Energy Demand and Supply Outlook for 2050 in US Building Sector [1]

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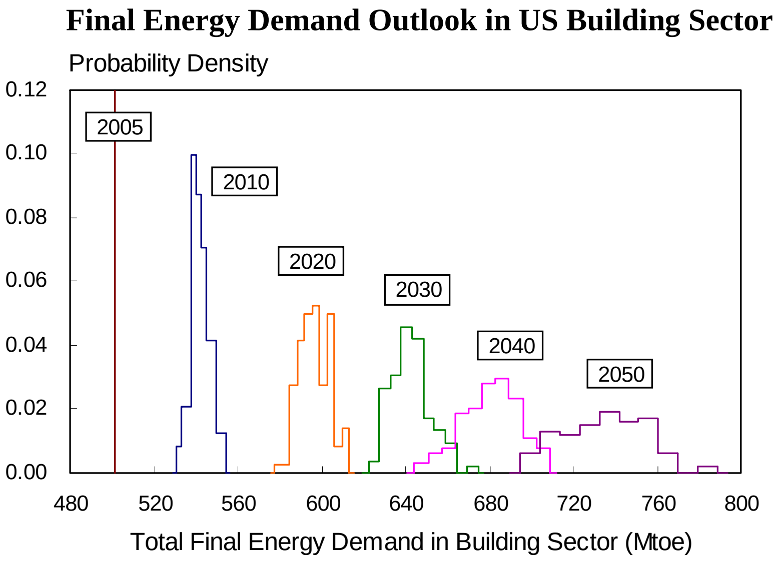
ABSTRACT

The U.S. Department of Energy (USDOE) is building a new long-range (to 2050) forecasting model which explicitly incorporates uncertainty of economic and technological parameters. In order to contribute to the DOE project, we developed the module to evaluate the energy demand and supply in U.S. building sector up to 2050. This module covers both commercial and residential buildings at the U.S. national level using an econometric forecast model of floorspace requirement, and a model of building stock turnover as the basis for forecasting overall demand for building services. Although the module is fundamentally an engineering-economic model with technology adoption decisions based on cost and energy performance characteristics of competing technologies, it differs from standard energy forecasting models by including considerations of passive building systems, interactions between technologies (such as internal heat gains), and on-site power generation.



(Note) The above result is derived assuming statistical distribution through probability distribution function in major exogenous values used in Reference Scenario, such as GDP, population and technological cost.

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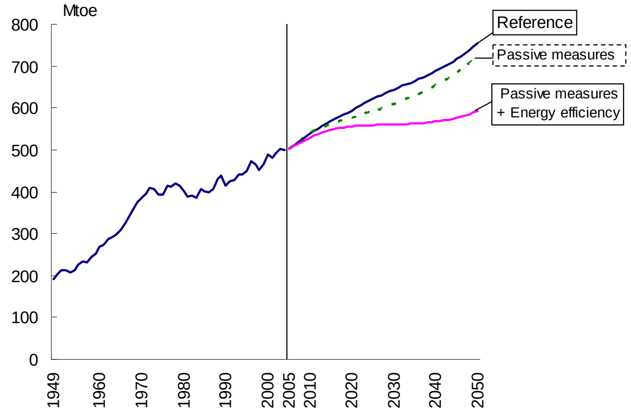
Energy demand in US building sector is projected to grow from 501 Mtoe in 2005 to 754 Mtoe in 2050. If passive measures such as insulation, natural ventilation, and natural lighting are more aggressively implemented, then the energy demand is likely to increase up to 722 Mtoe in 2050, exhibiting a reduction of 32 Mtoe from the current reference projections. If rapid adoption of energy efficient technologies along with passive measures are implemented, then the energy demand is projected to increase up to 593 Mtoe in 2050, showing a reduction of 161 Mtoe from current reference projections. Thus, the accelerated penetration of energy efficient technologies such as LED lighting, heat-pump water heating, and highly efficient electric appliances, together with improving passive attributes is expected to play an important role in massive energy conservation.

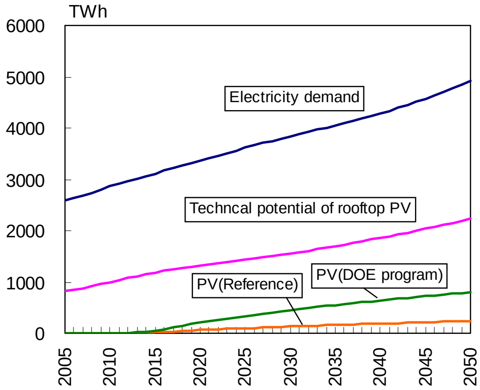
Energy Demand Outlook in US Building Sector



(Note) Actual energy demand data: EIA/DOE, "Annual Energy Review 2006," Report No. DOE/EIA-0384 (2006). Projection is expected value under statistical behavior of exogenous variables.

In energy supply side, photovoltaic (PV) generation is expected to play an effective role in ensuring demand-side energy security in the US building sector. The share of PV generation in electricity demand is projected to be 5% in 2050. If DOE continuously fund PV R&D effort, the share is likely to reach 16%. In those amounts, electricity purchase is forecast to be curtailed and self-sufficiency in end-use energy supply is expected to be enhanced.

PV Generation in US Building Sector



(Note) "Reference" scenario only considers baseline industrial R&D effort. "DOE program" scenario incorporates currently planning DOE R&D activity. Illustrated electricity demand is calculated under Reference Scenario.

1. Introduction

The perception that our energy future looks increasingly uncertain, and that climate change requires us to explore radically different technology pathways has precipitated the search for new or accelerated technology research and development (R&D) and the analysis tools necessary to guide it. The work presented in this paper is part of the ongoing development of the long-term energy forecast model, which follows in a long history of modeling in support of planning and budgetary activities at the U.S. Department of Energy (USDOE). This model was commissioned to better support management, research direction, and budgetary decision-making for future R&D efforts. Specifically, it will be used to comply with the Government Performance Results Act of 1993 (GPRA), which requires federal government agencies, including USDOE, to predict and track the results of their programs and report them as a part of their obligations to the U.S. Congress (Gumerman 2005). While this process may at first blush seem like a harmless bureaucratic exercise, the wider implications of research budgets and priorities being determined based on faulty or misleading forecasts are serious. At a minimum, misdirection of limited public R&D funds could result. By developing this model, USDOE seeks to develop a tool that will help define a range of possible outcomes rather than accepting a potentially misleading scalar prediction, and to aid in the development of programs robust to our uncertain destiny.

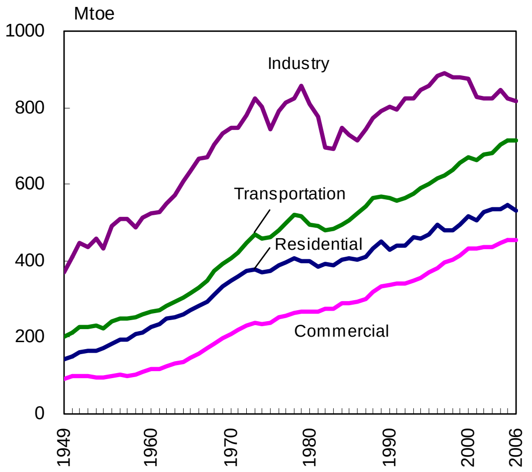
This project is not intended to be a replacement for the Energy Information Administration’s (EIA’s) National Energy Modeling System (NEMS), which provides the basis for the Annual Energy Outlook (AEO), and subsequently for many energy policy studies. Rather, the project is an adjunct that allows modeling of economy-wide energy costs and consumption out to 2050 (NEMS currently forecasts to 2030) with minimal user effort or expertise. This emphasizes characterizing the robustness of expected benefit streams of new technologies given the uncertain nature of energy futures, whereas NEMS is solidly rooted in historic and current conditions. Also in the interests of speed and because the belief that global equilibriums are rarely experience in the real-world, no iterations towards solutions in one time step are allowed; rather outputs from one time step are inputs to the next.

This paper develops energy scenario to 2050 in US building sector renovating the existing modeling concept (Marnay, 2008) and describes the motivation to build up long-term energy forecasting model, but it is primarily focused on the effort to develop the first incarnation of the building sector module. This effort creates a rare opportunity to address some of the fundamental concerns that are widespread in the building energy simulation and forecasting community, such as: representing building end-use interactions, allowing competition between active and passive approaches, recognizing the key role of retrofits of existing buildings, integrating selection of on-site generation, etc. The entire project is evolving, and the motivations for reporting on the approach at this time to this audience include the hope that feedback from the building energy modeling community can guide the future shape of the model. Note that the future direction of Federal buildings energy research will rest in part upon its results. Finally, it should be noted that working within an uncertainty framework allows for extension of typical forecasting to consider real options and other techniques derived from portfolio theory (Awerbuch 2003, Siddiqui 2007).

2. US Energy Demand in End-use Sector

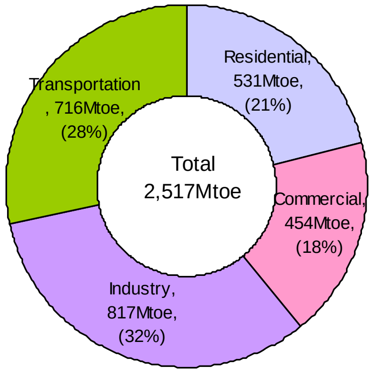
Before explaining the outline of the model and its simulation results, US energy consumption is briefly introduced. The industrial sector uses about one-third of the total energy. The residential and commercial sectors combined use even more than this - 40 percent of all energy. These latter two sectors include building types such as houses, offices, stores, restaurants, and places of worship. Energy used by the transportation sector accounts for more than a quarter of all energy used. All four major sectors recorded tremendous growth in their use of energy. The industrial sector used the biggest share of total energy and showed the greatest volatility; in particular, steep drops occurred in the sector in 1975 and 1980-1983 largely in response to high oil prices and economic slowdown.

Figure 2-1. Energy Demand by End-Use Sector



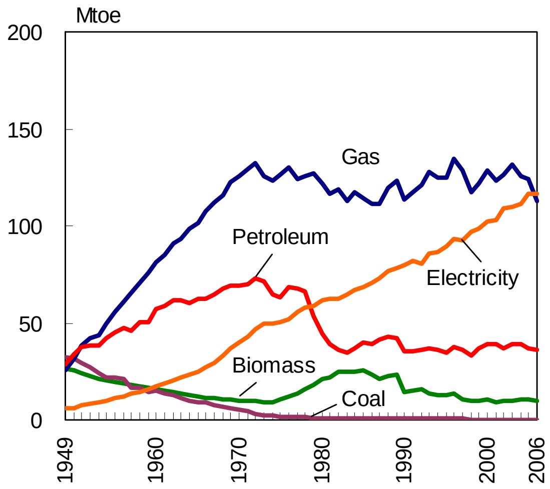
(Source) EIA/DOE, "Annual Energy Review 2006," Report No. DOE/EIA-0384 (2006)

Figure 2-2. Energy Demand by End-use Sector in 2006



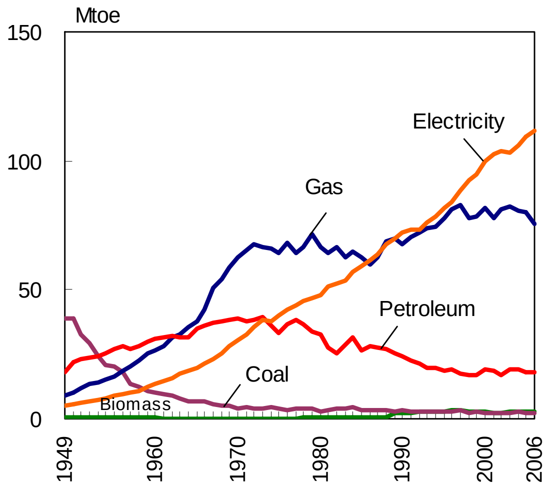
(Source) EIA/DOE, "Annual Energy Review 2006," Report No. DOE/EIA-0384 (2006)

Figure 2-3. Energy Demand in Residential Sector by Energy Source



(Source) EIA/DOE, "Annual Energy Review 2006," Report No. DOE/EIA-0384 (2006)

Figure 2-4. Energy Demand in Commercial Sector by Energy Source



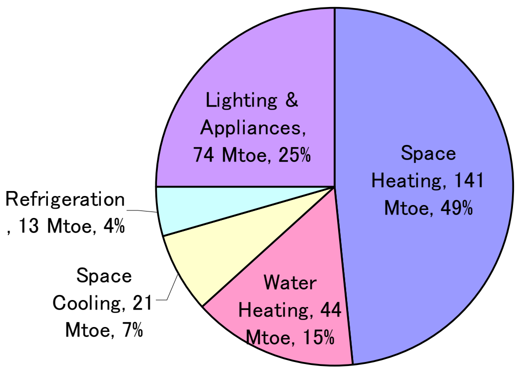
(Source) EIA/DOE, "Annual Energy Review 2006," Report No. DOE/EIA-0384 (2006)

Primary energy consumption by the United States in 2006 was about 2.5 billion oil equivalent tons (hereafter referred to as "tons"), five times as large as Japan whose primary energy consumption was approximately 0.5 billion tons. The transportation and industrial sectors used approximately 0.7 and 0.82 billion tons, respectively. Primary energy consumption by *each* of these sectors exceeded the primary energy consumption of Japan as a whole. Consumption of approximately 0.53 billion tons by the residential sector and approximately 0.45 billion tons by the commercial sector, which together constitute the "consumer sector," accounted for about 40% of the total.

