results from a wide range of studies of feedback mechanisms on consumers (primarily residential). The studies reviewed provide convincing evidence that consumers will

[1] Peak load demand reductions can be obtained from either energy efficiency or conservation measures. The peak load reductions are larger for measures that reduce consumption for an end use that tends to be higher during peak load periods (hot summer days in most of the United States), like air conditioning and commercial lighting. Thus, energy efficiency and conservation can make a valuable contribution to the same objective (managing peak load demand) and, hence, compete with smart grid assets like demand response. Unlike peak load demand, however, they have a significant negative impact on utility revenues and may require regulatory action to motivate utilities to make increased use of them. They do not require the communications or the coordinated control that characterize smart grid assets, so the peak load effect of energy efficiency and conservation is not a subject of this analysis.

change their energy consumption behavior in response to feedback, and that the conditions surrounding feedback, such as frequency and specificity, are influential variables. This implies that a smart grid/metering system may yield considerable savings in terms of end-use conservation, with a basic goal of time-of-use load shifting. Feedback tends to be most effective when it:

- is based on actual usage data
- is provided on a frequent basis (daily is better than weekly, etc.)
- involves goal setting and choice
- is provided over a year or more
- involves specific behavioral recommendations regarding appliances
- involves normative or historical comparisons.

Fischer (2008) contends that these items favor the smart grid capabilities offered by AMI and two-way communication networks, which provide an effective way of engaging the consumer and providing tailored feedback.

The energy-use reductions achieved from a range of projects examined by Fischer (2008) range from 5% to 20%, with a median of approximately 6%. Similar results have been observed in utility field studies reviewed by Faruqui et al. (2009). We have adopted this estimate of the potential. The key issue surrounding these results is whether they are sustainable over a time period of years and decades. Given that consumers generally volunteer for such studies, there may be some built-in bias up front. More importantly, does the consumer continue to seek out feedback, or internalize it and translate that into permanent changes in behavior?

To be conservative, we have shifted the range of uncertainty lower, to a low of 1% and a high of 10%. We assume that, with respect to the contribution of a smart grid, a direct reduction of 6% in electricity consumption only for the residential and small/medium commercial building sectors. At a minimum, such a feedback mechanism requires an interval meter that is fundamental to a smart grid. Large commercial buildings and industrial customers generally already have such meters, and consume enough energy to install relatively sophisticated feedback systems and pay a staff member to monitor energy use, so it is difficult to assert that a smart grid is essential to achieving similar savings in this customer class.

Quite substantial potential reductions of 3% in electricity consumption and associated CO_2 emissions are estimated in Table 3.3, with the calculations documented in Attachment 2. No indirect reductions from capital or cost savings are expected.

Table 3.3. Estimated Direct Impacts of the Conservation Effect of Consumer Information and Feedback Systems

Reduced Energy Consumption (2030)					Electric Sector Annual Reductions (2030)			
			Baseline Electricity Consumption		Energy		Carbon Emissions	
Est. %	Low %	High %	End-Use Sector(s)	(10^9 kWh/year)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ yearr)
6	1	10	Residential	1722	3	155	3	92
6	1	10	Small/Medium Commercial Buildings	854				

Two-way communications like that provided by a smart grid AMI network is also required if the feedback information is centrally processed and delivered in near real time; billing inserts do not provide the timelines or frequency characteristic of effective feedback. Whether a web-based billing information portal is sufficiently engaging over the long run remains to be proven. The expense of a dedicated home energy display would not be required if the information can be effectively delivered using the internet. Google is already offering such a capability on their user-specific home page, when granted access to the data from the meter.

Currently existing software tools can estimate a customer's appliance and equipment usage based on population average values and offering generic guidance on saving energy. More specific and effective feedback and advice can be provided to the consumer if the demand response control (e.g., a thermostat) is used to provide on/off status information for the device it controls. Even in a fully deployed smart grid, we do not anticipate that virtually every customer will participate in demand response programs. However, we do anticipate that, participation in smart grid deployments by 2030 will be high enough that smart thermostats and smart appliances will be widespread, and they can provide the basis for end-use breakdowns.

The breakdown process can be conducted either centrally at the utility, or within the home or business. The advantage of the latter is that it strictly maintains the privacy of the customer. The disadvantages are that it requires additional processing power and software installation in a home or building energy-management system and it cannot offer comparisons with the energy consumption of peer groups.

3.1.2 Joint Marketing of Energy Efficiency and Demand Response Programs

Joint marketing of energy efficiency and demand response programs would provide customers a unified vision that connects utility programs and education materials. This mechanism would capture the synergy between energy efficiency and demand response programs, saving costs in administering, advertising, educating, and recruiting, to make each more cost effective and impactful. The coordination would also enable the most cost- and/or CO_2-effective solution to be implemented by consumers. This mechanism is summarized here, with detail on the literature review and conclusions provided in Attachment 1.

Electricity customers want to be presented with a unified vision of how they can change their electricity consumption to save money and help the environment, without the technical terminology that asks them to distinguish between energy efficiency and demand response programs. This strongly suggests that consumers should be provided "one-stop shopping" when connecting to utility programs and consumer education materials. The strong synergy between energy efficiency and demand response programs can also be exploited to save advertising, educating, recruiting, measurement, and evaluation costs. In addition, energy efficiency measures generally also produce peak load reductions and associated costs, which should be accounted and incentivized as peak load savings.

This indirect mechanism would combine the administration of energy efficiency and demand response[1] programs to achieve cost savings that could be reinvested in efficiency programs. However, the literature review and contact with experts in the energy efficiency and demand response fields did not reveal any program data or information that could be used to estimate administrative cost reductions or increases in program effectiveness. Based on this finding, indirect reductions in electricity and associated CO_2 emissions shown in Table 3.4 and calculated in Attachment 2 are estimated to be zero, as no basis could be estimated for determining administrative cost reductions or increases in program effectiveness that might ensue. No direct reductions are expected.

Table 3.4. Estimated Indirect Impacts of Jointly Marketing Energy Efficiency and Demand Response Programs

Avoided Expenditure Reinvested to Save Carbon (2030)						Electric Sector Annual Reductions (2030)			
			Baseline Captial Expenditure			Energy		Carbon Emissions	
Est. %	Low %	High %	Investment	(10^9 $)	Savings (10^9 $)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ year)
0	0	1	10% Demand Response, Residential @ $400/kW & 8.8¢/kWh	15	0.0	0	0	0	0
0	0	1	10% Demand Response, Small/Medium Commercial Buildings @ $300/kW & 8.8¢/kWh	6	0.0				

However, to place the potential of this mechanisms in perspective, if combining the marketing and outreach of energy efficiency and demand response programs resulted in a 1% savings in program operating costs and the savings were re-invested in energy efficiency, a reduction in electricity supply of 3 B kWh (0.05%) and associated CO_2 emissions of 1.4 MMT (0.04%) might be expected. This is based on the combined potential for the residential and small/medium commercial building sectors. Because of the complexity of energy-using systems in large commercial and industrial customers, we anticipate that both energy efficiency and demand response programs will need to be delivered with a customer-specific focus in which a smart grid may play only a small role.

Further investigation of the potential for jointly marketing energy efficiency and demand response programs is suggested.

3.1.3 Key Enabling Technology: Disaggregation of Total Loads into End Uses

This section describes how the measurement and communication capabilities of a smart grid can be leveraged to provide unprecedented detail on customer end-use consumption. While the ability to disaggregate loads does not provide direct or indirect reductions, it forms the technical basis for providing remote diagnostics for HVAC loads via a smart grid, as discussed in Section 3.1.4 (Mechanism C), and for improved M&V of energy savings from efficiency measures, as described in Section 3.1.5

[1] Demand response is most closely associated with curtailment behavior, as distinct from energy efficiency measures and behavior. While often achieving similar goals, demand response is principally designed to reduce peak/critical loads through load shifting and may not provide direct reduction in energy use, whereas energy efficiency is designed to reduce overall energy consumption and provide long-term savings. Both are intended to provide monetary savings to consumers, but energy efficiency provides virtually no change in consumer comfort and usability, whereas demand response may have a short-term impact on consumer comfort and/or service.

(Mechanism D). It can also be used to "mine" for customer-specific energy efficiency and demand response opportunities that have been overlooked, and as the basis for enhancing feedback to consumers on their individual appliances and end uses, as discussed in Section 3.1.1 (Mechanism A). Thus, the addition of relatively straightforward automated analytic processes coupled with smart grid measurement and communication capabilities forms a key enabler for obtaining energy and carbon benefits.

The following four figures help show the improved end-use resolution that could be provided by smart grid technology. Figure 3.2 shows the monthly energy consumption profile for a residence from data obtained by a standard utility meter. The home is located in a hot desert climate with high summer peak load demand due to dozens of days in which the outside temperature exceeds 100ºF. With a monthly resolution, the energy consumption is actually at its ***lowest*** in the summer, making it impossible to discern much about the end-use consumption of the home without the use of an engineering model and a lot of assumptions that introduce considerable uncertainty.

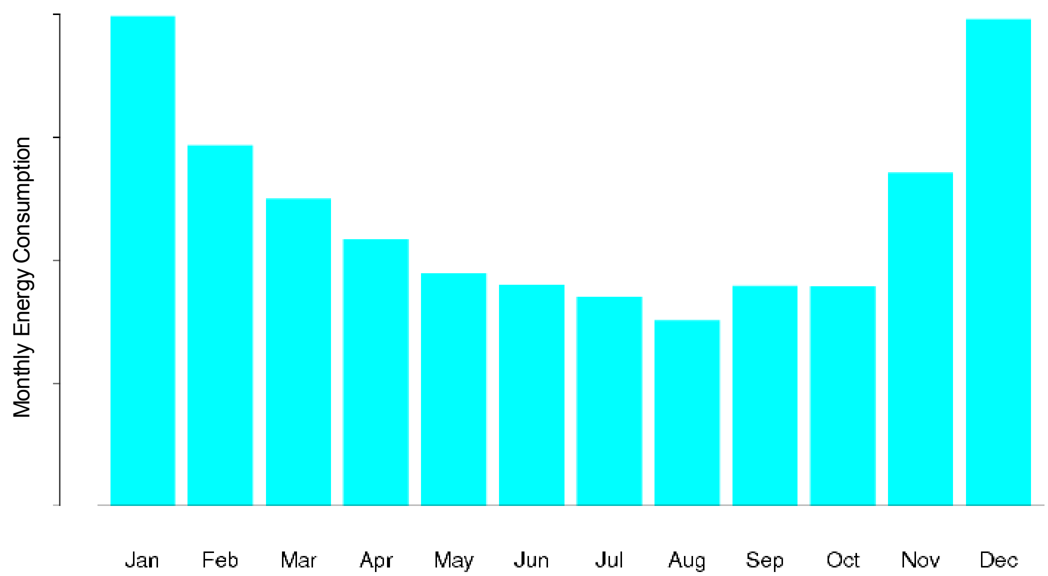


Figure 3.2. Monthly Energy Bills from Typical Home in a Hot Desert Climate

Figure 3.3 shows a profile of the same monthly energy bills plotted against the average monthly temperature. This is the technical basis for a well-known standard technique for analyzing monthly billing data, originally called the Princeton Scorekeeping Method (PRISM; Fels and Reynolds 1993). The PRISM method attempts to find the best statistical fit for three lines describing the heating, cooling, and base load (all other loads) for a building. The base load is estimated from the minimum monthly bills, assuming that it is relatively constant. Thus, the estimate of the base load is a horizontal line, as shown in Figure 3.3.

When the home is heated by electricity, the monthly load is expected to increase as the outdoor temperature decreases. The physics of heat flow suggests this relationship is linear with temperature, although when aggregated to the monthly level, there tends to be somewhat of an upward bend to this curve. The deviations in the monthly winter consumption data from the linear assumption in Figure 3.3 are illustrative of this effect. If the heating is provided by a heat pump, this curvature is greatly exaggerated, because it is much less efficient at supplying heat when it is colder. The scarcity of the monthly data and the effect of the curvature make it difficult to fit these lines with a high degree of confidence.