Energy consumption by energy source has also changed throughout the years. Coal, which had been important to residential and commercial consumers in the building sector throughout the 1950s and 1960s, was gradually replaced by other forms of energy. Petroleum consumption peaked in the early 1970s. Natural gas consumption grew fast until the early 1970s and then, with mild fluctuations, held fairly steady in the following years. Meanwhile, electricity use expanded dramatically due to the introduction and adoption of new electrical appliances.

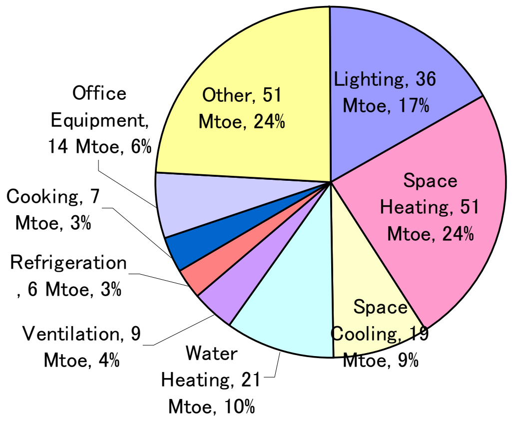
In the US residential sector, natural gas is the most widely used energy source, followed by electricity, heating oil and propane. Natural gas and heating oil (fuel oil) are used mainly for home heating. Electricity may also be used for heating, cooling, plus lighting, and runs almost all of the appliances including refrigerators, television and computers. Many homes in rural areas use propane for heating, while others use it to fuel their barbecue grills. In the commercial sector, electricity and natural gas are the most common energy sources used. Commercial buildings also use district heat, which is a central heating and cooling plant that distributes steam, hot water, or chilled water to all of the different buildings.

Figure 2-5. Energy Demand in Residential Sector by Service in 2005



(Source) EIA/DOE, "Annual Energy Review 2006," Report No. DOE/EIA-0384 (2006)

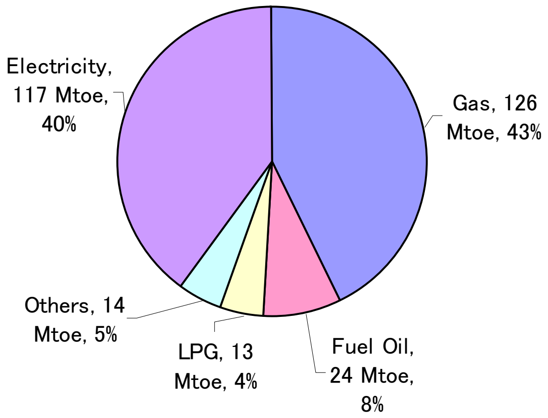
Figure 2-6. Energy Demand in Commercial Sector by Service in 2005



(Source) EIA/DOE, "Annual Energy Review 2006," Report No. DOE/EIA-0384 (2006)

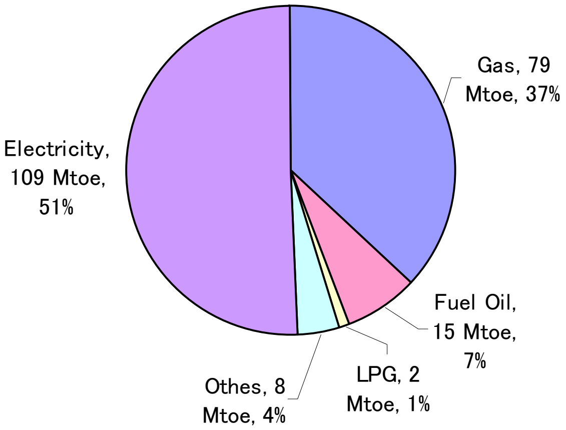
In terms of the breakdown in energy service demand, almost half of the average home's energy consumption is used for heating, 15 percent is used for water heating, 7 percent for cooling rooms, and 4 percent for refrigeration. Almost one-fourth of the energy used in homes is used for lighting and appliances. Commercial buildings, on the other hand, include a wide variety of building types, e.g. offices, hospitals, schools, police stations, places of worship, warehouses, hotels, barber shops, libraries, shopping malls, and each has unique energy needs; but, as a whole, commercial buildings use almost half of their energy for heating, cooling and lighting.

Figure 2-7. Energy Demand in Residential Sector by Energy Source in 2005



(Source) EIA/DOE, "Annual Energy Review 2006," Report No. DOE/EIA-0384 (2006)

Figure 2-8. Energy Demand in Commercial Sector by Energy Source in 2005



(Source) EIA/DOE, "Annual Energy Review 2006," Report No. DOE/EIA-0384 (2006)

3. The Importance of Uncertainty

The type of forecasting conducted in support of policymaking and planning in the U.S. has typically paid scant attention to the significant uncertainty inherent in many aspects of such analysis. Forecasts are frequently presented as point estimates only, or as point estimates with sensitivity cases or side scenarios.[2] A preeminent example of the point forecast with side scenarios is the AEO.

Despite the obvious importance of uncertainty in any forecasting endeavor, the stability of conditions in the later part of the twentieth century fostered complacency. Figure 3-1 shows the AEO forecasts of wellhead natural gas prices. The years in which the forecasts were made are shown, as is the actual trajectory of prices to date. Notice that the forecasts change year-by-year towards the extrapolation of recent prices. Additionally, while some forecasts featured falling prices followed by an upswing, of the 23 forecasts displayed, only the ones made around 1990-92 came close to identifying the key turning point that occurred around 1995. Finally, conduct the mental exercise of extrapolating the outer boundary of 1985 and 1997 forecasts out to 2050. The range of possible forecasts contained in those boundaries is vast, and these are not representations of uncertainty per se, they are actual point forecasts, just made in different eras.

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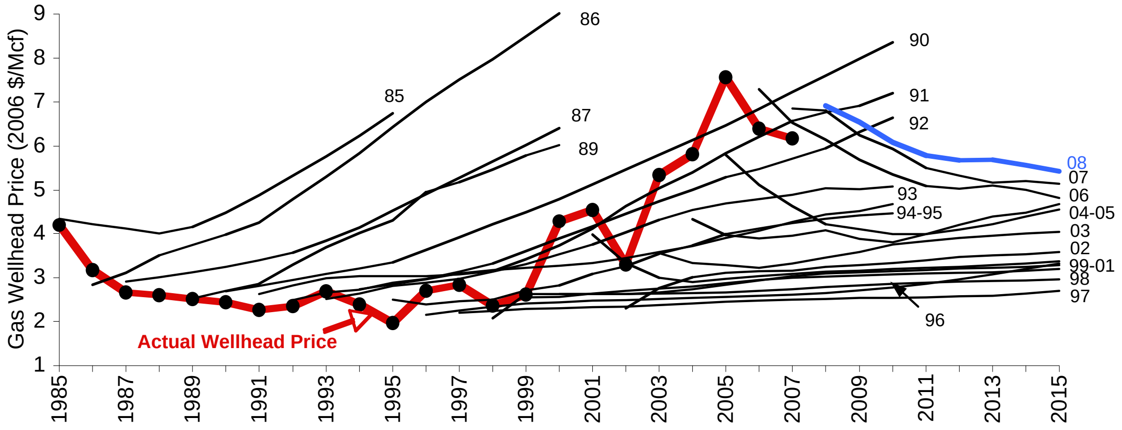
[2] In general, a sensitivity case is a rerun of an analysis in which just one input is changed, while a scenario is one with multiple variables adjusted.

Figure 3-1. EIA Forecasts of Natural Gas Price



(Source) EIA 2008 & 2008a, AEO from several years

In addition to the unpredictability of technology evolution, there are several common aspects to how uncertainty enters into a forecast, and most of them are familiar and intuitive: inaccuracy of historic data, errors in methods, unexpected external conditions, price volatility, etc. All of these argue for modeling the future with key scalar variables replaced by probability distributions that reflect our level of confidence in our forecasts of their values. Such an approach is the simple principle by which the model developed here is being constructed on a platform.

Before exploring the model, it is worth noting a key aspect of forecasting that our model does not address. Energy history may have turned a corner around the same time the millennium turned. A long period of relative stability that lasted from the mid-1980's appeared to come to an abrupt end. Fuel prices became more volatile and have generally increased, raising overall costs. Note that introducing uncertainty into certain variables does not imply that we can produce forecasts that include discontinuities, and indeed, these might be the events forecasters would be most interested in predicting. Rather, our approach provides a wide distribution around forecasts to reflect the uncertainty of point forecasts. Nonetheless, the model estimates and their uncertainty bounds are still highly smoothed curves, and any "corners" can only be introduced by the modeler (Short et al. 2007 and Siddiqui 2007).

4. Model Structure

Similar to NEMS, the architecture of model is that all energy producing and consuming activities in the economy are modeled using a set of interconnected modules representing the key sectors, where the inputs to one module are the outputs from others (SEDS 2008). Planned or existing modules are currently called Macroeconomic Activity, World Oil,[3] Coal, Natural Gas, Renewable Fuels, Liquid Fuels, Transmission, Electricity, Industry, Buildings, and Transportation. Also like NEMS, the model uses energy and capital costs to determine economically optimal technology adoption. Unlike NEMS, it is designed to favor simplicity over detail, with the goal of providing a system that produces results quickly out to 2050. It does not

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[3] All modules except World Oil are at the U.S. national level.

iterate towards an equilibrium, rather outputs of one time step are inputs to the next, and an effort is being made to keep the modules consistent enough for users to delve into them. Also, to allow user control over runtime, it is designed around a variable user-chosen time step. Note that the emphasis on fast execution time is motivated by the need to achieve stochastic results with acceptable variance reduction.

4.1 Generic Structure

In the spirit of developing a tool that is relatively easy to program and with the goal of transparent logic, our task was to develop a standard module *Template* that encapsulates the core logic of engineering-economic decision-making that could be used in every module. The Template is basically a code library that standardizes the process of defining and quantifying service demands, such as annual kWh of domestic hot water (DHW), to be met with specific technologies using a logit market segmentation. It also standardizes the data input to characterize each technology (lifetime, performance, unit costs, etc.) and the calculation of its market share at each time step. The Template assumes that there is a stock of existing equipment, then the logit market share calculations are used to determine what new equipment is chosen to meet expanding and replacement requirements. Consumption rates of fuels at each time step are calculated by determining how much fuel is required to operate the stock of existing equipment to exactly meet the service demands. Thus, the Template, and our model generally, can be thought of as a systems or stock model (see Chapter 1 of Hannon and Ruth).

There are clearly benefits to the simplifying assumptions of the Template and the standardization it provides; however, fitting it to any of the energy sectors inevitably creates problems, and buildings are no exception. First and foremost, the Template was designed to trade-off the attributes of similar technologies for meeting a single service demand. For example, all else being equal, it chooses a more efficient refrigerator over a less efficient one to meet requirements for refrigeration service; however, many of the best examples of energy saving potential in buildings do not fit the pattern of simple efficiency improvements to existing technology. Such examples are better thought of as changes of approach, e.g. passive reduction in active service requirement versus more efficient active systems for meeting requirements. Inevitably, the trade-off between the convenience of a common module structure and representing the details of a sector proves tricky. One of the fundamental issues with the buildings sector is that radical changes in service provision might be necessary to meet climate change goals, but some of the immediate problems encountered include the following:

- a major research area for buildings concerns whole systems design, commissioning, and operation that takes advantage of several components working together to create mutual benefits and sometimes eliminates equipment, which is technically dissimilar to single service technologies, such as vehicles;

- passive approaches, such as insulation, daylighting, and building orientation, provide tangible building services but consume no energy directly and often augment the effects of mechanical systems;

- internal heat gains decrease the demand for heating in winter and in large commercial buildings in some climates are the dominant source of cooling demand in the summer, and these effects confound rigid concepts of energy services;

- on-site generation of electricity that offsets external electricity purchase without reducing consumption by on-site appliances requires site-specific economic evaluation, and in some cases, co-produces waste heat that can off-set other building energy requirements;

- tastes for provision of services in buildings could change radically, e.g. a preference for smaller homes might emerge, or similarly, exogenous forces could influence building design choice, e.g. changing available home mortgage options.

Many of the best strategies for lowering net energy use by buildings fall into this list. On top of this, climate has a major effect on the service demands to be met within a given building, so service demands were estimated for 9 climate zones, although results are only reported nationally.

4.2 Implementation Flow of the Buildings Module

The residential and commercial sectors can be thought of as a series of stock models running in parallel that track equipment characteristics and market share as time progresses. The stock of equipment required is determined by the overall demand for its services, e.g. lumen·hour. At each time step, a series of calculations are performed that take input macroeconomic data and fuel prices and output estimates of fuel consumption requirements for provision of a set of building services, i.e. lighting, DHW, ventilation, refrigeration, other loads, heating, and cooling. Those calculations are performed as follows (see also Figure 4-3-1):

(1) The total demand for floorspace for residential and commercial buildings is forecasted using a simple linear multivariate econometric regression model with the following independent variables: GDP, population, a time lag, and disposal personal income (DPI).[4]

(2) A building stock model determines required new construction at each time step to meet floorspace demand. The floorspace stock model also tracks demolition based on average building lifetimes.

(3) Current floorspace is multiplied through by the expected service demand intensities to arrive at the total raw service demands. In the case of heating and cooling, floorspace is disaggregated by climate region so that heating and cooling degree days (HDD & CDD) can serve as appropriate service intensities.

(4) The total raw service demands are adjusted for the influence of passive technologies, such as insulation and daylighting, as well as other mitigating factors, such as internal heat gains and infiltration.

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[4] Note that SEDS has a Macroeconomic Module to forecast these parameters, and there is also a harness that includes the values used in NEMS.

(5) The residual service demands are passed on to specific stock models as these must be met by active, i.e. fuel consuming, technologies.

(6) Every service-specific stock model tracks the amount of each technology available at each time step considering retirements, and calculates how much new equipment will be needed.

(7) The amount of each type of new equipment put into service is determined by an engineering-economic calculation using a logit function to determine market shares. The current logit parameters are determined through maximum likelihood estimation (MLE) or somewhat arbitrary.

(8) Fuel type, efficiency, and technology market share are then used to determine total fuel consumption.

(9) Fuel consumption is then offset by on-site generation with or without combined heat and power as appropriate (this capability is in development).

(10) Fuel consumption is summed across all demand-specific stock models to yield total fuel demands.

After the sequence defined above has been executed for each time step, the projections of floorspace, service demands, technology market share and quantities, energy consumption and fuel use are available for examination and interpretation; however, if any of the macroeconomic or other inputs are based on a probabilistic distribution rather than scalar values, the model runs multiple times with Monte Carlo drawing methodology.

4.3 Passive Characteristics in Buildings

Given the strengths of the Template in modeling stocks of single-service, single-fuel technologies, it was adopted for this purpose within many parts of the buildings module. Nonetheless, some of the most promising future building efficiency developments rely on improving system integration and passive designs; therefore, much of the challenge and effort in the development was the creation of a framework that could capture these alternative paths while still providing quick run-times and a transparent structure for users. Two particular objectives were crucial in shaping the building module:

(1) to accommodate technologies that do not consume fuel, e.g., windows, but strongly affect multiple other energy consuming technologies; and

(2) to recognize interactions between end-uses, particularly the heat gains from lights and electrical equipment that are sometimes more important than envelope losses in determining the heating and cooling requirements of commercial buildings, and also play a significant and growing role in residential buildings.

Figure 4-3-1. Main Calculation Steps *(T represents a copy of the Template.)*

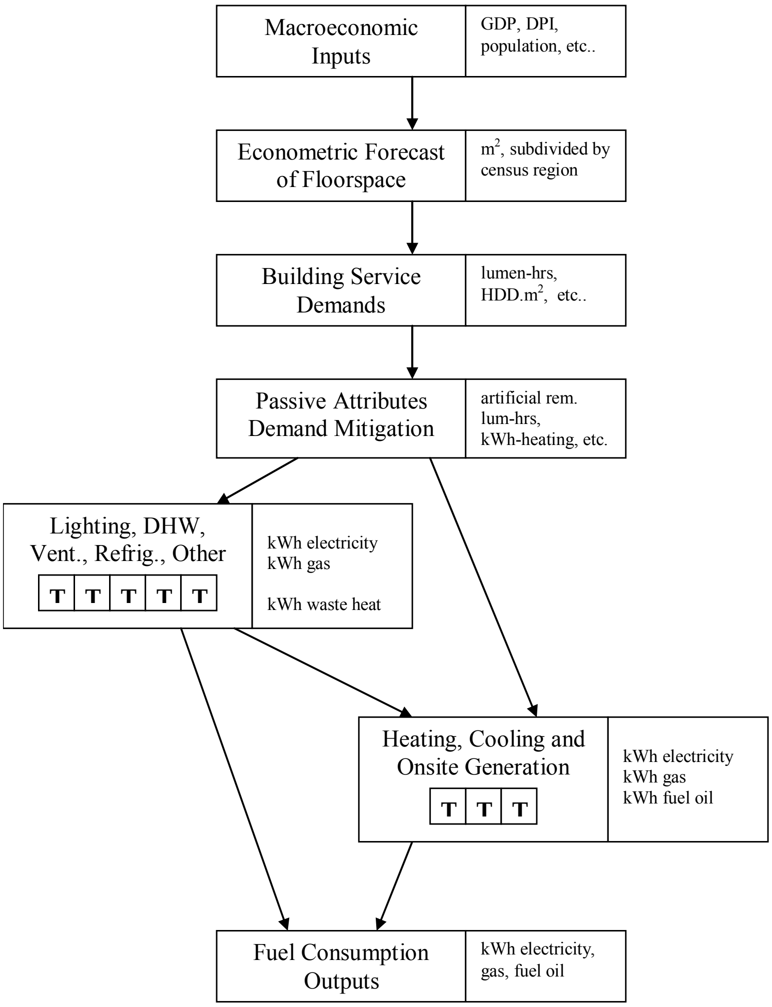


Figure 4-3-1 shows the basic structure that is used in both the residential and commercial sub-modules. The *Passive Attributes* sub-module considers the aspects of the building shell that meet, mitigate, or intensify the heating, cooling, ventilating, and lighting service requirements. The elements in this sub-module are special in that they do not consume any fuel, and in that they are described by a vector of properties, e.g. daylighting effectiveness, natural ventilation effectiveness, solar gain intensities in heating and cooling seasons, and the envelope heat-transfer intensities in the heating and cooling seasons. The two sub-modules which follow use copies of the Template to determine equipment choice between available technologies for each service, with each technology meeting a single service. The sub-module denoted *Lighting, DHW, Ventilation, Refrigeration, Other* addresses technologies meeting these end-uses, and calculates the internal heat gains generated by them. The *Heating, Cooling and On-site Generation* sub-module uses these internal heat gains, along with the passive attributes of the building shell to determine the heating and cooling load that must be met by active technologies, and also will consider options for buildings to self-provide some of its energy requirements.

4.4 Floorspace Forecast and Tracking Building Stock

Commercial and residential floorspace models were fit by stepwise regression to historic data for this purpose (PNNL 2006) as shown in Table 4.4.1.

Table 4-4-1. Used Econometric Commercial and Residential Floorspace Models

	model	**adjusted R^2-value**	**coefficients / t-statistics**
Commercial	$F_t = 0 + C_2 POP_t + C_3 GDP_t$	0.97556915	C_1 = nA / nA; C_2 = 0.014364 / 39.41; C_3 = 0.0003059 / 22.77
Residential	$\ln FR_t = C_2 POP_t + C_4 \ln DPI_t$	0.95994454	C_2 = 0.005712 / 21.31; C_4 = 0.152549 / 19.08

F_t	commercial floorspace in year t [10^9 m^2]
POP_t	population in year t [10^6]
GDP_t	U.S. Gross Domestic Product in year t [\$$10^9$, chained (2000)]
C_2	POP coefficient
C_3	GDP coefficient
FR_t	residential floorspace in year t [10^9 m^2]
DPI_t	disposal personal income total [10^9 dollars, chained (2000)]
C_4	coefficient for DPI

Because shell integrity is assumed to be different between existing and new buildings, it is important to segregate floorspace accordingly. Estimates of projected commercial and residential floorspace include additions, assumed to be the difference between the surviving floorspace and the total floorspace requirement forecast by the preceding econometric equations. Over time, the existing stock declines as buildings are demolished, estimated by a logistic decay function, the shape of which depends upon two parameters, mean building lifetime and the parameter γ, which corresponds to the rate at which buildings retire near their median expected lifetime (see Equation 4.4.1).

$$Survival\ Rate = \frac{1}{1 + \left(\frac{y - y_0}{Average\ \ Lifetime} \right)^{\gamma}} \qquad \text{(Equation 4.4.1)}$$

y: year, y_0: year of construction

Average Lifetime and γ are based on the commercial demand module documentation from NEMS (EIA 2007). Based on this data set, the average lifetime of commercial buildings is assumed to be 73.5 years, and γ is 2.0. The resulting decay function and building stock compostion are depicted in Figures 4-4-1 to 4-4-3. Figure 4-4-2 and 4-4-3 show the breakdown between pre and post 2005 construction, with the 2050 stock roughly equally split between them.