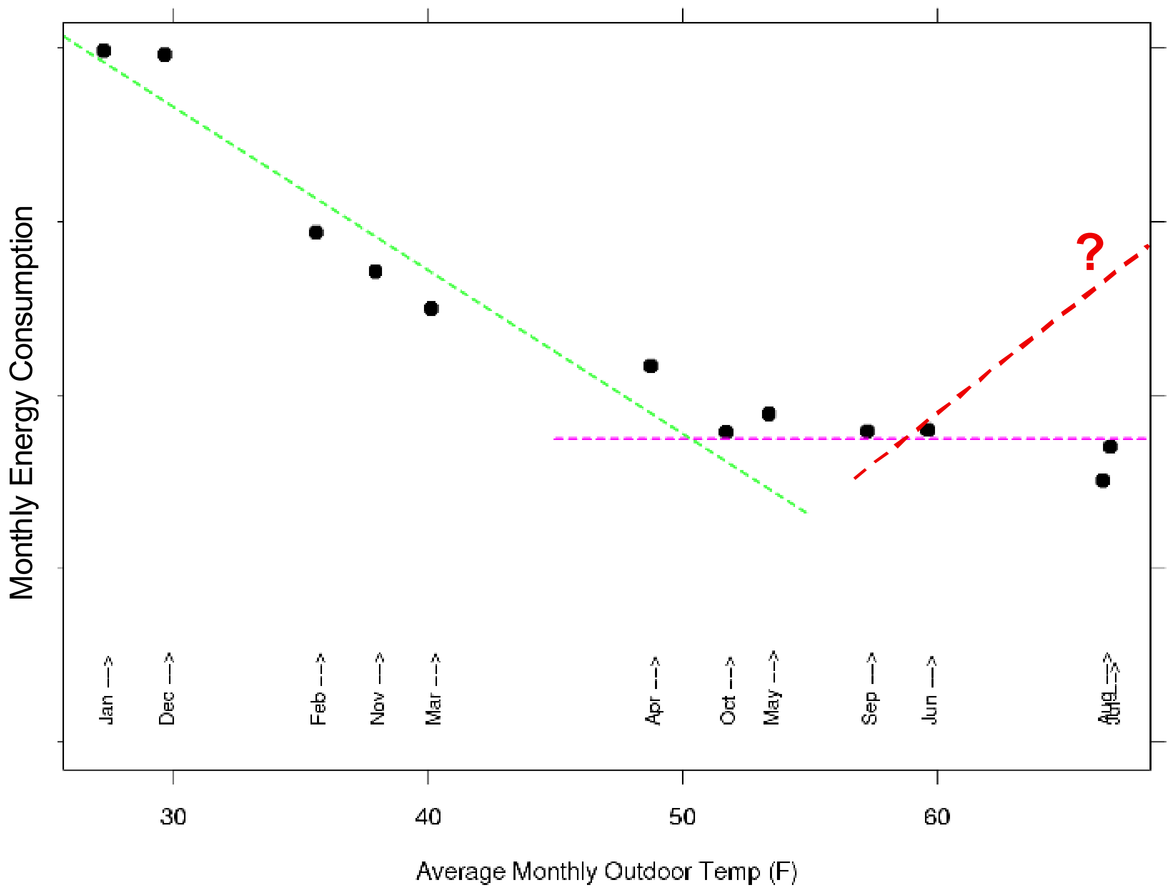


Figure 3.3. Monthly Energy Bills from Typical Home vs. Monthly Average Temperature

Trying to estimate the air-conditioning loads in this home using monthly data is impossible. The relationship between consumption and temperature in the summertime is non-existent and estimating the end-use consumption is highly uncertain, particularly the expected air-conditioning load. It is not unreasonable to make the interpretation that there is no air-conditioning load in this home—in fact, this is far from the case.

PRISM-type methods were developed for the purpose of energy efficiency program evaluations involving hundreds or thousands of buildings, rather than providing building-specific analyses. Despite their limitations, they are suitable for this purpose as long as any errors introduced by the limitations of the method are random from one building to the next. They are considerably less well suited to detailed analysis of individual buildings, as illustrated here.

Figure 3.4 shows the increased information content that can be provided by leveraging smart grid assets. First, thousands of hourly intervals of consumption from a smart meter provide a much stronger statistical basis for fitting a line or a curve to the data. Second, examining the results separately for each hour of the day provides much additional clarity. Third, with the additional use of the on/off signal that could be provided by a smart thermostat, the total consumption provided by a smart meter can be disaggregated into subtotals for heating, cooling, and "other" base loads with reasonable precision.

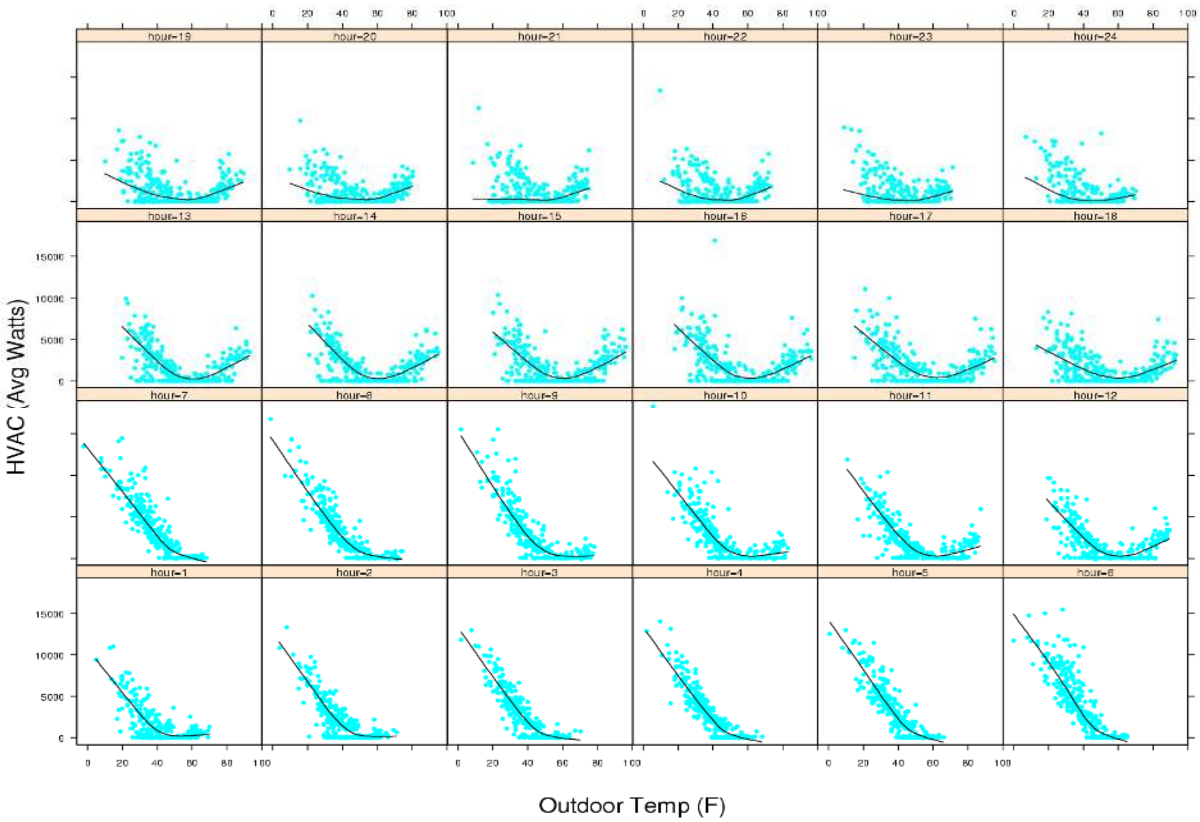


Figure 3.4. Hourly Load Data vs. Temperature, One Plot for Each Hour

This process is entirely analogous to what has been termed *non-intrusive load monitoring* (NILM; Drenker and Kader 1999). NILM uses short interval readings from a meter and uses a cluster analysis to look for common changes in the level of power consumption. These can then be mapped to a specific major appliance, e.g., a space heater, air conditioner, or water heater, either by 1) rules of thumb, if the consumption level is relatively standard, as for water heaters, or 2) manually activating major appliances and denoting the cluster into which the resulting load is mapped.

The same basic process can be applied to a smart-grid-based system by using the on/off status signal from the thermostat instead of the cluster analysis. This provides an unequivocal signal with which to flag on/off events. More importantly, for mass deployments in which the process must be completely automated, it inherently associates the changed consumption level to a specific appliance or load, eliminating the need for the manual tests. Integrating the resulting on/off events and power levels over time produces a good breakdown of the end-use composition of the total load collected by a smart meter.

Figure 3.4 provides separate plots of the HVAC energy consumption for each hour of the day as a function of the outside temperature for that hour. The air-conditioning load becomes readily apparent with this more granular data. In hours 1 a.m. through 10 a.m. (hours 1 through 10), there is no apparent cooling load. From 11 a.m. through 10 p.m. (hours 11 through 22), the right side of the distribution increases markedly, showing the air-conditioning load with increased clarity.

As a final step, models can be fit to each of the disaggregated end-use subtotals. Figure 3.5 shows non-linear, non-parametric fits (a lowess curve) for each of three end-use load subtotals for hour 15 (3 p.m.). These are stacked, i.e., the top curve represents the total load. The end-use load is the distance between the curves (or the x-axis).

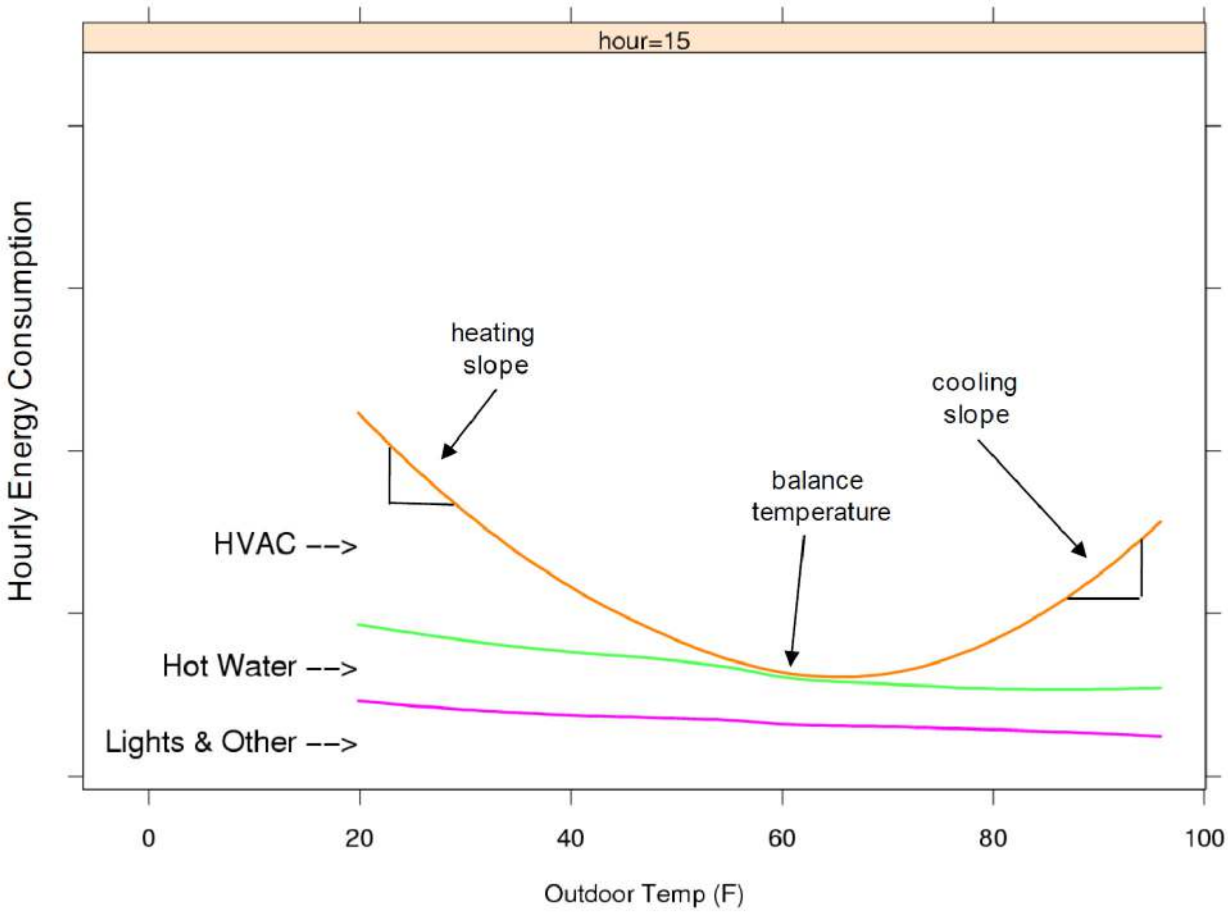


Figure 3.5. Non-Linear Models of Three End-Use Load Subtotals for Hour 15 (3 p.m.)

Such models provide several additional types of information. First, the subtotals themselves form a much finer end-use resolution with which to spot changes in consumption for smaller appliances and loads from lights and electronics. Second, it should be noted that the consumption for water heating and for lighting plus "other" loads (the rest of the appliances in the home) are not constant throughout the year, but instead have a pronounced linear trend increasing with colder outside temperatures and winter months. This is typical of U.S. residences that have been metered at the end-use level, in which virtually all non-HVAC end uses increase 10% to 20% or more from summer to winter, on average (Pratt et al. 1993). Thus, the assumption of PRISM-like methods−that the base load is a constant−tends to overstate heating and understate cooling loads.

Finally, the shape of the HVAC model provides important clues about the home's thermal performance upon which to base further analysis. The balance temperature—the outside temperature at which the home needs neither heating or cooling because of heat gains from appliances and the sun–is noted as approximately 60ºF. Thermal physics suggest the balance temperature is the ratio of these heat gains to the envelope heat coefficient (the heat loss per degree F indoor-outside temperature difference). The slope of the heating and cooling parts of the curve indicate the ratio of the heat loss coefficient and the heating or cooling system efficiency, respectively.

The information that can be derived from a smart grid's infrastructure can provide deeper and much more valuable insights into the performance of individual buildings and populations of customers than simple analysis of monthly bills. With the advent of AMI, near-real-time communication systems, and the advanced data management and demand response control strategies, a smart grid may be capable of:

- providing simple diagnostics of energy systems to provide early detection of problems
- supporting high-fidelity M&V of savings from energy efficiency programs
- ensuring the persistence of savings from energy efficiency over time
- data mining to identify customers with significant energy efficiency opportunities
- providing detailed feedback to customers on how to reduce their energy costs and carbon footprint
- analyzing the effects of behavior on energy consumption for populations of customers
- attributing carbon credits to utilities or customers, as appropriate.

The first two bullets are mechanisms analyzed in the next two sub-sections of this report.

It is important to understand what, if any, the marginal costs for deploying a smart grid capable of delivering these benefits are. The cost of AMI and associated communication systems are justified by other services preformed, and near-universal deployment of AMI in a smart grid is generally a given. The time resolution provided can bring about some of these potential benefits.

The additional insight provided by the disaggregation of the total load into end uses in homes and small commercial buildings is dependent upon the deployment of smart thermostats, at a minimum. These thermostats need to be capable of providing on/off status for heating and cooling back to a home or building's local area network, or the AMI meter itself. Such capabilities are available today and by 2030 we assume such thermostats will be nearly universal, since enough consumers will be participating in demand response programs to drive marginal hardware costs down to negligible levels. This assumes that direct load-control approaches, which do not require a thermostat but simply interrupt power to a device, are not the predominant form of demand response. This assumption is based on industry trends to more consumer-friendly approaches using thermostats, and the diminishing differential in cost between the two approaches.