Figure 4-4-1. Building Survival Function for Commercial Floorspace

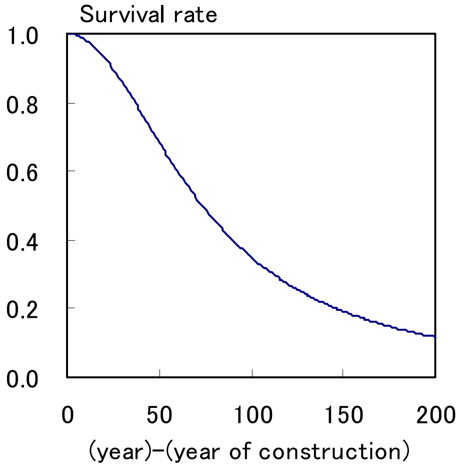


Figure 4-4-2. The Prospect of Commercial Floorspace

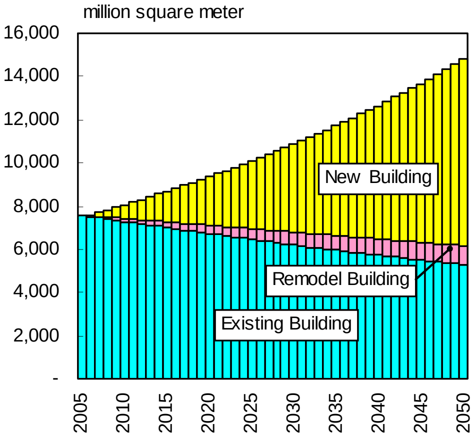
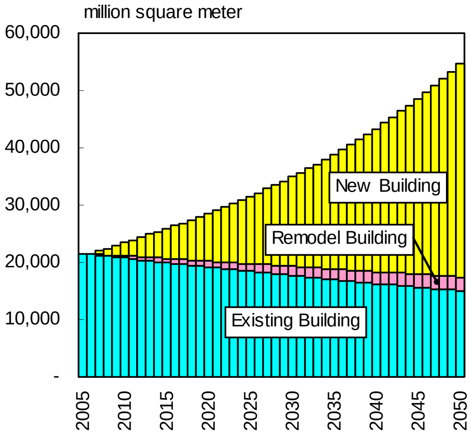


Figure 4-4-3. The Prospect of Residential Floorspace



4.5 End-use Technology in Building Sector

The module tracks the capacity and characteristics of different end-use technologies throughout the simulation as listed and grouped by their energy service category as shown in Table 4-5-1.

Table 4-5-1. Technologies Tracked in the Building Sector

Commercial Sector	Residential Sector
Passive Technology	Passive Technology
SolarGains	SolarGains
Building Insulation	Building Insulation
Daylighting	Daylighting
NaturalVentilation	NaturalVentilation
Lighting	Lighting
Incandescent	Incandescent
Flourescent	Flourescent
Cfl	Cfl
LED (current soa)	LED (current soa)
LED (DOE goal ssl)	LED (DOE goal ssl)
Halogen	Halogen
HID	HID
Refrigeration	Refrigeration
Low (pre 1993)	Low (pre 1993)
Medium (conventional)	Medium (conventional)
High (Energy Star)	High (Energy Star)
Ultra-high (future)	Ultra-high (future)
Domestic hot water(DHW)	Domestic hot water(DHW)
Conventional gas storage	Conventional gas storage
High-efficiency gas storage	High-efficiency gas storage
Condensing gas storage	Condensing gas storage
Conventional oil-fired storage	Conventional oil-fired storage
Minimum Efficiency electric storage	Minimum Efficiency electric storage
High-eff. electric storage	High-eff. electric storage
Demand gas (no pilot)	Demand gas (no pilot)
Electric heat pump water heater	Electric heat pump water heater
Solar with electric back-up	Solar with electric back-up
Ventilation	Ventilation
Other load	Other load
Space heating	Space heating
Low (<80 AFUE gas)	Low (<80 AFUE gas)
Medium (80-90 AFUE gas)	Medium (80-90 AFUE gas)
High (90+ AFUE gas)	High (90+ AFUE gas)
Medium (80-85 eff oil)	Medium (80-85 eff oil)
High (85+ eff oil)	High (85+ eff oil)
Electric resistance	Electric resistance
Air source HP	Air source HP
Ground source HP	Ground source HP
Space cooling	Space cooling
Packaged (low)	Low (central AC)
Packaged (high)	High (central AC)
Electric recip chiller (low)	Low (room AC)
Electric recip chiller (high)	High (room AC)
Electric centrifugal chiller (low)	PV
Electric centrifugal chiller (high)	Conventional Technology
Rotary screw chillers (low)	Advanced Technology
Rotary screw chillers (high)	
Individual Room AC	
Absorption chillers	
PV	
Conventional Technology	
Advanced Technology	

4.6 Mathematical Description of Model Structure

The residential and commercial sectors can be thought of as a series of stock turnover models running in parallel that track equipment characteristics and market share as time progresses. In energy supply appliance selection, logit function are used to assign a share of the energy service demand growth to the competing technologies. The logit computes a market share based on the technologies' levelized costs of energy and the other influential factors. Capital costs, fuel costs are used to calculate the levelized cost of energy for each technology. Capital costs can be decreased by R&D and learning. The effects of R&D are treated with uncertainty and can be adjusted to try to capture the level of government investment in R&D. The combination of all these factors produces a levelized cost of energy that is used to determine how the market share of new capacity additions will be given to the competing technologies. Once the stock of capacity has been changed to reflect additions and retirements, the expected amount of energy supply, based on installed capacity, that can be produced from each technology is calculated. Knowing the amount of energy supply from each end-use technology and the corresponding energy intensity, the fuel demand is calculated. This leads to a CO_2 emissions calculation that is determined by the carbon content of each fuel.

Index

yr: year (2005 - 2050)
se: sector (commercial, residential)
cr: census region
vin: index of vintage [1…*VinMax*]
fl: Type of floorspace (Newly added floospace, Existing floorspace, Remodelling floorspace)
ef: efficiency level (high efficiency, medium efficiency, low efficiency)
at: passive attributes (Heating(solar gain)[kWh/ m^2], Cooling(solar gain)[kWh/ m^2], Heat passing rate(heating)[UA/m^2], Heat passing rate(cooling)[UA/m^2], Daylighting[lumen*hours/m^2], Natural Ventilation[%/ m^2])
sr: Energy Service Type(Space Heating, Space Cooling, Refrigeration, Ventilation, Lighting, Water Heating, Other)
tech: technology in each energy service
ene: energy source

■ Floorspace Stock

Newly-built Floor Space

Newly added floorspace is calculated through the difference of econometric-based floorspace prediction and total stock of floorspace.

$$AddSpace_{yr,se,cr} = EconFloorSpace_{yr-1,se,cr} - TotSpaceStock_{yr-1,se,cr}$$

$$TotSpaceStock_{yr,se,cr} = \sum_{vin} SpaceByVintage_{yr,se,cr,vin}$$

$AddSpace_{yr,se,cr}$: Newly added floorspace in year *yr*, sector *se* and census region *cr* [m^2]

$EconFloorSpace_{yr,se,cr}$: Total floorspace in year *yr*, sector *se* and census region *cr* ,estimated by econometric equation [m^2]

$TotSpaceStock_{yr,se,cr}$: Total floorspace stock in year *yr*, sector *se* and census region *cr* [m^2]

$SpaceByVintage_{yr,se,cr,vin}$: Floorspace vintage in year *yr*, sector *se*, census region *cr* and vintage *vin* [m^2]

Retired Floor Space

The type of retired floorspace consists of retirement due to its lifetime (last vintage of floorspace) and demolishment. Total retirement floorspace is the sum of those.

$$RetireSpace_{yr,se,cr} = SpaceFlowVintage_{yr,se,cr,'VinMax'} + \sum_{vin} SpaceRetire_{yr,se,cr,vin}$$

$RetireSpace_{yr,se,cr}$: Total retired floorspace in year *yr*, sector *se*, and census region *cr* [m^2]

$SpaceFlowVintage_{yr,se,cr,vin}$: Floorspace flow to next vintage in year *yr*, sector *se*, census region *cr* and vintage *vin* [m^2]

$SpaceRetire_{yr,se,cr,vin}$: Demolished floorspace in year *yr*, sector *se*, census region *cr* and vintage *vin* [m^2]

Total Additional Floor Space

Total additional floorspace is composed of newly-built floorspace and retired floorspace.

$$TotAddSpace_{yr,se,cr} = Max[0, AddSpace_{yr,se,cr} + RetireSpace_{yr,se,cr}]$$

$TotAddSpace_{yr,se,cr}$: Total additional floorspace in year *yr*, sector *se* and census region *cr* [m^2]

Floorspace Stock Balance

Inter-temporal floorspace stock balance is described by recurrence formula including existing floorspace, newly-built floorspace, retirement of floorspace and demolishment.

$$\begin{aligned} & SpaceByVintage_{yr,se,cr,vin} \\ & = SpaceByVintage_{yr-1,se,cr,vin} + AddVinSpace_{yr-1,se,cr,vin} - SpaceFlowVintage_{yr-1,se,cr,vin} - SpaceRetire_{yr-1,se,cr,vin} \end{aligned}$$

$AddVinSpace_{yr,se,cr,vin}$: Newly added floorspace in year *yr*, sector *se*, census region *cr* and vintage *vin* [m^2]

Additional Vintage Balance

First vintage is newly-built floorspace and each vintage experience aging and move to other vintage class.

if $vin = 1$

$$AddVinSpace_{yr,se,cr,vin} = TotAddSpace_{yr,se,cr,vin-1}$$

if $vin = 2$ to $VinMax$

$$AddVinSpace_{yr,se,cr,vin} = SpaceFlowVintage_{yr,se,cr,vin-1}$$

Lifetime of Vintage

Lifetime of each vintage is determined by maximum survival time of building divided by the number of vintage.

$$FloorTimeInVintage_{se} = \frac{MaxSurvTime_{se}}{FloorNumOfVintage_{se}}$$

$FloorTimeInVintage_{yr,se,cr,vin}$: Amount of time the floorspace spends in each vintage in sector *se* [years]

$MaxSurvTime_{se}$: Maximum survival year of floorspace in sector *se* [years]

$FloorNumOfVintage_{se}$: Number of vintage in floorspace in sector *se*

Floorspace Flow to Next Vintage

Floorspace flow to next vintage is defined as aging vintage multiplied by survival rate.

if $yr < BaseYear + FloorTimeInVintage_{se}$

$$SpaceFlowVintage_{yr,se,cr,vin} = \frac{InitialStockByVintage_{se,cr,vin}}{FloorTimeInVintage_{se}} * SurvRate_{se,vin}$$

if $yr > BaseYear + FloorTimeInVintage_{se}$

$$SpaceFlowVintage_{yr,se,vin} = AddVinSpace_{yr-FloorTimeInVintage_{se},se,cr,vin} * SurvRate_{se,vin}$$

$InitialStockByVintage_{se,vin}$: Initial stock of floorspace by vintage in sector *se*, census region *cr* and vintage *vin* [m^2]

$SurvRate_{se,vin}$: Survival rate of floorspace in sector *se* and vintage *vin*

Demolishment of Floorspace

The rest of survived aging floorspace is treated as demolished floorspace.

$$SpaceRetire_{yr,se,vin} = SpaceFlowVintage_{yr,se,vin} * \frac{1 - SurvRate_{se,vin}}{SurvRate_{se,vin}}$$

Existing and Newly-built Floorspace

Existing floorspace is calculated as initial existing stock excluding retired floorspace. Newly-built floorspace is defined as the sum of additional space and retired space.

$$InitialFloorspace_{se,cr} = \sum_{vin} InitialStockByVintage_{se,cr,vin}$$

(Existing stock)

If $yr = base\_year$
$$GrossExistFloorspace_{yr,se,cr} = InitialFloorspace_{se,cr}$$
else
$$GrossExistFloorspace_{yr,se,cr} = GrossExistFloorspace_{yr-1,se,cr} - RetireSpace_{yr-1,se,cr}$$

If $yr = base\_year$
$$Floorspace_{yr,se,cr,"Existing"} = InitialFloorspace_{se,cr}$$
else
$$Floorspace_{yr,se,cr,"Existing"} = (1 - RemodelRate) * Floorspace_{yr-1,se,cr,"Existing"}$$

(Remodelling stock)

$$Floorspace_{yr,se,cr,"Remodel"} = GrossExistFloorspace_{yr,se,cr} - Floorspace_{yr,se,cr,"Existing"}$$

(Newly-built stock)

$$Floorspace_{yr,se,cr,\text{"New"}} = Floorspace_{yr-1,se,cr,\text{"New"}} + AddSpace_{yr-1,se,cr} + RetireSpace_{yr-1,se,cr}$$

$Floorspace_{yr,se,cr,fl}$: Floospace in year *yr*, sector *se*, census region *cr* and floorspace type *fl* [m^2]
$InitialFloorspace_{se,cr}$: Initial floospace in sector *se*, census region *cr* [m^2]
$RemodelRate$: Annual remodelling rate in existing floorspace [%]

■ Floorspace Adopting Passive Measures

Floorspace Adopting Passive Measures

$$PassiveAttributesFloorspace_{yr,se,cr,fl,ef,at} = Floorspace_{yr,se,cr,fl} * PassiveShare_{yr,se,cr,ef,at}$$

$PassiveShare_{yr,se,cr,fl}$: Adopting ratio of passive measures in year *yr*, sector *se*, census region *cr*, efficiency level *ef*, and passive attributes *at* [%]

$PassiveAttributesFloorspace_{yr,se,cr,fl,ef,at}$: Floorspace adopting passive measures in year *yr*, sector *se*, census region *cr*, floorspace type *fl*, efficiency level *ef*, and passive attributes *at* [m^2]

Floorspace Share Adopting Passive Measures

Stock-based floorspace share adopting passive measures

$$PassiveAdoptRatio_{yr,se,cr,ef,at} = \frac{\sum_{fl} PassiveAttributesFloorspace_{yr,se,cr,fl,ef,at}}{\sum_{fl} Floorspace_{yr,se,cr,fl}}$$

$PassiveAdoptRatio_{yr,se,cr,ef,at}$: Floorspace share adopting passive measures of efficiency level *ef* in year *yr*, sector *se*, census region *cr*, floorspace type *fl*, and passive attributes *at* [%]

Characteristics of Passive Measures in Stock Based floorspace

Calculate stock-based floorspace characteristic of solar gain, heat passing rate, daylighting and natural ventilation.

$$PassiveAttributesFloorStock_{yr,se,cr,at} = \sum_{ef} PassiveAdoptRatio_{yr,se,cr,ef,at} * PassiveAttributes_{se,ef,at}$$

$PassiveAttributes_{se,ef,at}$: Characteristics of passive measures of efficiency level *ef* in sector *se* and passive attributes *at*

$PassiveAttributesFloorStock_{se,ef,at}$: Stock-based floorspace characteristics of passive measures of efficiency level *ef* in sector *se* and passive attributes *at*

Envelop Heating and Cooling Load

Calculate envelope heating and cooling load by multiplying heat passing rate with heating degree days.

$$EnvelopeHeatingLoad_{yr,se,cr} = HDDSquaremeter_{yr,se,cr} * PassiveAttributesFloorStock_{yr,se,cr,'HeatPassingRate'}$$
$$EnvelopeCoolingLoad_{yr,se,cr} = CDDSquaremeter_{yr,se,cr} * PassiveAttributesFloorStock_{yr,se,cr,'HeatPassingRate'}$$
$$PassiveAttributesFloorStock_{yr,se,cr,'HeatPassin\,gRate'} = UValue[\frac{W}{m^2 \cdot K}] \cdot \frac{24kWh}{1000W \cdot day} \cdot f_s \cdot f_B$$

$EnvelopeHeatingLoad_{yr,se,cr}$: Building envelope heating load in year *yr*, sector *se*, census region *cr* [kWh]
$EnvelopeCoolingLoad_{yr,se,cr}$: Building envelope cooling load in year *yr*, sector *se*, census region *cr* [kWh]
$HDDSquaremeter_{yr,se,cr}$: Heating degree days multiplied by floospace in year *yr*, sector *se*, census region *cr* [HDD*m^2]
$CDDSquaremeter_{yr,se,cr}$: Cooling degree days multiplied by floospace in year *yr*, sector *se*, census region *cr* [CDD*m^2]
f_s, f_b : Calibration factor

Solar Heating and Cooling Gain

Calculate solar heat gain by multiplying solar gain intensity with floorspace.

$$SolarHeatingGain_{yr,se,cr} = \sum_{fl} Floorspace_{yr,se,fl} * PassiveAttributesFloorStock_{yr,se,cr,'SolarGain(Heating)'}$$
$$SolarCoolingGain_{yr,se,cr} = \sum_{fl} Floorspace_{yr,se,fl} * PassiveAttributesFloorStock_{yr,se,cr,'SolarGain(Cooling)'}$$

$SolarHeatingGain_{yr,se,cr}$: Heating gain by solar in year *yr*, sector *se*, census region *cr* [kWh]
$SolarCoolingGain_{yr,se,cr}$: Cooling gain by solar in year *yr*, sector *se*, census region *cr* [kWh]

Heating and Cooling Load

Heating load is evaluated through aggregating building envelope load, solar heat gain and building internal gain.

$$Heating_{yr,se,cr} = HeatSpace_{se} * (EnvelopeHeatingLoad_{yr,se,cr} - SolarHeatingGain_{yr,se,cr} + InterHeatGain_{yr,se,cr})$$
$$Cooling_{yr,se,cr} = CoolSpace_{se} * (EnvelopeCoolingLoad_{yr,se,cr} + SolarCoolingGain_{yr,se,cr} + InterCoolGain_{yr,se,cr})$$

$Heating_{yr,se,cr}$: Heating load in year *yr*, sector *se*, census region *cr* [kWh]
$Cooling_{yr,se,cr}$: Cooling load in year *yr*, sector *se*, census region *cr* [kWh]
$HeatSpace_{se}$: The share of heating building space in year *yr*, sector *se* [%]
$CoolSpace_{se}$: The share of cooling building space in year *yr*, sector *se* [%]
$InterHeatingGain_{yr,se,cr}$: Internal heating gain in year *yr*, sector *se*, census region *cr* [kWh]
$InterCoolingGain_{yr,se,cr}$: Internal cooling gain in year *yr*, sector *se*, census region *cr* [kWh]

Energy Service Demand

Calculate energy service demand by multiplying energy service intensity with floorspace.

$$EnergyService_{yr,se,sr} = EnergyServiceUnit_{yr,se,sr} * \sum_{cr}\sum_{fl} Floorspace_{yr,se,cr,fl}$$

$EnergyServiceUnit_{yr,se,sr}$: Energy service demand in year *yr*, sector *se* and energy service carrier *sr*
$EnergyService_{yr,se,sr}$: Energy service demand in year *yr*, sector *se* and energy service carrier *sr*

Energy Service Demand (Lighting and Ventilation)

Calculate energy service demand considering the effect of renewable passive characteristics of daylighting and natural ventilation.

if (*sr* = *'Lighting'* and *at* = *'Daylighting'*)

$$EnergyService_{yr,se,sr} = EnergyService_{yr,se,sr} - \sum_{cr} PassiveAttributesFloorStock_{yr,se,cr,at} * \sum_{fl} Floorspace_{yr,se,cr,fl}$$

if (*sr* = *'Ventilation'* and *at* = *'Natural Ventilation'*)

$$EnergyService_{yr,se,sr} = EnergyService_{yr,se,sr} * (1 - PassiveAttributesFloorStock_{yr,se,cr,at})$$

■ Stock Model of Appliances

Newly-added appliance

Newly added appliance is estimated through the difference of econometric-based service demand forecast and total stock of appliance.

$$AddService_{yr,se,cr,sr} = EnergyService_{yr-1,se,cr,sr} - TotStock_{yr-1,se,cr,sr}$$

$$TotStock_{yr,se,cr,sr} = \sum_{tech} \sum_{vin} StockByVintage_{yr,se,cr,sr,tech,vin}$$

$$RetireService_{yr,se,cr,sr} = \sum_{tech} FlowVintage_{yr,se,cr,sr,tech,'VinMax'}$$

$$TotAddition_{yr,se,cr,sr} = Max[0, AddService_{yr,se,cr,sr} + RetireService_{yr,se,cr,sr}]$$

$AddService_{yr,se,cr,sr}$: Increase in appliance in year *yr*, sector *se*, census region *cr* and energy service carrier *sr*

$EnergyService_{yr,se,cr,sr}$: Energy service demand in year *yr*, sector *se*, census region *cr* and energy service carrier *sr*

$TotStock_{yr,se,cr,sr}$: Total appliance stock in year *yr*, sector *se*, census region *cr* and energy service carrier *sr*

$RetireService_{yr,se,cr,sr}$: Retired appliance stock in year *yr*, sector *se*, census region *cr* and energy service carrier *sr*

$FlowVintage_{yr,se,cr,sr,tech,vin}$: Energy service stock flow to next vintage in year *yr*, sector *se*, census region *cr*, energy service carrier *sr*, technology *tech* and vintage *vin*

$TotAddition_{yr,se,cr,sr}$: Total additional energy service in year *yr*, sector *se*, census region *cr* and energy service carrier *sr*

$StockByVintage_{yr,se,cr,vin}$: Appliance stock vintage in year *yr*, sector *se*, census region *cr,* technology *tech* and vintage *vin*

Logit-based Selection of Appliance

Market share of appliance is calculated by dividing the utility from each technology by the sum of utility from all technologies. Utility is determined by raising the number of attributes, such as the levelized cost of energy for the various appliances, to a scaling factor, α. The scaling factor determines how sensitive the logit is to differences in the attributes, for instance, the levelized cost; if the scaling factor equals zero, then equal market share will be given to each technology, whereas, if the scaling factor is much greater than 1, the technologies with the most desirable attributes, such as lowest levelized costs of energy, will gain most of the market share. Utility is a function of certain elements of the vector of attributes and scaling factor α, generally linear in parameters. In this paper, levelized costs of each appliance is only incorporated as an attribute in utility function.

$$TechShare_{yr,se,cr,sr,tech} = \frac{exp(Utility_{yr,se,cr,sr,tech})}{\sum_{tech} exp(Utility_{yr,se,cr,sr,tech})}$$

$$Utility_{yr,se,cr,sr,tech} = \sum_{attr} \alpha_{yr,se,cr,sr,tech,attr} * x_{yr,se,cr,sr,tech,attr}$$

$$TotAddTech_{yr,se,cr,sr,tech} = TotAddition_{yr,se,cr,sr} * TechShare_{yr,se,cr,sr,tech}$$

if $vin = 1$

$$AddVintage_{yr,se,cr,sr,tech,vin} = TotAddTech_{yr,se,cr,sr,tech}$$

if $vin = 2$ to $VinMax$

$$AddVintage_{yr,se,cr,sr,tech,vin} = FlowVintage_{yr,se,cr,sr,tech,vin-1}$$

$\alpha_{yr,se,cr,sr,tech}$: scaling parameter for the logit function

$TotAddition_{yr,se,cr,sr}$: Total additional energy service in year *yr*, sector *se*, census region *cr* and energy service carrier *sr*

$Utility_{yr,se,cr,sr,tech}$: Total utility for each technology in year *yr*, sector *se*, census region *cr*, energy service carrier *sr* and technology *tech*

$TechShare_{yr,se,cr,sr,tech}$: Share of each technology in year *yr*, sector *se*, census region *cr*, energy service carrier *sr* and technology *tech*

$TotAddTech_{yr,se,cr,sr,tech}$: Additional energy service technology in year *yr*, sector *se*, census region *cr*, energy service carrier *sr* and technology *tech*

$AddVintage_{yr,se,cr,sr,tech,vin}$: Newly added energy service technology in year *yr*, sector *se* , census region *cr*, energy service carrier *sr,* technology *tech* and vintage *vin*

Appliance Stock Balance

This formulation describes appliance stock balance.

$$\begin{aligned} & StockByVintage_{yr,se,cr,sr,tech,vin} \\ & = StockByVintage_{yr-1,se,cr,sr,tech,vin} + AddVintage_{yr-1,se,cr,sr,tech,vin} - FlowVintage_{yr-1,se,cr,sr,tech,vin} \end{aligned}$$

Spending Time in Vintage

Following equation explains lifetime of each vintage.

$$TimeInVintage_{yr,se,sr,tech} = \frac{LifeTime_{yr,se,sr,tech}}{NumOfVintage_{se,sr,tech}}$$