Electric water heaters are likely to be similarly equipped (with load-control devices capable of reporting on/off status) in parts of the country, because they are important targets for demand response today, and involve little perceptible sacrifice in amenity. Smart appliances are the focus of an intense development effort on the part of manufacturers today. If utility programs provide incentives such as rebate programs, or if such features are required by standards, then smart appliances may similarly become nearly universal elements of a smart grid within the coming 20 years.

If the disaggregation process takes place "inside the meter," then a suitable processor to host the analysis of the signals is required, and the results could be delivered through an AMI communications network without extending its capabilities. This simple analysis can be a background process on a home computer, built into cable television systems, hosted by a home energy display platform, or conducted within the meter itself, for example.

If the disaggregation process takes place at the utility, then the meter must integrate and store the additional on/off signals. This type of modest improvement in AMI meter capabilities is already being contemplated in third-generation designs. An alternative is for the AMI communication network to have enough bandwidth to send the data in real time. This may come to pass for other reasons as smart grid assets are used for more sophisticated, real-time purposes, such as providing ancillary services (which will be significantly increased by renewable wind and solar generation, as discussed in Sections 3.2.1 and 3.2.2).

The cost of AMI and communication systems are justified by other services performed, which leaves the cost of measurement technology and central analysis functions to be covered. Of these two functions, it is likely in many cases that the cost of the measurement capability will be included in the technology as part of the demand response, and therefore justified on that basis.

Thus, it is certainly possible that all the capabilities needed to enable these benefits will be present in a smart grid in the future. It is doubtful, however, that the potential benefits for energy, alone (the bulleted list) above will be sufficient to pay for them. What is important is that these potential "side-benefits" for enhanced capabilities be taken into consideration when designing a smart grid. This would leave the software that conducts the analysis and display functions as the primary cost. As it is for most software products, spreading this cost over large numbers of customers is the key to keeping costs down.

3.1.4 Deployment of Diagnostics in Residential and Small/Medium Commercial Buildings

This topic examines the potential reductions in energy consumption and carbon emissions that can be obtained from the provision of energy system diagnostics enabled by a smart grid to optimize energy use and reduce operating costs for energy and maintenance. A smart grid's real-time sensing and communication assets coupled with end-use information enable automated profiling of systems to detect malfunctions and alert the consumer immediately. In addition to detecting malfunctions, improvements in operation can be identified, such as verifying the operation of night setback of thermostats or identifying abnormal lighting and plug loads. This mechanism is summarized here, with detail on the literature review and conclusions provided in Attachment 1.

The technical basis for using smart grid assets to break down total energy use into end-use subtotals is discussed in Section 3.1.3. Here we focus on the use of this information to provide diagnostic services in residential and small/medium commercial buildings (commercial buildings less than 50,000 ft^2 in floor area), primarily for HVAC systems where the most significant energy-wasting failures occur. A smart grid's communications and sensing enable automated profiling of these systems to detect such malfunctions and alert consumers immediately. This is feasible because the HVAC systems in these classes of buildings are reasonably simple, served by unitary, single-zone equipment and thermostats, and they're uniform in design and operation.

A property of the refrigerant cycle in heat pumps and air conditioners is that their output and efficiency tend to drop together, while their input remains relatively constant. Thus, using the slope of the cooling curve (see Figure 3.5) and the run-times established by thermostat on/off status signals, declining efficiency could be detected long before complete failure of the equipment makes it obvious. Heat pumps that are providing inordinate amounts of heat with their auxiliary electric resistance backup are a similarly important target.

Another diagnostic check would be on the economizer function of commercial building ventilation systems. The economizer enables the building to supply 100% air from outdoors to obtain "free cooling" when air conditioning is required and the outside air is cool and dry enough. Economizers can save large amounts of energy in commercial buildings—when they work properly. Economizers are notorious for failing because the moveable air dampers tend to get stuck if not properly maintained. When not working properly they do not provide the savings and can even waste additional energy by remaining in the open (100%) position all the time. The "hole" that proper economizer operation leaves in the heating/cooling curve of Figure 3.5 can be a simple basis for diagnosing these problems.

A second service that the smart grid can provide is scheduling routine maintenance and extending equipment life. Another service is automated fault detection and diagnostics to remotely identify and diagnose real and potential problems before equipment fails and requires costly repairs. Improved maintenance would also reduce emissions of chlorofluorocarbon (CFC) refrigerants for units not yet using hydro-chlorofluorocarbons (HCFCs) that minimize such impacts.

The diagnostic services can be delivered by a smart grid in two ways. The first is by sending the necessary data to the utility or a third party for analysis at a central location. The other is by downloading the required software applications onto a platform within the customer premise. The former requires an enhanced communications network capability. The latter requires a suitable platform in the home or building energy-management system with the processing power and storage to accomplish the analysis.

The large, complex HVAC systems prevalent in larger commercial buildings are custom designed and built-up from chillers, boilers, cooling towers, and multi-zone air-handling units connected by water and air distribution systems. The nature of HVAC system design and operation in large buildings makes them less amendable to the kinds of simple, uniform diagnostics that can be supported by a smart grid. Additionally, large commercial buildings often have a dedicated staff or contractor and onsite equipment to set up and perform diagnostics and operations functions that can help detect problems, which could lead to energy savings (Brambley et al. 2009). Thus, while the potential for diagnostics to save energy in these buildings is as large, or even larger, than in homes and small commercial buildings, we do not ascribe the potential savings for large buildings to a smart grid.

Of course, diagnosing a problem does not result in energy savings unless the problem actually gets fixed. Anecdotal evidence suggests that pointing out problems and providing an estimate of the amount of energy being wasted may be insufficient to spur repairs in commercial buildings. Thus, it may be necessary to couple detection of problems with utility programs that affect the needed repairs. Linkage with energy efficiency or demand response programs that involve the relevant end uses is one such possible mechanism, particularly where utility efficiency investments are involved.

An important consideration pertains to data access and consumer privacy. Because of the sensitive nature of some of the data involved, use or transmission of the data outside the customer's premises should require the full knowledge and consent of the consumer. When utility or third-party investment is involved this may be a programmatic requirement. A solution is conducting diagnostics with software applications within the customer's premises, but this requires timely access to data from the meter and demand response controls. These are important smart grid policy questions that must be addressed to guide development of this mechanism.

The direct reductions in electricity and associated CO_2 emissions calculated in Attachment 1, Appendix C, and shown in Table 3.5 are based on the literature review and the author's experience. These are based on our estimate that potential reductions of 15% in the residential sector for heating and cooling electricity (with a range of 10% to 20%) and 20% in small/medium commercial building sectors for HVAC and lighting (with a range of 10% to 30%) are achievable through implementation of smart grid technologies. Large commercial buildings are excluded for the reasons described above. No indirect reductions in operational or capital costs are expected.

A discussion of the basis for these estimates from the literature examined and more details on the building diagnostics are provided in Attachment 1, Mechanism C.

Table 3.5. Estimated Direct Impacts for Enabling Mass Deployment of Diagnostics in Residential and Small/Medium Commercial Buildings

Reduced Energy Consumption (2030)					Electric Sector Annual Reductions (2030)			
			Baseline Electricity Consumption		Energy		Carbon Emissions	
Est. %	Low %	High %	End-Use Sector(s)	(10^9 kWh/year)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ yearr)
15	10	20	Residential (Heat Pump & Air Conditioner)	331	3	152	3	90
20	10	30	Small/Medium Commercial Buildings (HVAC + Lighting)	510				

3.1.5 Measurement & Verification for Energy Efficiency Programs

The precision measurements that could be obtained by leveraging a smart grid could be used to provide additional value by offering M&V of energy savings from end-use efficiency programs on a real-time basis, for all participants, with great transparency and accuracy in the calculation of r energy and CO_2 emission reductions. Most evaluations of utility energy efficiency programs today are based on three general approaches:

- *Stipulation of energy savings*, based on simple in-situ or bench-scale tests that compare consumption with and without the efficiency measure, combined with assumed average operating times for appliances and equipment (that may be obtained from metered patterns)

- *Analysis of monthly electricity bills*, comparing before and after periods, normalized for outside temperature effects, to estimate savings
- *Short-term metering*, as recommended by the International Performance Measurement & Verification Protocol (IPMVP) in increase transparency and reduce risk (EVO 2007).

Stipulation of savings is particularly applicable for process loads such as motors, where use schedules are well understood, and similarly for lighting systems and electronics (if heating and cooling impacts can be ignored).

The PRISM-type methods discussed in Section 3.1.3 were developed specifically for the purpose of energy efficiency program evaluations, particularly those involving heating and cooling efficiency. For this application, they are typically employed to fit two- or three-part linear models to monthly billing data from a period prior to an efficiency retrofit, and again for a period after a retrofit. The consumption for both pre- and post-retrofit periods can be adjusted using the models to reflect a normal weather year. The difference between the normalized consumption for the two time periods is the savings attributed to the retrofit. These methods are desirable for programs that involve large numbers of buildings because, even for program targets other than heating and cooling, changes in other end uses, such as lighting, reduce internal heat gains and reduce cooling but increase heating. This interaction is taken into account by the methodology. Aside from the methodological difficulties, the principal limitation of this approach is estimating small levels of savings with confidence, amidst large overall consumption totals.

More detailed short-term monitoring is recognized by the IPMVP as a superior approach that overcomes this shortcoming by eliminating the need to make assumptions about use schedules and avoiding issues surrounding the difference between bench-scale tests and actual energy use in the field. If the short-term monitoring includes heating and cooling end uses, then the effects of changed internal heat gains on net savings can be properly accounted for as long as the data collected captures a full seasonal swing of weather. This approach does require significant labor to install metering equipment and collect the data, thus it is typically applied to a relatively small, random sample of participants over a short time period.

An approach that leverages smart grid communications and controls, as described in Section 3.1.3, can provide many of the benefits of short-term monitoring, but without the costs for field labor to install monitoring equipment and collect data. If it can be standardized and automated, it can be integrated into utility billing systems as a routine procedure. Once the procedures are developed and programmed, the cost to deploy it should be relatively independent of the number of customers involved, or the duration over which it is used. Employing it for all program participants eliminates the labor costs for developing samples and for recruiting participants for field measurement.

A review of the literature on efficiency program M&V is described in Attachment 1, Mechanism C, and briefly summarized here. Currently, 3% of total program costs are typically allocated for traditional M&V (DOE/FEMP 2009). The cost of conducting M&V by leveraging smart grid assets is unknown. Certainly, all labor involved will not be eliminated, but if high-quality M&V approaches are desired, it could displace a significant fraction of the cost of approaches, such as short-term metering. If these costs are assumed to represent a third of the overall costs of M&V, then a savings of 1% of program operational costs could be realized.

Using this estimate, if the savings were reinvested to obtain further cost-effective energy efficiency at an average cost of 8.8¢/kWh, potentially 0.5% of the electric sector energy and associated CO_2 emissions could be achieved as indirect reductions, as indicated in Table 3.6. This relatively modest savings assumes that these M&V approaches apply only to the residential and small/medium commercial building sectors (less than 50,000 ft^2 in floor area). It also assumes that energy efficiency programs are operated to achieve a 10% overall improvement in energy efficiency for these customer segments. Larger buildings and industrial customers are assumed to warrant more sophisticated and specially designed M&V approaches, and no attribution of savings from the programs is included in this estimate.

Table 3.6. Estimated Indirect Impacts of Measurement & Verification for Energy Efficiency Programs Leveraging a Smart Grid

Avoided Expenditure Reinvested to Save Carbon (2030)						Electric Sector Annual Reductions (2030)			
			Baseline Captial Expenditure			Energy		Carbon Emissions	
Est. %	Low %	High %	Investment	(10^9 \$)	Savings (10^9 \$)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ year)
1	0	2	10% Energy Efficiency, Residential @ 8.8¢/kWh,10-Year Life	152	1.5	0.5	26	0.5	15
1	0	2	10% Energy Efficiency, Small/Medium Commercial Buildings @ 8.8¢/kWh,10-Year Life	75	0.8				

There is obviously considerable uncertainty about whether these cost savings are achievable. We acknowledge this by indicting a range of potential cost savings that includes zero. Pending further research to better quantify the savings potential, and the cost of developing automated methodologies, the reader is left to accept or reject the assertions made regarding this mechanism.

We also estimate the direct impact for the additional energy efficiency that can be deployed as a result of the improved ***quality*** of M&V. This stems from the methodological advantages that approaches based on smart grid have over stipulation methods and methods based on analysis of monthly bills, which are otherwise assumed to remain viable and common approaches to M&V. Among other advantages, this allows the separation of the effects of physical thermal performance of a building and equipment from the behavior-driven effects of appliance and equipment loads and thermostat settings. This separation provides deep insight into how and why savings occur for any given technology, and provides an engineering basis for estimating savings in new construction, whereas prior baseline performance does not.

Quality also stems from the ability to ensure ***persistence*** of savings for new energy efficiency technologies with considerable potential, like heat pump water heaters, whose long-term performance is uncertain, which limits its penetration. These are usually actively controlled technologies that can fail in modes that reduce savings but shield the user from impacts of lost amenity, as opposed to passive technologies integral to building envelopes, for example. This benefit of ensuring persistence is beyond that which short-term metering can provide.

These effects are extraordinarily difficult to estimate. The additional reductions in electricity and CO_2 emissions resulting from the deployment of additional, marginally cost-effective energy efficiency technologies calculated in Attachment 2 are based on EPRI's estimate of 7% (EPRI 2009), other information in the literature review, and the author's experience. Potential direct reductions of 7% are estimated for cooling and electric heating in the residential sector (with a range of 5% to 20%), and 7% in the small/medium commercial building sectors for HVAC and lighting (with a range of 5% to 20%).