Flow to next vintage is described as follows.

$$FlowVintage_{yr,se,cr,sr,tech,vin} = \frac{StockByVintage_{yr,se,cr,sr,tech,vin}}{TimeInVintage_{yr,se,sr,tech,vin}}$$

$TimeInVintage_{yr,se,sr,tech}$: Amount of time the technology spends in each vintage in year *yr*, sector *se*, energy service carrier *sr* and technology *tech* [years]

$LifeTime_{yr,se,sr,tech}$: Maximum survival year of technology in year *yr*, sector *se*, energy service carrier *sr* and technology *tech* [years]

$NumOfVintage_{se,sr,tech}$: Number of vintage of technology in sector *se*, energy service carrier *sr* and technology *tech*

Energy Requirement Stock Balance

This formulation describes recursive equation of energy requirement (energy input to appliances) balance.

$$ReqmByVintage_{yr,se,cr,sr,tech,vin}$$
$$= ReqmByVintage_{yr-1,se,cr,sr,tech,vin} + ReqmAddVintage_{yr-1,se,cr,sr,tech,vin} - ReqmFlowVintage_{yr-1,se,cr,sr,tech,vin}$$

$ReqmByVintage_{yr,se,cr,sr,tech,vin}$: Energy requirement by vintage in year *yr*, sector *se*, census region *cr*, energy service carrier *sr*, technology *tech* and vintage *vin*

$ReqmFlowVintage_{yr,se,cr,sr,tech,vin}$: Energy requirement flow to next vintage in year *yr*, sector *se*, census region *cr*, energy service carrier *sr*, technology *tech* and vintage *vin*

$ReqmAddVintage_{yr,se,cr,sr,tech,vin}$: Newly added energy requirement in year *yr*, sector *se*, census region *cr*, energy service carrier *sr*, technology *tech* and vintage *vin*

if $vin = 1$

$$ReqmAddVintage_{yr,se,cr,sr,tech,vin} = ReqmIntsty_{yr,se,cr,sr,tech} * TotAddTech_{yr,se,cr,sr,tech}$$

if $vin = 2$ to $VinMax$

$$ReqmAddVintage_{yr,se,cr,sr,tech,vin} = ReqmFlowVintage_{yr,se,cr,sr,tech,vin-1}$$

$ReqmIntsty_{yr,se,cr,sr,tech}$: Energy requirement intensity in year *yr*, sector *se*, census region *cr*, energy service carrier *sr* and technology *tech*

Average Energy Requirement Intensity

$$AvgReqmIntsty_{yr,se,cr,sr,tech,vin} = \frac{ReqmByVintage_{yr,se,cr,sr,tech,vin}}{StockByVintage_{yr,se,cr,sr,tech,vin}}$$

$AvgReqmIntsty_{yr,se,cr,sr,tech,vin}$: Average energy requirement intensity in year *yr*, sector *se*, census region *cr*, energy service carrier *sr*, technology *tech* and vintage *vin*

Energy Demand

$$ReqmFlowVintage_{yr,se,cr,sr,tech,vin} = AvgReqmIntsty_{yr,se,cr,sr,tech,vin} * FlowVintage_{yr,se,cr,sr,tech,vin}$$

$$ReqmByVinByEne_{yr,se,cr,sr,tech,ene,vin} = ReqmByVintage_{yr,se,cr,sr,tech,vin} * Energy_{tech,ene}$$

$$EneDemand_{yr,se,cr,ene} = \sum_{sr}\sum_{tech}\sum_{vin} ReqmByVinByEne_{yr,se,sr,tech,ene,vin}$$

$Energy_{tech,ene}$: Energy carrier which technology consumes in technology *tech* and energy source *ene*

$ReqmByVinByEne_{yr,se,cr,sr,tech,ene,vin}$: Energy requirement by vintage by energy source in year *yr*, sector *se*, census region *cr*, energy service carrier *sr* , technology *tech*, energy source *ene* and vintage *vin*

$EneDemand_{yr,se,cr,ene}$: Energy demand in year *yr*, sector *se*, census region *cr* and energy source *ene*

4.7 Data Sources

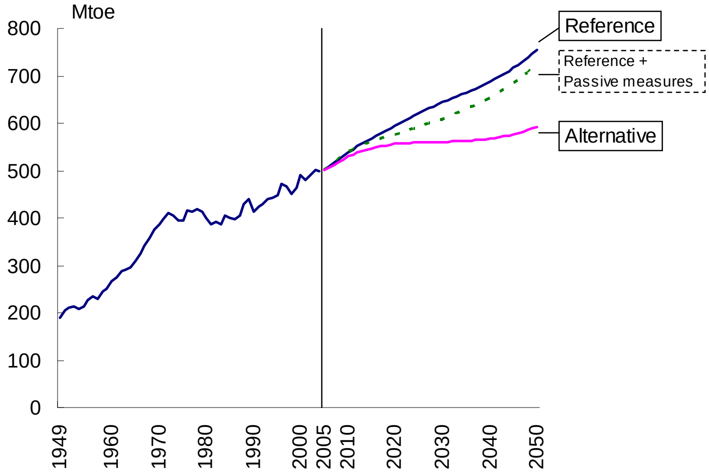
Historical floorspace input data are based on PNNL's commercial and residential energy intensity indicators, which in turn are based on EIA's Commercial Buildings Energy Consumption Surveys (CBECS) and Residential Energy Consumption Surveys (RECS). The final energy demand data, obtained from PNNL, CBECS, RECS as well as the Annual Energy Review (AER) for 2005, for each fuel were divided by the floorspace estimates for 2005 and used for service demand forecasting. Equipment types were considered for refrigeration, space cooling, space heating, lighting, water heating, and ventilation. All other end-uses were categorized as plug loads. The installed equipment stock information is based on Berkeley Lab's own calculations derived from appliance manufacturers' shipments data, CBECS (CBECS 2007), RECS (RECS 2001), and AEO-07 (EIA, 2007a).

5. Overview of Results

5.1 Energy Demand

For the purpose of analyzing the future trajectory of energy demand in the US building sector, we assume the following two scenarios: reference scenario and alternative scenario. In the reference scenario, probable economic growth, demographic factors and energy prices are assumed in developing the prediction. The alternative scenario is based on the reference scenario but includes additional rapid adoption rate of more energy efficient and environmentally compatible technologies due to learning-by-doing effects and eventual facility cost reductions.

Figure 5-1-1. Energy Demand Outlook in US Building Sector



(Note) Actual energy demand data: EIA/DOE, “Annual Energy Review 2006,” Report No. DOE/EIA-0384 (2006). Projection is expected value under statistical behavior of exogenous variables.

Energy demand in the US building sector is projected to grow from 501 Mtoe in 2005 to 754 Mtoe in 2050. If additional passive measures such as insulation, natural ventilation, and natural lighting are aggressively implemented, the energy demand is likely to increase up to 722 Mtoe in 2050, exhibiting a reduction of 32 Mtoe compared with the reference scenario. In the alternative scenario, assuming rapid adoption of energy efficient technologies as well as the passive measures, the energy demand is forecast to increase up to 593 Mtoe in 2050, showing a reduction of 161 Mtoe compared to the reference scenario. Thus, energy efficient technologies and improved passive attributes of buildings are expected to play important roles in massive energy conservation.

Energy demand in the US commercial sector is projected to expand from 211 Mtoe in 2005 to 373 Mtoe in 2050, and in the residential sector from 290 Mtoe in 2005 to 381 Mtoe in 2050. In case of the alternative scenario, the energy demand in commercial sector is likely to decrease by 58 Mtoe by 2005, and in residential sector, by 91 Mtoe. In the residential sector, progressive energy conservation measures will eventually cause the energy demand to stagnate, and 2050 energy demand level will be similar to that of 2005.

The electricity demand in US building sector is forecast to increase from 222 Mtoe (2,581 TWh) in 2005 to 436 Mtoe (5,070 TWh) in 2050. In case of the alternative scenario, the demand will decrease by 84 Mtoe (977 TWh) in 2050 in comparison with reference scenario.

Gas demand in the building sector is expected to grow from 203 Mtoe in 2005 to 246 Mtoe by 2050, and in the alternative scenario, will grow to only 194 Mtoe in 2050.

Figure 5-1-2. Energy Demand Outlook in US Commercial Sector

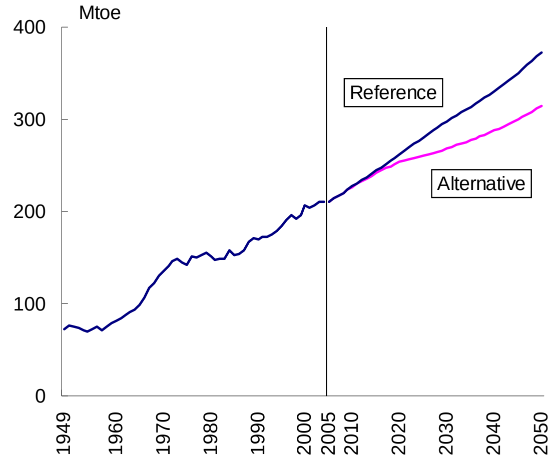


Figure 5-1-3. Energy Demand Outlook in US Residential Sector

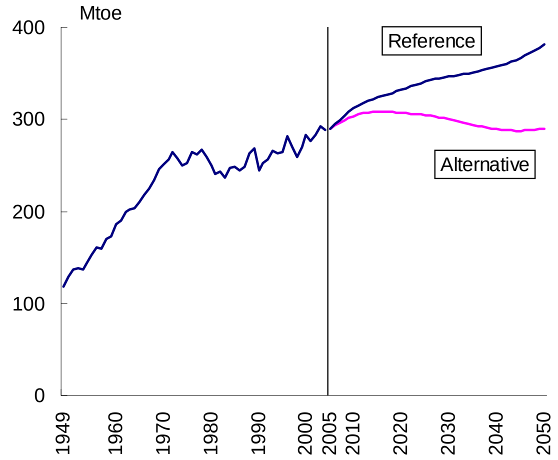


Figure 5-1-4. Electricity Demand Outlook in US Building Sector

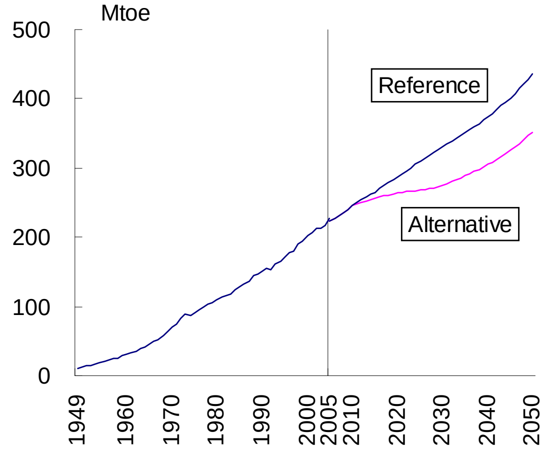
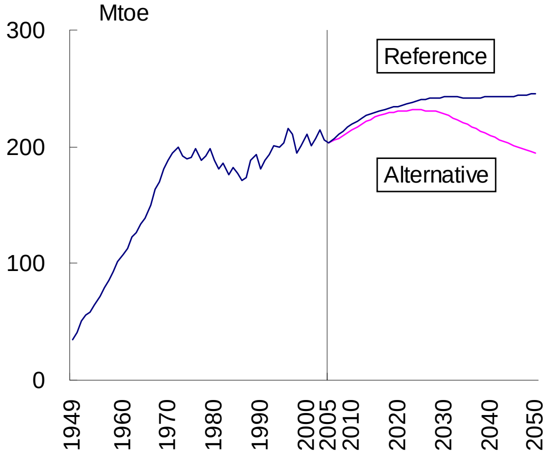


Figure 5-1-5. Gas Demand Outlook in US Building Sector



In this simulation, key exogenous factors such as GDP and population are assumed to have statistical distribution.

In terms of average value, GDP is projected to grow at an average annual growth rate of 2.6% from 11 trillion dollars (2005 US dollar) in 2005 to 35 trillion dollars in 2050. Similarly, population is forecast to increase from 297 million people in 2005 to 429 million in 2050, at an average annual increasing rate of 0.8%. In order to add uncertainty to these parameters, uniform distribution is adopted and applied in a following manner.

$$Parameter_{Probabilistic,Year} = X_{Year} * Parameter_{Deterministic,Year}$$

$$P_{Year}(x_{Year} \le X_{Year} < x_{Year} + dx_{Year}) = f_{Year}(x_{Year})dx_{Year}$$

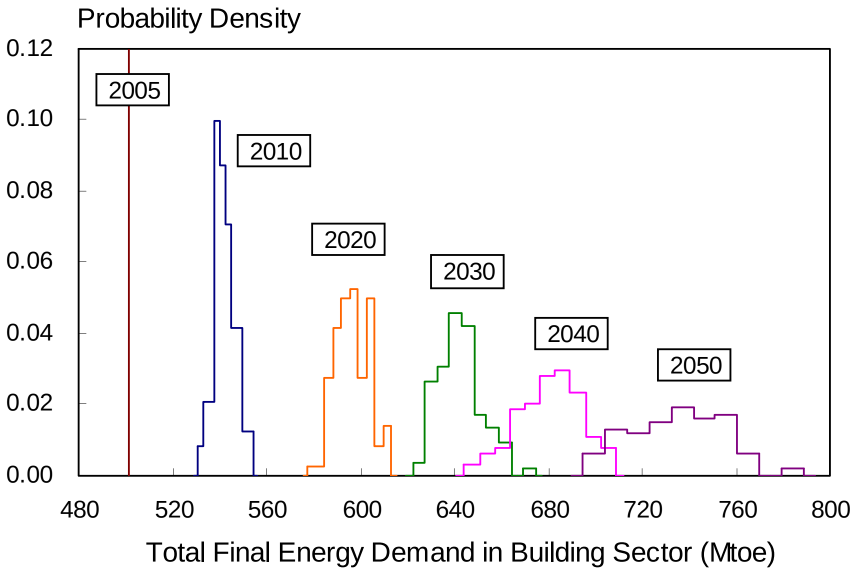
$$f_{Year}(x_{Year}) = \begin{cases} \dfrac{1}{b_{Year} - a_{Year}} & for \quad a_{Year} \le x_{Year} \le b_{Year} \\ 0 \quad for & x_{Year} < a_{Year}, x_{Year} > b_{Year} \end{cases}$$

$$a_{Year} = 0.95 - 0.1 * \frac{Year - BaseYear}{45}, \quad b_{Year} = 1.05 + 0.1 * \frac{Year - BaseYear}{45}$$

Year: Year from 2005 to 2050, *BaseYear*: 2005, *Deterministic*: Deterministic simulation, *Probabilistic*: Probabilistic simulation, *Parameter*: Exogenous variable such as GDP, population, energy price, facility cost of technology etc., *X, x*: Probabilistic random variable, *f(x)*: probability density function

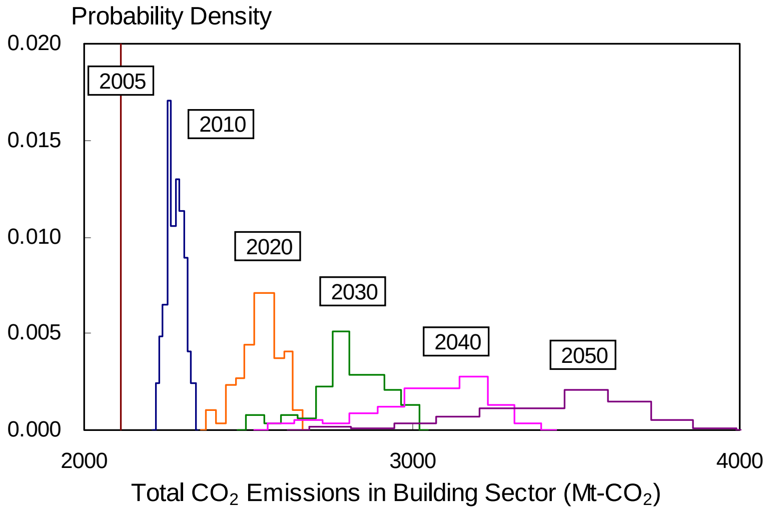
It is assumed that GDP will potentially grow to 2050 annually by 2.3% at minimum and 2.8% at maximum, and that population will show an annual growth rate of 1.0% at maximum and 0.6% at minimum. Accordingly, Figure 5-1-6 and 5-1-7 show the final energy demand and corresponding CO_2 trend respectively under these statistical assumptions, which illustrates that the magnitude of uncertainty gradually becomes increasing toward 2050.

Figure 5-1-6. Energy Demand Outlook in US Building Sector



(Note) The above result is derived assuming statistical distribution through probability distribution function in major exogenous values used in Reference Scenario, such as GDP, population and technological cost.

Figure 5-1-7. CO$_2$ Emissions in US Building Sector



(Note) The above result is derived assuming statistical distribution through probability distribution function in major exogenous values used in Reference Scenario, such as GDP, population and technological cost.

5.2 Appliance Selection

5.2.1 Space Heating and Cooling

In this end-use model, we explicitly take into consideration the consumer adoption of energy supply appliances. Final energy demand in both commercial and residential sector is disaggregated into space heating, space cooling, lighting, refrigeration, domestic hot water, ventilation and other load, and equipment selection is implemented in the each category.

For example, in the commercial sector at reference scenario, the configuration of space heating and space cooling equipment is developed as shown in the following figure.

Figure 5-2-1. Configuration of Space Cooling Equipment in US Commercial Sector for 2050 (Reference)

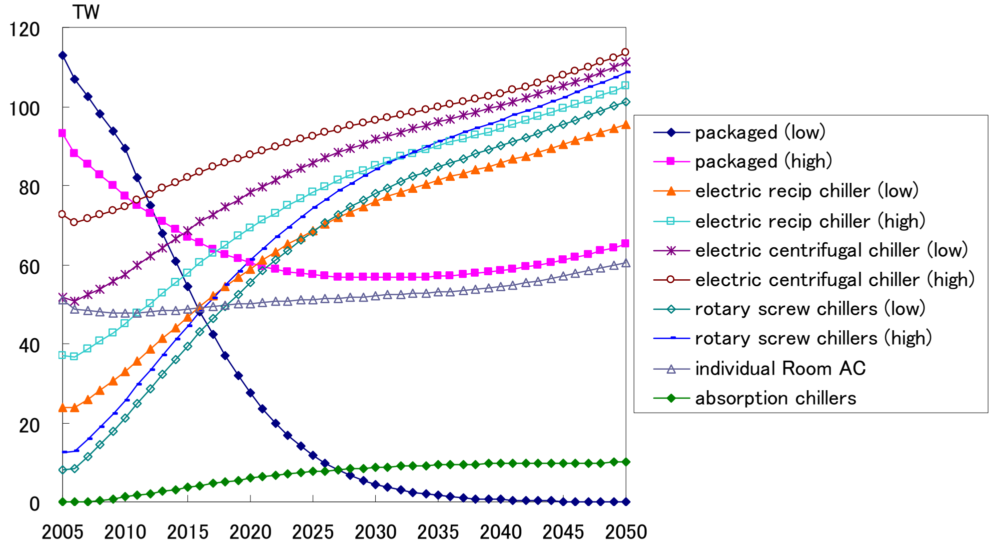
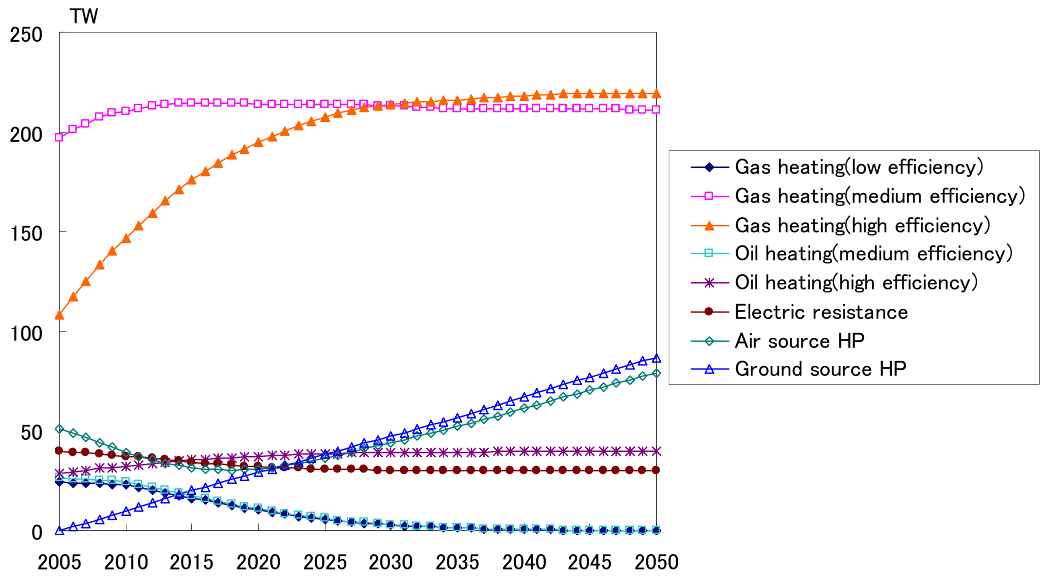


Figure 5-2-2. Configuration of Space Heating Equipment in US Commercial Sector for 2050 (Reference)

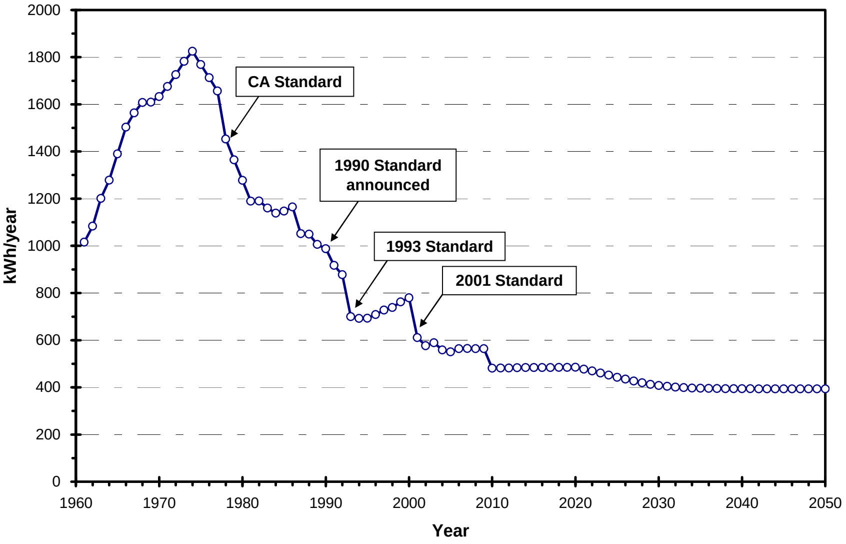


Space heating and cooling demand account for about 60% of the energy use in a typical U.S. home, making it the largest energy expense for most households. A wide variety of technologies are available for heating and cooling, and they achieve a wide range of efficiencies in converting their energy sources into useful heat or cool air supply. An air-source heat pump can provide efficient heating and cooling for a typical home. When properly installed, an air-source heat pump can deliver one-and-a-half to three times more heat energy to a home than the electrical energy it consumes. Geothermal heat pumps (GHPS, sometimes referred to as earth-coupled, ground-source, or water-source heat pumps) are also regarded as promising, has and they have been in use since the late 1940s. GHPs use the constant temperature of the earth instead of outside air as the exchange medium. This allows the system to reach fairly high efficiencies (300%-600%) on the coldest of winter nights, compared to 175%-250% for air-source heat pumps on cool days. The biggest benefit of GHPs is that they use 25%–50% less electricity than conventional heating or cooling systems. This translates into a GHP using one unit of electricity to move three units of heat from the earth. According to the EPA (Environmental Protection Agency), geothermal heat pumps can reduce energy consumption—and corresponding emissions— by up to 44% compared to air-source heat pumps, and up to 72% compared to electric resistance heating with standard air-conditioning equipment.