Using this estimate, potential reductions of 1% of the electric sector energy and associated CO_2 emissions could be achieved, as indicated in Table 3.7. These relatively modest savings assume that these M&V approaches apply only to the relatively sophisticated types of HVAC equipment and systems in the residential and small/medium commercial building sectors (less than 50,000 ft^2 in floor area) and lighting in those commercial buildings. Larger buildings and industrial customers are assumed to warrant more sophisticated and specially designed M&V approaches, and no attribution of savings from the programs is included in this estimate.

Table 3.7. Estimated Direct Impacts of Measurement & Verification for Energy Efficiency Programs Leveraging a Smart Grid

Reduced Energy Consumption (2030)					Electric Sector Annual Reductions (2030)			
			Baseline Electricity Consumption		Energy		Carbon Emissions	
Est. %	Low %	High %	End-Use Sector(s)	(10^9 kWh/year)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ yearr)
7	5	20	Residential (Heat Pump & Air Conditioner)	331	1	59	1	35
7	5	20	Small/Medium Commercial Buildings (HVAC + Lighting)	510				

3.1.6 Shifting Load to More Efficient Generation

A smart grid facilitates shifting load from peak load to shoulder or off-peak-load periods using demand response and distributed generation and storage. Doing so with demand response or storage and can save energy and carbon emissions, depending upon the mix of base, intermediate, and peak load generating resources being used at any given time to serve customers for a given utility. This is illustrated in
Figure 3.6, which shows an actual coal-based Midwestern U.S. utility's load duration curve[1] on the left axis and a colored block whose height on the right axis indicates the carbon footprint of the marginal power plant operating during any given hour of the year.

The carbon footprint for the natural-gas-fired peak load power plants is almost as high as that for the coal-fired base-load power plants. This is because the heat rate (energy conversion efficiency from fuel) for simple cycle combustion turbines (CTs) used to supply peak loads is generally low because their limited annual run-time is too low to justify the more expensive, efficient combined-cycle power plant that serves intermediate loads. Thus, every kilowatt-hour saved is not "born equal" in terms of its carbon impact, and demand response that shifts load from peak load times to intermediate load periods (or, less frequently, to base load) will have an important carbon impact that is worth taking into account. This simple example avoids the much greater complexity of accounting for carbon emissions as renewable generation becomes a significant contributor in the future.

[1] A load duration curve is used to provide the relationship between generating capacity utilization by hour of a year (8760 hours) in decreasing increments by hour.

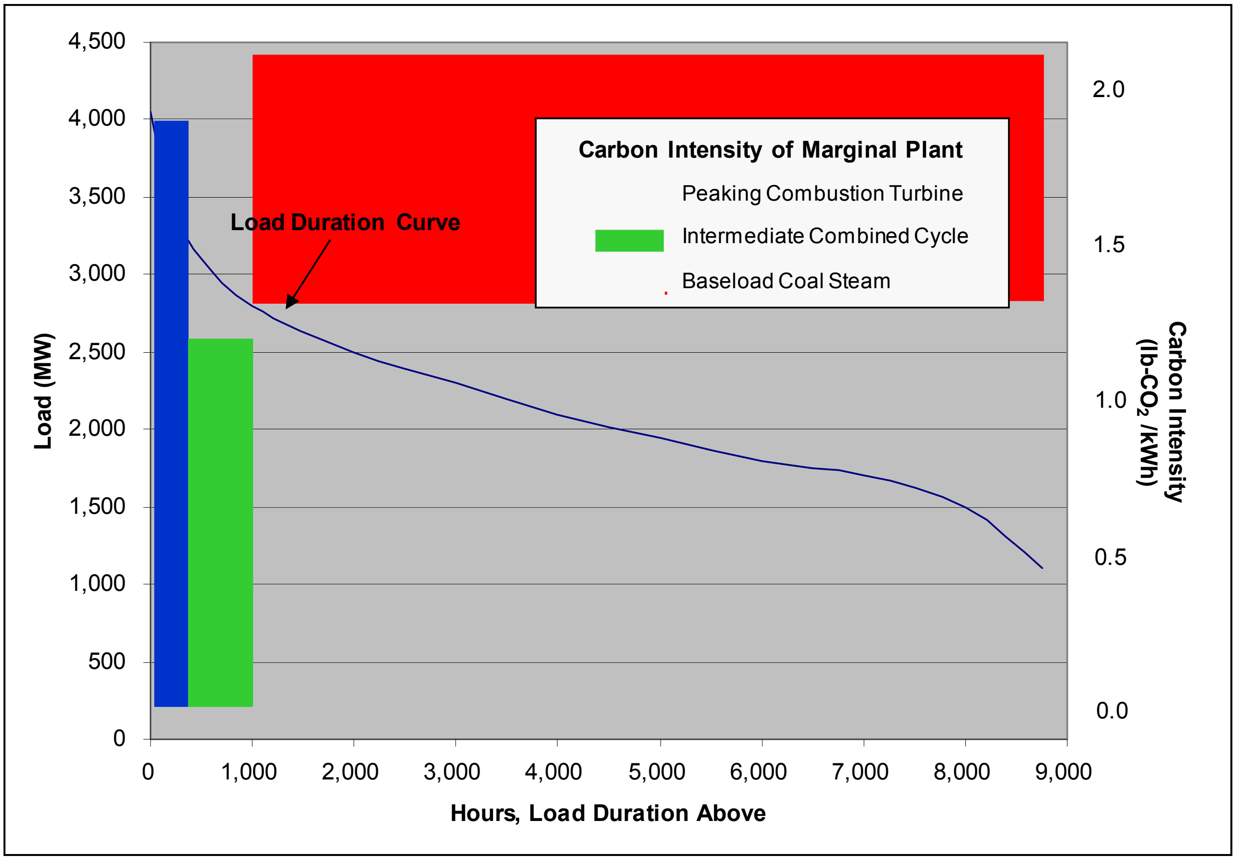


Figure 3.6. Load Duration Curve and Carbon Dispatch of a Typical Coal-Based Utility

The smart grid can provide reductions in primary energy and CO_2 emissions by shifting peak load to more efficient lower emission base and intermediate generation resources. Load shifting enabled by a smart grid can shift electricity production from less efficient peak load generating resources (less than 30%) to more efficient intermediate resources (~40%) that have lower carbon emissions per unit of energy supplied. In cases where the load is shifted to base-load power plants that are not coal-fired, even greater carbon savings can be realized. Utility programs have shown that shifting load from peak load generating power plants to more efficient off-peak-load power plants provides such reductions: the California "Shift & Save" quantifies the reduced CO_2 emissions at between 10% and 20%. The carbon footprint of base-load generation is likely to be reduced in the future as more renewable and clean-coal-fired power plants enter the system to join nuclear and natural-gas-fired power plants to displace current coal-fired power plants.

The estimation of energy and carbon benefits achievable by load shifting is challenging because of the highly dynamic nature of the power plant dispatch options that provide literally thousands of options for re-arranging the generation mix, and the corresponding generating efficiency and carbon intensity of the input fuel. To estimate the potential reductions, a simplified analysis was conducted using load duration curves for each of 12 North American Electric Reliability Corporation (NERC) sub-regions. Sufficient load was shifted from high demand hours to provide a 10% reduction in peak load in each sub-region, or in the amount of capacity of natural-gas-fired CTs in each sub-region, whichever is less. On average, this involved shifting load for 168 hours per year.

In general, the load was shifted to natural-gas-fired combined-cycle power plants, which reduces energy input and CO_2 emissions because of their lower heat rates (higher fuel efficiency). For three of the regions in which there is a lower proportion of combined-cycle capacity and coal-fired power plants (East Central Area Reliability Coordinating Agreement, Mid-America Interconnected Network, and Mid-Continent Area Power Pool [MAPP]), a portion of the energy was shifted to coal-fired power plants (50%, 40%, and 80%, respectively). This produces energy savings because of their lower heat rates, but causes higher CO_2 emissions because of the higher carbon content of coal compared to natural gas.

The results of the analysis described in Attachment 1, Mechanism E, are summarized here. The reductions in electricity and CO_2 emissions calculated in Attachment 2 for this analysis are shown in Table 3.8. The estimated potential from the load-shifting capabilities of smart grid technologies are small: a direct reduction of 0.04% in total electricity supplied to the grid (with a range of 0.02% to 0.06%), and 0.03% reduction in associated CO_2 emissions (approximately 75% of the electricity reduction). No indirect reductions are expected.

Table 3.8. Estimated Direct Utility Energy and Carbon Reductions for Shifting Load to More Efficient Generation

Reduced Energy Consumption (2030)					Electric Sector Annual Reductions (2030)			
			Baseline Electricity Consumption		Energy		Carbon Emissions	
Est. %	Low %	High %	End-Use Sector(s)	(10^9 kWh/year)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ yearr)
0.04	0.02	0.06	Total Electric Supply	4968	0.04	2	0.03	1

These reductions are quite small. This is fundamentally because of the relatively few hours per year the load needs to be shifted to produce a 10% reduction in peak load (168 hours on average), and the average power shifted during those hours is only about 5% (approximating the area of the "wedge" shifted as a triangle). So, the overall energy shifted is correspondingly small (about 0.1% of the total generation), and in the limit this could only produce 0.1% savings even if the generation used to meet it were entirely renewable.

A dispatch algorithm that shifts load more frequently could produce larger reductions. It would presumably have energy and CO_2 reductions as its primary objective, rather than peak load management. Since demand response is limited by the willingness of participants to forgo some amenity or service value, it may not be possible to utilize demand response assets on a daily basis in such an algorithm. Energy storage could play a much more frequent role in such a dispatch algorithm, as long as such frequent use would not reduce its lifetime. Among the options for storage, compressed air or pumped hydro storage could play a much more significant role than battery-based storage for this purpose.

3.1.7 Support Additional Electric Vehicles and Plug-In Hybrid Electric Vehicles

This topic examines how advanced load management technologies for EV, "smart charging," can improve the overall national energy efficiency and reduce carbon emissions of LDV transportation. This mechanism is summarized here, with detail on the literature review and conclusions provided in Attachment 1.

Replacing gasoline-fueled LDVs with vehicles that derive a significant fraction of their energy from electricity is one option for reducing our dependence on foreign oil and the carbon footprint of transportation at the same time. Compared to burning gasoline in an engine at relatively low operational efficiency, generating electricity with a power plant and putting that energy into an on-board battery to propel a vehicle it is significantly more fuel-efficient. It is estimated that with today's mix of power plants and vehicles, this would provide an approximate 30% improvement in energy consumption per VMT and a 27% reduction in CO_2 emissions, while reducing imports of foreign oil by 52% (Kintner-Meyer et al. 2007).

PHEVS are often cited as a solution that bridges the need for better transportation efficiency and consumers desire for travel range. With the advent of better battery technology, PHEVs may be supplanted by EVs, but the reduced fuel and emissions are the same per VMT when powered with electricity.

Analysis has shown that with today's load shape and generation capacity, it should be possible to supply over 70% of the energy[1] for the U.S. LDV fleet (cars, vans, SUVs, and light trucks) without building additional generation or transmission—if their charging times are carefully managed to strictly avoid charging during peak load hours. If this can be accomplished, there is downward pressure on electricity prices because the cost of the existing grid infrastructure is spread over more unit sales of energy (Scott et al. 2007). That will help keep electricity an affordable and viable alternative to gasoline.

The ability to *manage* the charging time period and shift the vehicle load off peak is the enabling characteristic of smart charging technologies that would be supplied by a smart grid. The analysis documented in Attachment 1, Mechanism F, focuses on determining the impact of a smart grid on achieving savings from PHEVs or EVs. First, it must be recognized that the primary investment from which any savings are derived is from the vehicle itself, not a smart grid. While a smart grid is designed to help keep electricity prices down, and that will help electric-powered vehicles penetrate, the dominant influence on their penetration is likely to be cost and performance in the eyes of the consumer. That is primarily driven by battery technology.

The impacts of a smart grid analyzed here focus on the question of how many ***additional*** PHEVs/EVs can be supported by using smart charging. Driving data from a large sample of vehicles was used to estimate when vehicles arrive at home in the evening, and it was assumed that charging of their batteries would immediately commence at 120 volts. On the average day in the peak load season, many of these vehicles begin charging while the grid is still in a peak load condition. The (base case) analysis first determined how many vehicles could be accommodated before they caused the total load to exceed the available excess generating capacity on that day was exceeded (less reserve margins).[2] This was then compared to the number of vehicles that could be supported in each of 13 regions comprising the entire United States *with* smart charging, and the difference attributed to a smart grid.

The result is that smart charging raises the share of electric VMT by 9 percentage points−from 64% to 73% of the LDV fleet. This allows the grid to support 18 million more PHEVs and EVs beyond the 140 million supportable with ***unmanaged*** charging.

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[1] Or, equivalently, 70% of the VMT.

[2] This analysis implicitly assumes that since both are driven by population growth, to a first order the number of vehicles grows at the same rate as the electric generating capacity.

The reductions in electricity and CO_2 emissions calculated in Attachment 2 are based on this estimate. The estimated potential direct impacts are a net (petroleum minus electricity) reduction of 3% (with a range from 2% to 5%) in the energy consumption for LDV transportation at some point in the future, if EV/PHEV penetrations reach the 73% level discussed above. To place this in perspective with the potential impacts of the other mechanisms in this report, we translate this into equivalent reductions in U.S. electric sector energy and associated emissions of 3%, as shown in Table 3.9. These percentage impacts are nearly the same because the energy for LDVs and electric power consumption are nearly the same. No indirect reductions in electricity or capacity are expected.

Table 3.9. Estimated Direct Utility Energy and Carbon Reductions from Supporting Additional Electric Vehicles and Plug-In Hybrid Electric Vehicles

Reduced Energy Consumption (2030)					Electric Sector Annual Reductions (2030)			
			Baseline Electricity Consumption		Energy		Carbon Emissions	
Est. %	Low %	High %	End-Use Sector(s)	(10^9 kWh/year)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ yearr)
3	2	5	Electricity Equivalent of Light Vehicle Transportation (cars, vans, SUVs, light trucks)	5135	3	139	3	82

Of course, electric-powered vehicles are not the only potential solution to the energy and carbon footprint of transportation. If an alternative solution predominates, the reductions may not be fully attributable to a smart grid. Bio-fuels are another important option, particularly coupled with cellulosic-conversion technology and clean diesel engines. Hydrogen is also an option, but if it is produced with renewable electricity, or coal-fired power plants with carbon-sequestration, conversion losses of 50% hinder its potential. Nuclear power plants could be used to produce hydrogen if costs were low enough to compensate for the conversion losses. They could also be used to produce electricity, but then managing charging with a smart grid would become even more important because nuclear power plants are not suited to ramp up and down to follow load.

There is currently much discussion about whether 120-volt charging will be the norm. In large vehicles like SUVs, charging at that voltage for a 30-mile range can take 12 hours or more. Shorter charging times may be desired by consumers, in which case 240-volt charging may become the standard. 240-volt outlets in garages of new homes are already required in California for this reason. To a first order, charging at 240 volts doubles the peak load impact of unmanaged charging, and therefore cuts the number of vehicles that can be supported with unmanaged charging in half. This reduces the fraction of electric VMTs that can be supported by the grid before smart charging is required to 32%, raising the smart grid's impact from 9% to 41%, more than quadrupling the estimated reductions to 13%. This highlights an issue that unmanaged PHEV charging may set new system peaks in some regions, rather than be "perfect valley-filling" solution under a managed charging paradigm.

This analysis ignores the possible additional benefits of managing the charging of EVs and PHEVs, and potentially discharging them as well, to provide ancillary services. This could provide an indirect benefit by reducing the costs for ancillary services required to integrate high levels of renewable wind and solar generation. These benefits could be substantial if there are enough vehicles to drive down the market cost of regulation below that of power plants. The impacts on the lifetime of using vehicle batteries this way is not yet known. Analyzing these potential impacts is left to future analysis.

3.1.8 Conservation Voltage Reduction and Advanced Voltage Control

This subsection describes how the smart grid can increase the efficiency of electricity delivery by managing the electric service voltage seen by end-use customers to reduce the distribution system losses and reduce the energy consumption of customer loads. End-use energy consumption has been shown to drop when the electric service voltage is reduced. This strategy, termed *conservation voltage reduction* (CVR), occurs primarily because the energy consumption of certain end-use loads such as incandescent lights and certain electronics go down as the voltage is decreased.

Conversely, electric losses in distribution systems tend to ***increase*** as voltage drops, because motors and other constant power loads tend to draw more current to compensate, and losses are proportional to the square of the current. Electric distribution system losses average around 5% and increase to 8% or more during peak load periods when voltage drops and current increases. A smart grid's measurement and communication capabilities provide an opportunity to continually optimize tradeoffs in service voltage and energy use by precisely controlling voltage within acceptable limits. This optimization process, which includes CVR, is ***advanced voltage control***.

The drop in voltage along the length of a feeder is illustrated in Figure 3.7 under peak and minimum load conditions. The voltage drops because of the power losses in the conductors and equipment on the feeder. The higher the load, the more current flows through the feeder and the higher the resultant voltage drop. The voltage standard for the United States for a single phase at a residential customer meter ranges from 126 volts to 114 volts, per ANSI C84.1 (ANSI 1996). Voltages higher or lower than that have the potential to damage customer equipment.

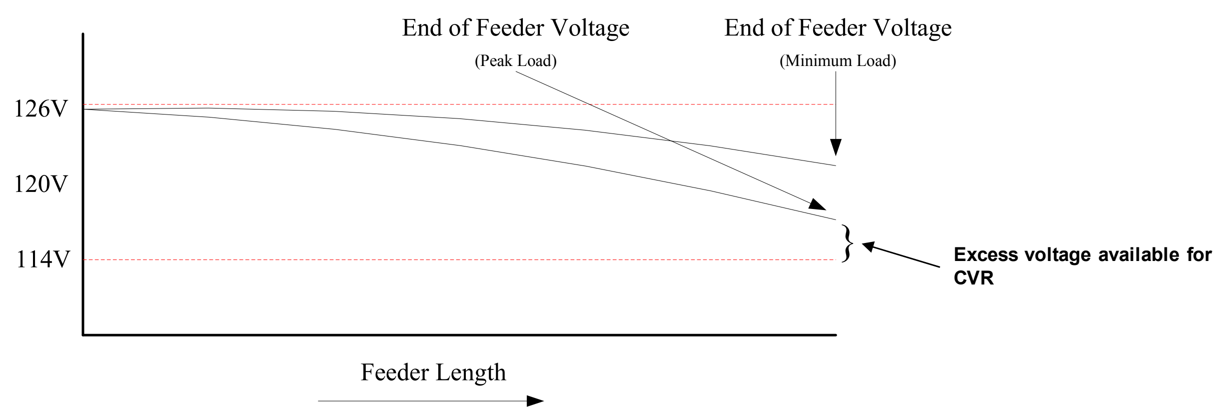

Figure 3.7. Voltage Drop Along a Feeder at Peak and Minimum Loads

Distribution operators maintain voltages for all customers within these limits by adjusting voltage at the substation transformers and voltage regulators at head of the feeder. In particularly heavily loaded feeders, additional voltage regulators are sometimes added along the length of the feeder to adjust the voltage. Typically, the voltage at the head of the feeder is set somewhat lower than the maximum 126-volt level, but a safety factor in the form of some excess voltage is provided at the end of the feeder.

CVR simply requires adding a measurement of voltage at the end of the feeder, or estimating it using load flow calculations. This low requirement for additional capital investment makes CVR an inexpensive efficiency measure. Then the voltage regulator at the head of the feeder is continually controlled to maintain the end-of-line voltage at the minimum level. This reduces the instantaneous power drawn by any load with constant impedance characteristics, and reduces overall customer energy consumption. Loads controlled by thermostats, like heating, cooling, and refrigeration, may not reduce consumption in proportion to the reduction in power because they operate with slightly longer cycles to satisfy the thermostat.

Winding losses in motors and transformers are also reduced, and motors may operate at a higher efficiency if their operation shifts to a more efficient operating point. On the other hand, motors in many applications also tend to maintain constant power output. This causes them to draw more current to compensate for the drop in voltage, which does nothing to reduce the electrical power drawn. This actually increases losses in the distribution system. So, while the technology behind CVR is relatively simple, understanding the impacts of CVR is somewhat complicated.

On heavily loaded or long rural feeders it is not always possible to maintain the proper voltage by adjustments of the substation voltage alone. In many cases, this is caused by heavy motor or air-conditioning loads with poor power factors. The lag of the current behind the voltage (indicated by the power factor) requires additional current to deliver a given amount of power, with attendant decrease in voltage. Shunt capacitors can be added to compensate for the poor power factor.

Figure 3.8 shows an example of a radial distribution feeder that has a very large voltage drop. To accommodate the large voltage drop, a shunt capacitor is placed approximately 60% down the length of the line. This has the effect of reducing line losses and voltage drop along the feeder. Today, these capacitors are usually continually active or they may be manually switched on and off. The smart grid will involve an extension of distribution SCADA systems along the length of the feeder so that these capacitors can be automatically controlled to compensate for the variation in the voltage throughout the day based on local voltage measurements. As shown in Figure 3.8, capacitor control can make extra voltage available for CVR by providing truly advanced voltage control to enhance load and loss reductions.

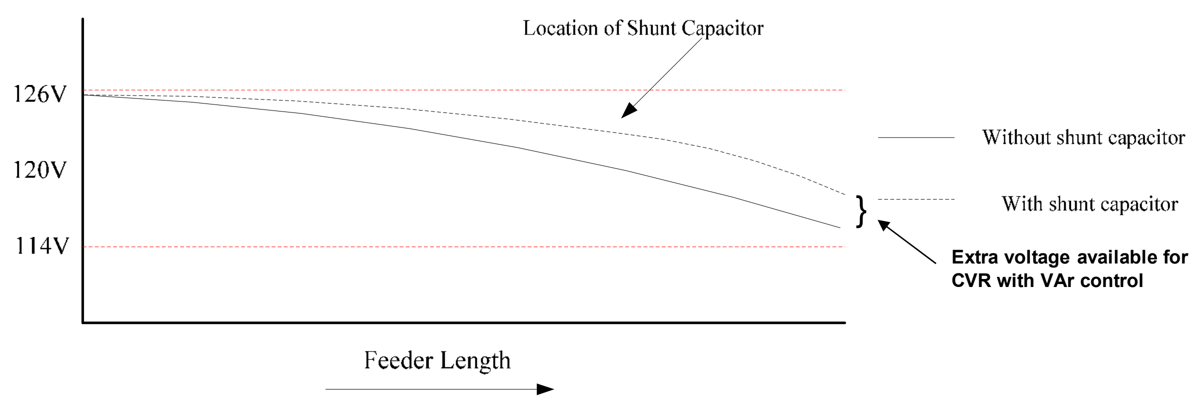

Figure 3.8. Effect of Reactive Power Control on Voltage Drop

The literature review detailed in Attachment 1, Mechanism G, suggests that CVR alone has empirically proven itself to be a viable method to reduce the peak load on a distribution feeder as well as being an effective form of conservation. The most comprehensive field study involved 31 feeders at 10 different substations and 11 utilities in the Pacific Northwest; it showed that a 1% change in distribution line voltage provided a 0.25% to 1.3% change in energy consumption, and that voltages could be reduced from 1% to 3.5% (Beck 2007).

Accurate determination of the CVR effects on any given feeder must include analysis of the electrical load as well as the design of the distribution system. The design of the distribution feeders includes everything from line and cable types, line and cable configurations, use of voltage correction capacitors, and use of tap-changing voltage regulators for transformers. Thus, extrapolating the CVR results to estimate the national potential is difficult.

Using advanced voltage control, we estimate that it is possible to reduce the existing consumption of electricity by approximately 1% with little investment. Such functionality is generally considered basic to a smart grid, so here we are simply trying to quantify its potential. Deploying full advanced voltage-control technologies could potentially increase this from 3% to 4%, which translates directly into substantial savings. The reductions in electricity and associated CO_2 emissions calculated in Attachment 2 and shown in Table 3.10 are based on information from the literature review and the author's experience. It is estimated that a direct reduction of 2% in total electricity supplied to the grid, with a range of 1% to 4%, can be achieved through implementation of smart grid technologies. No indirect reductions in electricity or capacity are expected.

Table 3.10. Estimated Direct Utility Energy and Carbon Reductions for Conservation Voltage Reduction and Advanced Voltage Control

Reduced Energy Consumption (2030)					Electric Sector Annual Reductions (2030)			
			Baseline Electricity Consumption		Energy		Carbon Emissions	
Est. %	Low %	High %	End-Use Sector(s)	(10^9 kWh/year)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ yearr)
2	1	4	Total Electric Supply	4968	2	99	2	59

3.2 The Smart Grid and Renewables

A smart grid can help integrate renewable resources into the grid by designing price or incentive signals to engage demand response and distributed storage, including that from PHEVs, to manage and absorb the short-term fluctuations ("noise") in the total load in a service territory, instead of using power plants to manage/absorb these fluctuations. Currently, power plants are continually turned up and down to provide this load following service (termed *regulation*), which wastes fuel and increases wear and tear on the power plants. The increased penetration of renewable generation resources increases the need for regulation services, as projected for California (CAISO 2007).

Regulation is one form of ancillary services needed to stabilize the grid during normal operations, and the need for regulation is expected to increase in order to manage high penetrations of renewables. An illustrative example of this occurred in February 2008, when the Electric Reliability Council of Texas (ERCOT) had to curtail power to many interruptible customers because wind production suddenly fell

1700 megawatts. The drop in output had been forecast, but occurred several hours earlier than expected, so power plants had not been scheduled for dispatch to provide the replacement energy and the *ramping services* to manage the transition. Some generation capacity is always held back but kept "hot" to handle a sudden contingency (*spinning reserves*), but this event exceeded the capacity of the spinning reserves and fast-acting *non-spinning reserves* to pick up the deficit in output. In addition, February is in the off-peak-load season in Texas when many power plants were down for scheduled maintenance. As a result of this deficit, grid frequency dropped quickly, and emergency curtailment contracts, mostly with large industrial customers, were called upon to drop load to prevent a potential blackout until additional power plants could be brought online.

These kinds of events are driven largely by errors in ***forecasts*** of renewable energy. They are a combination of probabilistic events, well described by the analogy to a "perfect storm," that power grid operators must plan to handle with little warning. In today's power grid with little renewable generation, contingency events are not infrequent, and the rules for good practice regarding how much capacity to have for regulation, spinning and non-spinning reserves, and emergency replacement energy (*re-dispatch*) have been well defined after decades of experience. Because these events are probabilistic, the quantity of services needed, which may be negligible initially, tends to accelerate as renewable resource penetration increases.

How much additional capacity is needed for these services, and how this quantity changes with the percentage of generation supplied by renewables, is the subject of considerable research. Most research conducted to date is focused on wind power, because it is penetrating much faster than solar power systems at present. A smart grid's demand response and distributed generation and storage assets can provide these services, easing operational stresses, and manage the increasing penetration of intermittent renewable resources.

To the extent that these assets (demand response, distributed generation, and distributed storage) can replace power plants in providing these services, extra plant capacity will not need to be constructed, and less fuel will be consumed. In Section 3.2.2, we estimate the direct impacts from the potential savings in fuel for the additional regulation services required by a 20% RPS requirement met by wind power, by providing the extra regulation with a smart grid's demand response and/or distributed storage resources. We also estimate the indirect impacts of saving capital investment in power plant capacity for providing the extra spinning reserves needed.

We do not provide a separate estimate for meeting a 20% RPS requirement with solar power generation for two reasons: wind power is expected to provide most of the needed additional RPS requirement, and research on the ancillary services required to meet an RPS requirement entirely or partially is relatively immature. To a first order, we assume the requirements are similar, and therefore the estimates in Section 3.2.2 for wind power also apply to a system with a mixture of wind and solar.[1]

Other smart-grid-enabled mechanisms for assisting the penetration of renewable generation, such as wide-area control and dynamic thermal rating schemes for transmission systems, are not analyzed in this report. Both of these could potentially increase the throughput capacity of existing transmission lines, and thereby reduce needs to construct transmission capacity in order to move renewable power long

[1] This neglects the generally beneficial effects of resource diversity, which is what a combination of wind and solar sources would provide.

distances to urban load centers. Wide-area control involves using high-precision data from phasor measurement units and high-performance computing techniques to analyze the transmission grid and reconfigure it as needed in real time. In principle, this could allow some relaxation of restrictions on key transmission corridors due to stability limitations, because the grid could be reconfigured instantly to relieve a stability contingency. Wide-area control technology is a long-term technology development focus for smart grids at the transmission level. When it may become practical, and how much additional new transmission capacity to serve renewable generation could be avoided, is not yet clear.

Dynamic thermal rating schemes are available today. They use sensors to account for the actual local weather conditions when computing the thermal capacity limits on transmission line segments, instead of assuming worst-case conditions, as is the current practice. When and where the wind is blowing can lower conductor temperatures and thereby reduce line sag enough so that additional power can be delivered. How much avoided transmission capacity this promising technology can deliver in practice is uncertain. While it can increase throughput on specific lines under certain conditions, many transmission systems are constrained by stability limits rather than thermal limits. Even when wind power output is high, it may not be blowing sufficiently at a key constrained transmission segment to sufficiently increase the throughput sufficiently to accommodate the increased generation. Further research is required on this subject before such estimates can be made.

Another way a smart grid can assist renewable generation is to remove barriers that may limit its penetration. Aside from the cost hurdles associated with providing extra ancillary services, more absolute barriers are not generally unforeseen by experts, at least until the renewable portfolio reaches levels above 20%. One example of such a barrier is explicitly addressed in Section 3.2.1 of this report: the limits to the amount of solar generation in neighborhoods, presumably from solar photovoltaic (PV) installations, before reverse power flow toward the substation occurs and distribution voltage control is lost (we do not attempt to ascribe savings associated with overcoming this barrier).

Perhaps the ultimate barrier that can be foreseen is the limit to the share of energy needs provided by renewable generation. Beyond ancillary services, other power plants will need to provide replacement energy for days and occasional weeks when renewable resources do not produce their average output. The first barrier is simply one of cost for the replacement reserve capacity. Although demand response is unlikely to produce significant energy for days at a time, a smart grid's storage resources may be able to provide a day or more, and backup distributed generation could provide supply over an even longer period.

An absolute limit on the share of energy that can be produced from renewable generation is eventually reached when the fuel consumed by power plants to supply replacement energy becomes the only non-renewable production by the grid. At that point, the addition of further renewable <u>capacity</u> does not result in a corresponding increase in production of renewable ***energy***.[1] A smart grid aggressively managing storage resources, potentially including batteries in PHEVs and EVs, becomes essential in overcoming this limit. Estimating when this limit is reached and the corresponding share of renewable electricity production becomes significant is extremely complex and beyond the scope of this report.

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[1] Unless it is from a new form of renewable generation that increases diversity, or that is not variable. Geothermal, tidal, and wave energy are some examples.

The following subsections summarize the two mechanisms that relate to the renewable energy application (the full text discussing the two mechanisms is contained in Attachment 1).

3.2.1 Support Penetration of Renewable Solar Generation

This section provides a simple estimate of how much solar generation can exist in a typical residential neighborhood, downstream from the substation, before reverse power flow can be expected.

The integration of solar PV generation at high penetration in distribution systems will eventually require two-way flows of electric power toward the substation when the energy from solar PVs exceeds the downstream customer loads. The voltage control and short-circuit protection schemes used by distribution systems today were not designed to operate with reverse/upstream power flow. A smart grid's assets can reduce these limitations and improve system stability and safety through dynamic protection schemes, voltage regulation and control, energy storage, and the provision of dynamic reactive power. DOE has a very active program that focuses on the integration of solar PV (http://www1.eere.energy.gov/solar/rsi.html).

Solar PV is an attractive method of achieving zero-emissions energy production because it readily scales to the needed level. This makes it ideal for applications ranging from relatively small residential rooftop applications to larger commercial and industrial rooftop applications. The existing electricity infrastructure can support a limited penetration of solar PV with the current operating schemes, although the limit varies from utility to utility and feeder to feeder, depending upon the size and diversity of the load. A smart grid holds the promise of allowing much greater penetrations of solar PV and thus much greater reductions in emissions.

To estimate how much solar generation can exist in a typical residential neighborhood before reverse power flow can be expected, we examine a worst-case condition. This consists of maximum solar output at noon on a perfectly clear day, in the spring or fall when neither heating or air conditioning is needed in homes, and in a neighborhood that uses natural gas for water heating (like most U.S. homes). The electrical load at noon for a home without heating, cooling, or water heating is about 1 kW (Pratt et al. 1993). In this case, reverse power flow will occur when the average home in the neighborhood has a solar PV array whose output exceeds 1 kW on a perfectly clear day.

The daily solar energy produced by a solar PV array varies by location due to latitude and cloud cover. To estimate the annual energy production of a 1-kW solar PV array, we begin with the annual average annual average incident solar radiation on a south-facing surface (with an optimal tilt, equal to the latitude), indicated for various locations in the United States by the color coding on the map in Figure 3.9. The annual energy produced by a 1-kW array is directly proportional to the average incident solar radiation, as described in Attachment 1, Mechanism H. This production is expressed as the *solar fraction* of the annual energy requirement of such a home that is supplied by the solar PV array. (i.e., the annual solar energy produced divided by the annual electricity consumed by the home (8600 kWh/year, including air conditioning; see Attachment 1, Mechanism H). The solar fraction is equivalent to the local's RPS from solar resources.

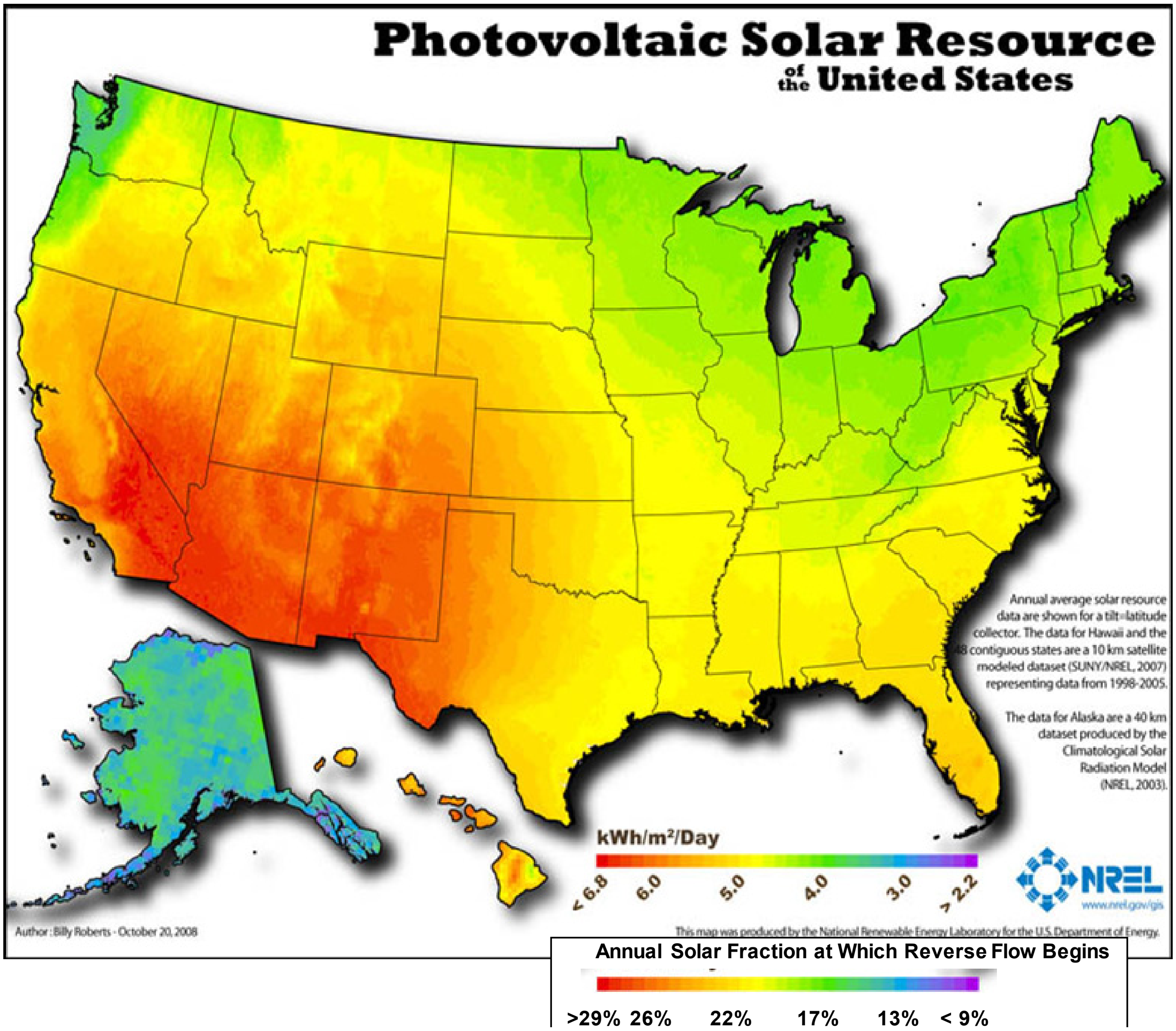

Figure 3.9. Annual Fraction of Energy from Residential Solar PV at Which Reverse Power Flow Begins

To indicate the maximum solar fraction before reverse power flow begins to occur, we have added a second scaling key to the color coding in Figure 3.9. The annual fraction of energy generated from such a 1-kW solar array is seen to range from a low of about 17% to a high of about 28% over most of the United States (excluding Alaska and parts of the Pacific Northwest). The median for the continental United States appears to be around 21%. If additional solar PV capacity is installed beyond the amount to supply this solar fraction, reverse power flow occurs because the output of the solar arrays on a clear day exceeds the 1-kW average load of each home.

Thus, the onset of reverse power flow appears to be a serious barrier to penetrations of solar PV systems in residential neighborhoods to achieve local RPS levels above about 20%. A smart grid could help circumvent this barrier by deploying and controlling additional voltage regulators and batteries, and by providing short-circuit protection schemes that adapt to on-the-fly reverse power flow. Further details are provided in Attachment 1, Mechanism H. Estimates of potential reductions in electricity and CO_2 emissions were not made for this mechanism, and there is not an obvious basis for estimating the indirect benefits of removing a barrier such as this. Further refinement of this crude estimate and creating a way to value it is a recommendation for further analysis.

3.2.2 Support Penetration of Renewable Wind Generation

This mechanism estimates the impacts of a smart grid in helping to mitigate challenges for integrating wind energy into the electric system. The contribution of electricity generated by wind turbines is increasing due to a combination of the improved economic competitiveness of wind power, state and federal tax credits, state renewable energy portfolio requirements, and consumer desire to purchase "green" electricity. However, the integration of wind energy poses challenges because of the unpredictability and steep ramp rates of wind resources, which must be compensated by the use of more traditional power plants (termed *load following* or *regulation*) that increase costs because of redundancy and maintenance to correct increased wear and tear. Smart grid technologies, primarily communication and control over demand response, and distributed generation and storage resources, can help replace fossil fuel capacity used to overcome the unpredictability and ramping issues, and thereby increase the level of wind generation into the electric system (Todd et al. 2009).

Wind energy has benefitted greatly from RPSs and tax credits, but it is characterized by intermittency and ramping that requires additional capacity to provide ancillary services in the form of regulation, load following, and scheduling. As discussed in Attachment 1, Mechanism H, a review of efforts to estimate this impact indicates that the electrical system can accommodate penetrations of wind energy on the order of 20% to 25% with only modest increases in the requirements for ancillary services (NWPPC 2007; CAISO 2007). These studies also indicate that wind integration is facilitated in cases where the service area is geographically large and has a diversity of loads. The contribution of the smart grid technology can replace the additional capacity used to provide ancillary services with smart grid assets by using advanced communication and control technologies.

The estimated potential reductions in electricity and CO_2 emissions attributable to implementation of smart grid technologies are based on the literature review and the author's experience. The direct impact of saving the fuel used for power plants offering regulation service is estimated based on the analysis in Parsons et al. (2006). Extra fuel is used for power plants because of the inefficiencies of continually changing their output. Parsons et al. (2006) estimated that the regulation requirement increases from 0.65% in the base case to 0.75% at the RPS level of 25%, for a four-utility combined balancing area with a peak load of about 21,000 MW.

We estimate that the fuel consumption for a power plant supplying regulation is 20% higher than it is in steady-state operation (with a range of 10% to 30%). Saving this fraction of the energy for the additional regulation required to achieve an RPS of 20%, 0.1% of total U.S. consumption, would result in saving the energy equivalent of 0.02% of U.S. electricity energy consumption and associated carbon emissions, as shown in Table 3.11. Note that 100% of the fuel used by such power plants is not saved, because they are supplying energy in addition to regulation. Rather, they waste fuel by moving their output up and down around their average operating points.

Table 3.11. Estimated Direct Impacts of Reduced Energy Needed to Supply Regulation for Wind Energy Penetration at 25% RPS

Reduced Energy Consumption (2030)					Electric Sector Annual Reductions (2030)			
			Baseline Electricity Consumption		Energy		Carbon Emissions	
Est. %	Low %	High %	End-Use Sector(s)	(10^9 kWh/year)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ yearr)
20	10	30	Fuel Savings for 0.1% Additional Regulation Requirement	5	0.02	1	0.02	1

This mechanism appears to have a negligible effect on energy and emissions because of the small amount of energy involved, although in certain areas of the country where regulation is monetized in wholesale markets, it is apparent that it is quite expensive to provide. It should be investigated as an indirect savings mechanism in future work, to reflect the potential of reduction in regulation costs.

It is worth noting that only a very small amount of load (approximately 0.7%) would need to participate in providing all the regulation needed by the grid, as would similarly small amounts of energy from storage or batteries.

We also estimate the potential indirect reductions from reinvesting the capital cost savings from avoiding the construction of extra generation capacity required for the total operating reserves (regulation, spinning, non-spinning, load following, and reserve margin) to support wind generation to meet. This has been estimated to increase from 5% of peak load capacity to 7% for an RPS of 25% (Smith et al. 2007).

We use the 2% difference to estimate the reduced reserve capacity, with a range from 1% to 3%. We assume the resulting cost savings, from avoiding over 1000 gigawatts of power plant capacity at $1000/kW, are reinvested in additional cost-effective energy efficiency or renewable generation at a levelized cost of 8.8¢/kWh. This results in very substantial estimated reductions of 5% of U.S. electricity consumption and associated CO_2 emissions, as shown in Table 3.12.

Table 3.12. Estimated Indirect Impacts of Reduced Needed Reserve Capacity for Wind Energy Penetration at 25% RPS

Avoided Expenditure Reinvested to Save Carbon (2030)						Electric Sector Annual Reductions (2030)			
			Baseline Captial Expenditure			Energy		Carbon Emissions	
Est. %	Low %	High %	Investment	(10^9 \$)	Savings (10^9 \$)	% of United States	(10^9 kWh/ year)	% of United States	(MMT/ year)
2	1	3	1111 GW Total Generation Capacity @ $1000/kW	1111	22	5	253	5	150

4.0 Comparison with Related Studies

Section 4.1 of this chapter presents a summary/review of the EPRI, The Climate Group, and Hledik assessments. Section 4.2 provides a comparison of these three and PNNL assessments.

4.1 Review of Related Studies

4.1.1 Electric Power Research Institute Green Grid Study

The EPRI report examined seven topic areas for which the smart grid can provide reductions in energy consumption and/or CO_2 emissions. Five of the topics were categorized as directly contributing to utility goals and provided reductions in both energy consumption and CO_2 emissions. The remaining two were not categorized as directly contributing to electric utility goals, and provided a reduction in CO_2 emissions. Estimates of the reductions in electricity and CO_2 emissions for the seven topic areas for the year 2030 are summarized in Table 4.1.

Table 4.1. EPRI Report: Smart Grid Energy Savings and Avoided CO_2 Emissions Summary (2030).

Emissions-Reduction Mechanism Enabled by Smart Grid		Energy Savings, 2030 (billion kWh)		Avoided CO_2 Emissions, 2030 (Tg CO_2)	
		Low	High	Low	High
1	Continuous Commissioning of Large Commercial Buildings	2	9	1	5
2	Reduced Line Losses (Voltage Control)	4	28	2	16
3	Energy Savings Corresponding to Peak Load Management	0	4	0	2
4	Direct Feedback on Energy Usage	40	121	22	68
5	Accelerated Deployment of Energy Efficiency Programs	10	41	6	23
6	Greater Integration of Renewables	--	--	19	37
7	Facilitation of Plug-in Hybrid Electric Vehicles (PHEVs)	--	--	10	60
	Total	**56**	**203**	**60**	**211**

Source: EPRI 2008
Note: Tg equals million metric tonnes (MMT)

The estimated reductions were drawn from information contained in the literature combined with expert insight to approximate the quantity of "… the energy savings and carbon reduction impact of selected discrete mechanisms to provide insight into the magnitude of smart grid environmental benefits (EPRI 2008)." A brief description of the mechanisms addressed in the study is provided here:

- *Continuous Commissioning of Large Commercial Buildings* provides monitoring of equipment "health" and energy consumption performance of large commercial buildings, with notification sent to the energy manager in cases of performance issues. The estimate is based on its application to large commercial buildings (>100,000 ft^2 in floor area) with the provision of electricity savings of 9% and market penetration ranging from 5% to 20%.

- *Reducing Line Losses* through voltage control and compensation for reactive power and line drop. The estimate is based on application of voltage control to the residential sector with voltage reduction of 1% to 4% and market penetration of 25% to 50%.
- *Energy Savings Corresponding to Peak Load Management* achieved through demand response and load control programs that utilize dynamic prices and automated demand response technologies. The estimate is based on other studies, results of field work and expert judgment.
- *Direct Feedback on Energy Usage* to consumers through advanced meters and display devices. The estimate is based on energy savings of 2.5% in the commercial and industrial sector, and 5% in the residential sectors with market penetration of 25% to 75% in all three sectors.
- *Accelerated Deployment of Energy Efficiency Programs* through M&V to reduce uncertainties regarding the performance and cost-effectiveness of energy efficiency measures, thereby increasing their deployment. The estimate is based on estimates of the maximum and realistic achievable levels of savings and expert judgment.
- *Greater Integration of Renewables* through communication and control strategies to compensate for temporal and intermittency factors. The estimate is based on the estimated fraction intermittency that the smart grid will resolve (12.5% to 25%) for the integration of electricity generated by an additional 50 MW of wind capacity in 2030. The reductions in CO_2 emissions are based upon EPRI's estimated generation profile for 2030, which provides CO_2 emissions of about 12%, slightly lower than the emissions based on the 2006 generation profile.
- *Facilitation of PHEVs* through price signals and behavior modification to encourage overnight charging, thereby improving the system load factor and utilization of base-load generation resources. The estimate is based on other studies and expert judgment.

4.1.2 Climate Group/Information and Control Technologies Report

One focus of the Climate Group report (often referred to as the ICT report) examined reductions in CO_2 emissions in four sectors (smart grid, road transportation, buildings, and travel substitution) that could be enabled by information and control technologies (ICT). This section provides the reduction in CO_2 emissions for the three topic areas in the smart grid sector. The buildings sector topic is not included in this discussion because the reduction is achievable without connection to the smart grid, although the ICT enable interaction with the smart grid, which may help ensure or further increase the estimated buildings' sector reductions.

Estimates of the reductions in energy consumption and CO_2 savings for the three topic areas for the year 2020 are summarized in Table 4.2. The estimates are based upon literature review and expert judgment, although the assumptions and analytical methodology underlying the estimates are not clearly stated.

Table 4.2. Climate Group Report: Smart Grid Energy Savings and Avoided CO_2 Emissions Summary (2020)

Topic	Energy Savings, 2020 (TWh)	CO_2 Emission Reductions,[a] 2020 (MMT)
Smart Grid	162-365	230-480
Integrate Renewable Resources	--	130-260
Reduce Transmission & Distribution (T&D) Losses	104-195	60-120
Real-Time Pricing	58-170	40-100

(a) Based on power sector CO_2 emissions of 2630 MMT.

A brief description of the topics:

- *Integrate Renewable Resources* through monitoring, communication, and control strategies to compensate for temporal and intermittency factors. The estimate is based on expert recommendations and President Obama's energy plan that renewables account for 10% to 25% of generating capacity.
- *Reduce T&D Losses* through voltage control and performance monitoring of grid components.
- *Real-Time Pricing* through communication of real-time prices to raise consumer awareness and integration of price signals with thermostats and appliances.

A second focus of the report was on policy mechanisms that could be used to facilitate and overcome the technical, economic, and behavioral barriers to implementing smart grid technologies. Policy thrusts need to address the business case for smart grid investments and to conduct demonstrations in federal utilities to stimulate private-sector smart grid efforts (Figure 4.1).

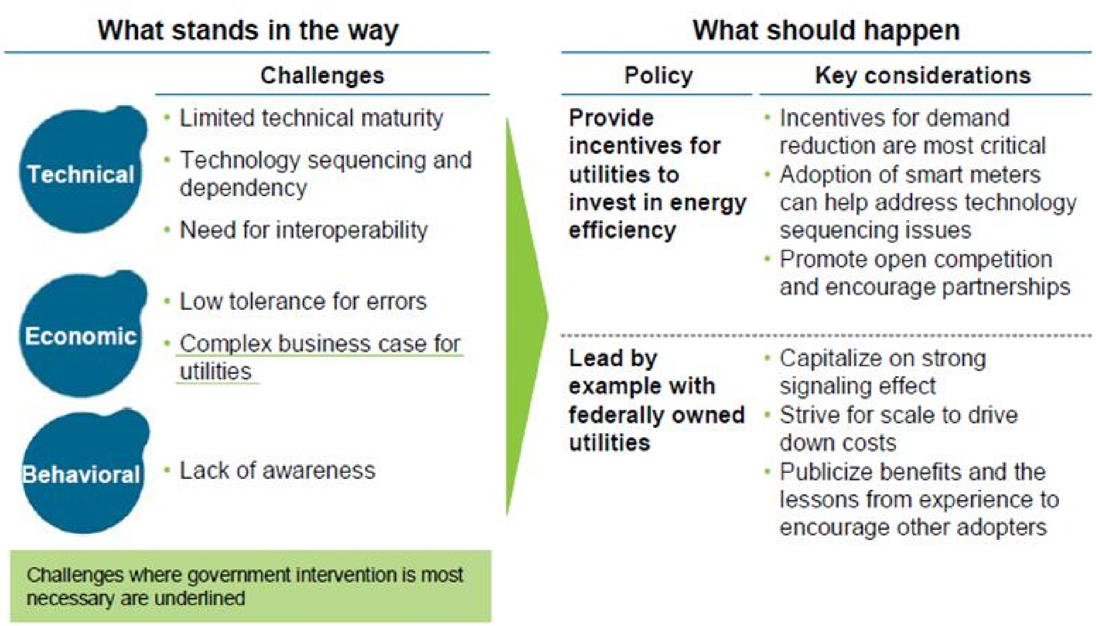

Figure 4.1. Climate Group Report: Policy Recommendations. Source: Climate Group Report

4.1.3 Hledik Article: How Green is the Smart Grid?

The paper "How Green Is the Smart Grid?" examined the energy and CO_2 impacts for two illustrative scenarios depicted in Figure 4.2 for the implementation of smart grid technologies in 2030, which are not intended to bracket the range of achievable reductions. The first is a "Conservative" scenario that uses cost-effective commercially available technologies (dynamic pricing, automating technologies, and information displays) in conjunction with the AMI. The second is an "Expanded" scenario that adds longer-term smart grid impacts obtained from distribution systems through increased penetration of renewable and distributed storage technologies. The scenarios were intended to examine two possibilities and were not intended as predictions of the future state.

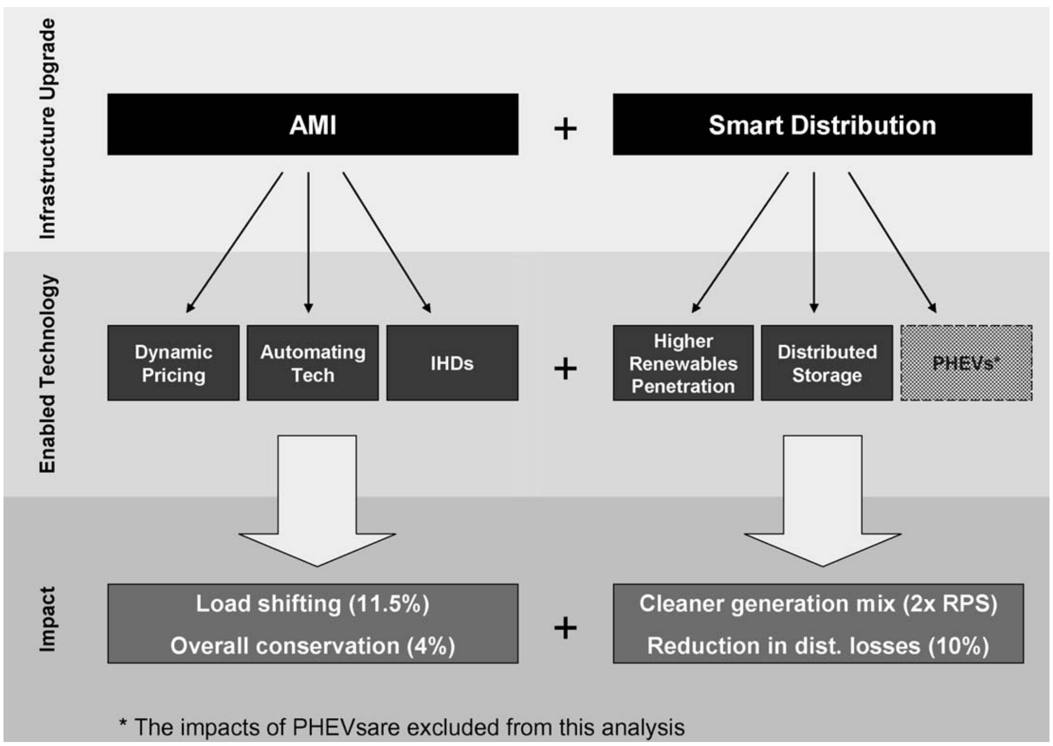

Figure 4.2. How Green is the Smart Grid? Conservative (Left Side) and Expanded Scenarios (Source: Hledik 2009)

The conservative scenario is based on an earlier analysis and the expanded scenario was based on the Regional Capacity Planning (RECAP) model that provides the least-cost mix of system generating resources for a given demand forecast. The use of the RECAP model enables differences in the regional the mix of generating resources and emission rates to be accounted for more accurately. The assumptions for the RECAP portion of the analysis are keyed to AEO 2008, and the magnitude of the energy and CO_2 outputs are comparable.

Estimates of the reductions in CO_2 for the topics in the conservative and expanded scenarios for the year 2030 are summarized in Table 4.3. The analysis assumes that the smart grid allows the penetration of renewable resources to double over the approximate 20% RPS level, but it is not apparent if the reduction in CO_2 emissions is for the entire penetration of ~40% or only the additional ~20%. This is mentioned, because the reduction in CO_2 emissions from increased renewable penetration is over 60% of the total at the40% penetration level, and they are still the largest category at nearly 50% of the total at the 20% penetration level.

Table 4.3. Smart Grid Energy Savings and Avoided CO_2 Emissions Summary (2030)

Topic	Energy Savings, 2030 (TWh)	CO_2 Emission Reductions,[a] 2030 (MMT)
Conservative Scenario -- Based on AMI		
Dynamic Pricing with Automation (Load Shifting)	NA	3
Dynamic Pricing with Automation (Energy Efficiency)	NA	99
In-Home Displays	NA	51
Expanded Scenario – Conservative Scenario plus Increased Renewables and Storage		
Integrated Renewable and Storage (Cleaner Generation)	NA	297
Integrated Renewable and Storage (Reduced Losses)	NA	21

(a) Based on power sector emissions of 3000 MMT

A brief description of the topics:

- *Dynamic Pricing with Automation (Load Shifting)* provides the reduction in peak load capacity through dynamic pricing with automating technologies.
- *Dynamic Pricing with Automation (Energy Efficiency)* provides the reduction in energy consumption through dynamic pricing with automating technologies.
- *In-Home Displays* provide the reduction in energy consumption through physical displays of the dynamic pricing.
- *Integrated Renewable and Storage (Cleaner Generation)* provides the effect of using lower-emission renewable generating and associated storage technologies.
- *Integrated Renewable and Storage (Reduced Losses)* provides the reduced losses due to the use of distributed renewable generating and associated storage technologies.

4.2 Comparison

A comparison of the three studies is difficult at best due to differences in number and definition/scope of the topics, analysis assumptions and methods, baseline data, and the time periods used to convey the reductions. The percentage reductions shown in Table 4.4 help remove the temporal component, but the above differences among the individual mechanisms examined in the four studies still makes a strict comparison tenuous.

Table 4.4. Comparison of Estimated Reductions in Energy Consumption and CO_2 Emissions

Mechanism	Reduced Energy Consumption and CO_2 Emissions, % Direct	Reduced Energy Consumption and CO_2 Emissions, % Indirect	Comment
PNNL			
Conservation Effect of Consumer Information and Feedback Systems	3	--	Relative to DOE/EIA 2030 Reference Case
Joint Marketing of Energy Efficiency and Demand Response Programs	--	0	
Deployment of Diagnostics in Residential and Small/Medium Commercial Buildings	3	--	
M&V for Energy Efficiency Programs	1	0.5	
Shifting Load to More Efficient Generation	<0.1%	--	
Support Additional EVs and PHEV	3	--	
Conservation Voltage Reduction and Advanced Voltage Control	2	--	
Support Penetration of Renewable Wind Generation, 25% RPS (assumed similar for solar PV)	<0.1	5	
Total	12	6	
EPRI			
Continuous Commissioning of Large Commercial Buildings	0.04 to 0.2	0.03 to 0.2	Relative to DOE/EIA 2030 Reference Case
Reducing Line Losses	0.1 to 0.6	0.07 to 0.5	
Energy Savings Corresponding to Peak Load Management	0 to 0.1	0 to 0.07	
Direct Feedback on Energy Usage	0.8 to 2.4	0.8 to 2.3	
Accelerated Deployment of Energy Efficiency Programs	0.2 to 0.8	0.2 to 0.8	
Greater Integration of Renewables	--	0.6 to 1.3	
Facilitation of PHEVs	--	0.3 to 2.0	
Total	1.1 to 4.1	2.0 to 7.2	
Climate Group			
Integrate Renewable Resources	--	-4.9 to -9.9%	Relative to 2020 DOE/EIA 2020 Reference Case
Reduce T&D Losses	2.3 to -4.3	-2.3 to -4.6	
Real-Time Pricing	-1.3 to -3.8	-1.5 to -3.8	
Total	3.6 to 8.1	8.7 to 18.3	

Table 4.4. (contd)

<table>
<tr><th>Mechanism</th><th>Reduced Energy Consumption</th><th>Reduced CO_2 Emissions, %</th><th>Comment</th></tr>
<tr><td colspan="4">Hledik</td></tr>
<tr><td>Dynamic Pricing with Automation (Load Shifting)</td><td rowspan="3">11.5% reduction in capacity
4% reduction in energy</td><td>0.1</td><td rowspan="6">CO_2 Emissions based on 2030 power sector emissions of 3000 MMT, which is approximately the DOE/EIA 2030 reference case</td></tr>
<tr><td>Dynamic Pricing with Automation (Energy Efficiency)</td><td>3.3</td></tr>
<tr><td>In-Home Displays</td><td>1.7</td></tr>
<tr><td>Integrated Renewable and Storage (Cleaner Generation)</td><td rowspan="2">10% reduction in distribution losses</td><td>9.7</td></tr>
<tr><td>Integrated Renewable and Storage (Reduced Losses)</td><td>0.7</td></tr>
<tr><td>Total</td><td></td><td>5.1 to 15.7</td></tr>
</table>

Note: The base from the percentages is forecasted net generation and total energy-related CO_2 emissions from the AEO 2008 (Tables A8 total sector electricity sales, and A18 total emissions, the estimates (i.e., numerators) in Tables 4.1, 4.2, and 4.3 were also based on the AEO 2008 forecasts, with slight modifications in some cases.

5.0 Recommendations and Issues

This section provides a summary of issues identified for each of the nine mechanisms and recommendations for addressing these issues. A more detailed discussion of each of the mechanisms, with recommendations, is contained in Attachment 1. In addition, a number of additional issues that may impact the penetration of smart grid technologies are presented.

5.1 Mechanism Recommendations

5.1.1 Conservation Effect of Consumer Information and Feedback Systems

This discussion provides recommendations to improve the understanding and effectiveness of feedback that makes consumers aware of their energy consumption and modifications they can make to behaviors in response to information and price signals. This feedback process is necessary to obtain the mutual benefits to customers and utilities from energy efficiency, demand response, diagnostics, and other programs that require interaction with and response from customers. A review of these mechanisms, with a complete list of recommendations for improving the design and implementation of feedback, is presented in Attachment 1.

Four methodological issues were identified in the review. The primary issue is the extent to which results are influenced by self-selection of sample respondents, because they may be more motivated with higher levels of environmental concerns and self-efficacy. A second methodological issue is that very few studies evaluated the persistence of the conservation and efficiency effects observed to ensure that behavior change is maintained and rebound effects are prevented. A third methodological issue concerns the sample size and variability of the studies, as in the studies reviewed; the samples were limited to no more than several hundred households that were as homogeneous as possible. The final methodological issue relates to the behavioral granularity of the conservation and efficiency effects reported to understand how the savings obtained from a program were actually achieved.

Separate recommendations were formulated to address each of these issues, with a common theme that called a large and diverse sample tracked over a long period of time (24 months), with a study tailored to examine the respective issue. An alternative would be to segment the large sample to examine the behavioral issues in parallel to develop a more robust feedback system. In either case, the examination should include additional issues pertinent to consumer behavior to better understand savings effects and behavioral "entry points" for various groups of consumers, as outlined in the review in Attachment 1.

5.1.2 Deployment of Diagnostics in Residential and Small/Medium Commercial Buildings

The issue is that many technologies are required to enable diagnostics in buildings to be performed through the smart grid. Some of these are being developed and marketed today; others are missing from the marketplace. The recommendation is to pursue development of analytic software-based technologies that either are needed for, or could contribute to, cost-effective automated energy management. They include those that: enhance and system operation in residential and small commercial buildings, automate fault detection and diagnostics, automate commissioning, enable price-based controls, and enable coordination and integration with other systems.

5.1.3 Joint Marketing of Energy Efficiency and Demand Response Programs

The issue is that customers are often confused by the differentiation between energy efficiency and demand response programs; combining the administration of these two types of programs would improve their effectiveness by eliminating the confusion and provide cost savings that could be reinvested in energy efficiency programs. This issue is not addressed in the literature and program data is not in the form that permits estimation of administrative cost reductions or increases in program effectiveness. The recommendation is to assess the impact of co-administering energy efficiency and demand response programs to determine the magnitude of reductions in administrative costs, energy efficiency, and demand response when the programs are administered together. This would enable extrapolation of how the implementation of smart grid technologies may influence the effectiveness (e.g., energy, capacity, and utility cost) of merging energy efficiency and demand response administrative/delivery structures.

5.1.4 Measurement & Verification for Energy Efficiency Programs

The issue is that M&V program evaluations of program effectiveness and technology performance are often limited by budget constraints, which lead to reductions in the scope and duration of the effort, as well as the methods used, and which decreases accuracy and transparency. The recommendation is to develop software-based analytic methods that leverage the smart grid's metering and communication abilities to expand the sample size, improve data granularity, and increase the duration of M&V efforts. This will provide for increased accuracy and transparency, lower cost, and assessment of persistence.

5.1.5 Shifting Load to More Efficient Generation

The issue is that estimation of reductions in energy and CO_2 emissions is subject to significant uncertainty due to the types of power plants that provide base, intermediate, peak load power, and the order for dispatch. It is recommended that the estimates of energy and CO_2 reductions that result from load shift be the subject of more methodical efforts to determine differences that may result by minimizing economic impacts, maximizing energy reductions, and maximizing CO_2 reductions.

5.1.6 Support Additional Electric Vehicles and Plug-In Hybrid Electric Vehicles

The issue is that analyses to date provide considerable uncertainty for the reduction in CO_2 emission due to the high dependency on the reference vehicle to which a PHEV or EV is compared, and the timing and duration of the charging influence on the carbon intensity. In addition, analyses do not provide a uniform estimate of the economic benefits of off-peak-load charging by utilizing higher efficient intermediate or base-load power plants. It is recommended to employ a more comprehensive analysis that analyzes the incremental energy, economic, and environmental benefits of load-management strategies of a growing EV fleet.

5.1.7 Conservation Voltage Reduction and Advanced Voltage Controls

The issue is that the majority of current knowledge regarding the effectiveness of voltage reduction and controls is empirical, and cannot be validated analytically. Consequently, we do not fully understand how new technologies will interact with CVR and thus be fully exploited. It is recommended to conduct additional research to improve understanding about the fundamental nature of CVR and how it can be exploited to interact with demand response and distributed energy resources to provide improved system operation with energy, capacity, and emission benefits.

5.1.8 Support Penetration of Solar Generation (Renewable Portfolio Standard > 20%)

The issue is that the tipping point where solar PV "helps" the system to become a limiting factor that is detrimental to the system cannot be simply stated, because of the variability of the solar resource and the size and diversity of the system. Additional research is needed to determine the feasible limit with existing technologies and to determine new operating strategies based on smart grid monitoring and control capabilities that allow for greater penetration of solar PV.

5.1.9 Support Penetration of Renewable Wind Generation (Renewable Portfolio Standard >20%)

The issue and recommendation is virtually identical to that for the integration of solar PV to determine the limit to integration of wind resources and the smart-grid-based operating and control strategies that consider load size and diversity, storage, and demand response to provide guidelines for implementation efforts.

5.2 Additional Issues

A number of issues not connected to the nine mechanisms examined in this report may impact the penetration of smart grid technologies:

- Proof of the cost effectiveness of smart grid technologies on the demand side may cause difficulty at state regulatory hearings for demand response resources (SmartGridNews.com 2009b). Related issues may be 1) the integration of smart grid elements into the IRP methodology commonly used by utilities and regulatory commissions, and 2) the inclusion of the monetized value of carbon, and 3) the inclusion of the monetized value of other emissions and impacts.
- An account of the energy and carbon savings that will accrue with the integration of solar PV and wind due to the reduction in unaccounted for parasitic loads associated with the operation of fossil-fuel powered plants (these loads increase with carbon capture) and transmission of electricity.
- An account of the energy and carbon savings that will result from a decrease in reactive power and a decrease in the load on the T&D networks .
- Development of a quantitative method to monetize improvements in power reliability and quality, and reductions in T&D congestion that will be realized with smart grid operations.
- Even though energy and CO_2 emissions typically go hand-in-hand, the smart grid may produce a greater reduction in CO_2 emissions than in energy use in cases in which the load is reduced from CO_2-

intensive peak load generating sources to less CO_2-intensive intermediate or base-load power plants. This presents an interesting future where demand response and distributed generation resources can be managed on strictly economic-based criteria, strictly CO_2-based criteria, or a mixture of both.

- To realize the estimated reductions the smart grid can deliver, two offsetting increases in consumption need to be accounted for. The first assumes that a server is needed in every distribution substation to monitor end-use loads, provide two-way communications with customers and, where user permitted, provide automated demand response. The number of distribution substations is unknown, so an assumption of 100,000 substations is made based upon an estimated 300 to 400 thousand feeders and 3 to 5 feeders per substation. Each server is expected to draw 1kw for every hour of the day throughout the year, thus increasing expected energy consumption by nearly 1 B kWh/year. The second assumes that demand response/GFA devices are installed in the entire stock of 466 M appliances (heat pumps, air conditioners, dryers, refrigerators, and freezers) (EIA-AEO 2008), individually draw a load of 1 to 5 w every hour of the day throughout the year, to additionally increase expected energy consumption by 4 to 20 B kWh. The combined effect of the two offsets may increase the 2030 electric utility sector energy and CO_2 emissions by 0.1% to 0.4%. While the increase is small and may not be considered important, it does point to the need for technology developers to minimize the increased loads of smart grid technologies.