5.2.2 Refrigeration

If the promotion of energy supply equipment is explicitly considered, It is possible to trace the energy efficiency of the equipment in each energy-end use category. The annual energy consumption of residential refrigerator, for instance, is estimated for 2050 as shown in Figure 5-2-3. The energy efficiency standard of refrigerator was announced in 1986, and the increase in the actual energy efficiency beginning in 1987 suggests that manufacturers began improving energy efficiency in preparation for the 1990 standard. The average energy consumption declines at a fairly quick pace between 1987 and 1993 due to the role of utility demand-side programs in this period. The energy efficiency values for the 2001 standard are based on the minimum efficiency regulations for various product classes and the estimated share of shipments in each class.

Figure 5-2-3. Energy Consumption of Refrigerator in US Residential Sector for 2050 (Reference)



(Source) Actual value is cited from database in LBNL

5.2.3 Lighting

Energy demand for lighting accounts for a large share in total energy consumption, approximately 10% in the residential sector and 20% in the commercial sector. The U.S. Department of Energy and its partners are working to promote lighting energy conservation and accelerate advances in solid-state lighting. Light-emitting diode (LED) technology is developing rapidly as a general light source. Solid-state lighting (SSL[5]) uses semi-conducting materials to convert electricity into light. It is the first truly new lighting technology to emerge for many years. While both technologies are evolving rapidly, LEDs are the more mature technology, particularly for white-light general illumination applications. For most illumination applications, however, white LEDs cannot yet compete with traditional light sources on the basis of performance or cost. The best white LEDs are similar in efficiency to CFLs, but most of the white LEDs currently available in consumer products are only marginally more efficient than incandescent lamps. Lumens per watt (lpw) is the measure of how efficiently the light source is converting electricity into usable light. The best white LEDs available today can produce about 45-50 lpw. For comparison, incandescent lamps typically produce 12-15 lpw; CFLs produce at least 50 lpw. Many LED products use only a small amount of energy, and therefore may appear energy efficient, but they often have very low light output. On-going research and development efforts are making steady progress in improving the performance of white LEDs to levels suitable for general lighting applications.

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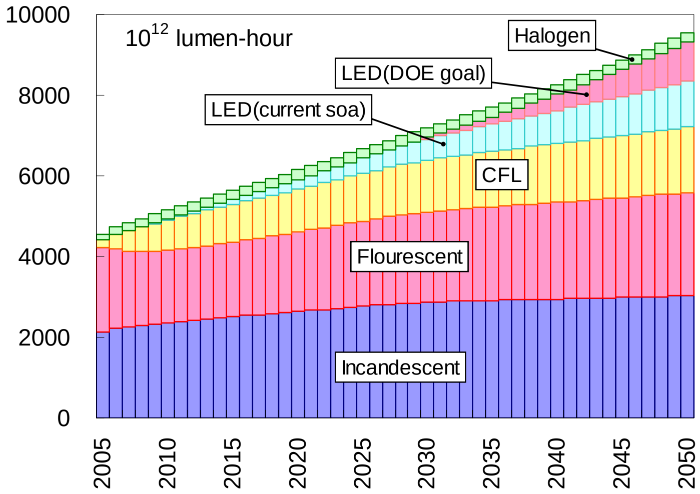
[5] SSL is an umbrella term encompassing different types of technologies including light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs).

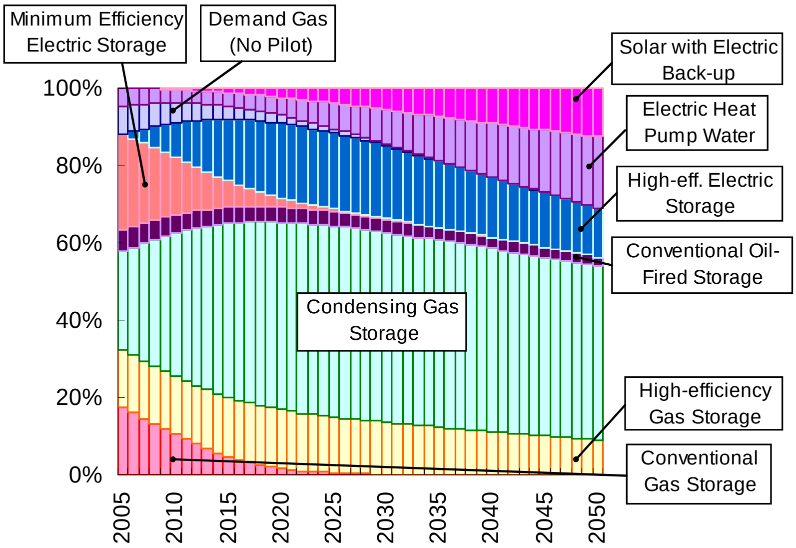
Figure 5-2-4. Lighting Technology in US Residential Sector for 2050 (Reference)



5.2.3 Water Heating

Water heating can account for about 20% of the energy consumed in typical home. It is possible to reduce water heating bills by selecting the appropriate water heater for homes or pools and by using some energy-efficient water heating strategies. In the area of hot water supply, electric water heating systems can potentially contributes to the mitigatint of fuel consumption. Heat pump water heaters use electricity to move heat from one place to another instead of generating heat directly. Therefore, they can be two to three times more energy efficient than conventional electric resistance water heaters.

Figure 5-2-5. Ownership Share of Water Heating Technology in US Residential Sector for 2050 (Reference)



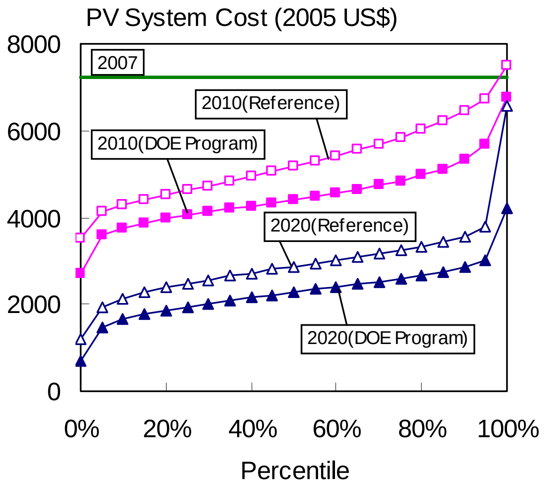
Solar water heaters—also called solar domestic hot water systems—can be a cost-effective way to generate hot water. Solar water heating systems almost always require a backup system for cloudy days and times of increased demand. Conventional storage water heaters usually provide backup and may already be part of the solar system package. Solar water heating systems usually cost more to purchase and install than conventional water heating systems. However, a solar water heater can usually save money in the long run. On average, if a solar water heater is installed, water heating bills should drop by 50%–80%. Also, because the sun is free, it is possible to protect against future fuel shortages and price hikes.

5.3 Photovoltaics (PV)

U.S. department of energy (DOE) has put a high priority on ensuring U.S. buildings are energy efficient and environmentally sustainable. The action plan includes improving Federal procurement of energy-efficient technology, such as photovoltaics. This commitment spearheads the Million Solar Roofs Initiative, which aims to install one million solar energy systems on residential, commercial, and public sector buildings by 2010. The Federal sector's portion of that goal is 20,000 facilities. Federal Energy Management Program (FEMP) plays a leading role in meeting this commitment by encouraging and facilitating the use of photovoltaics. Photovoltaics is a reliable technology used increasingly by Federal facilities to provide power in remote or difficult-to-access locations.

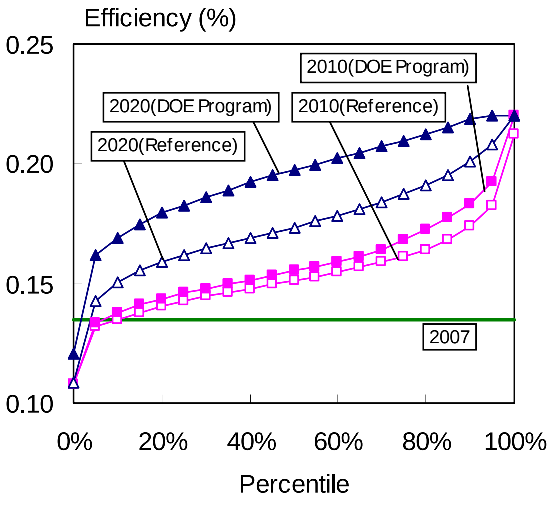
PV systems are used throughout the United States, but they are cost effective most often in areas with abundant sunlight, as the size and cost of the PV array for any application are directly related to the availability of the solar resource. The only major drawback of PV systems is the high initial cost for capital equipment. However, when the life-cycle costs (LCCs) of PV systems are compared to alternatives such as engine generators or long utility line extensions, PV is often the most economical option.

Figure 5-3-1. PV System Cost in Commercial Sector



(Source) Communication with DOE PV expert

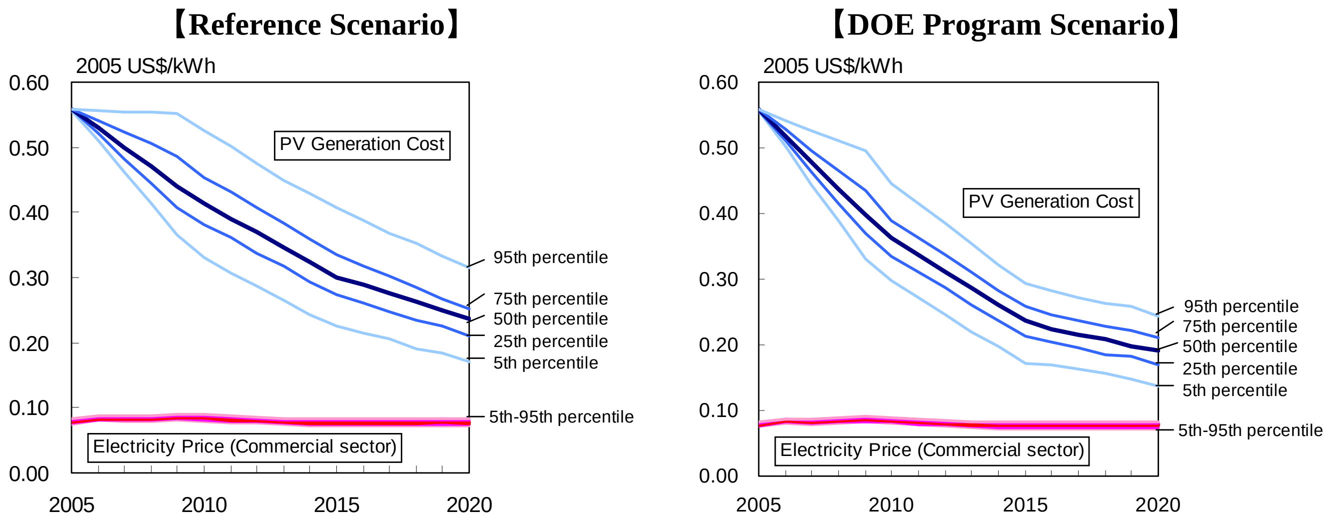
Figure 5-3-2. PV Efficiency in Commercial Sector



(Source) Communication with DOE PV expert

In order to evaluate the future deployment of PVs on rooftops in the building sector, we assume two scenarios in cost and conversion efficiency of PV. First scenario is the reference scenario which only considers baseline industrial R&D effort and excludes DOE R&D activity. Second scenario is DOE program scenario which incorporates current planning DOE R&D budget. In each scenario, probability distribution concerning cost uncertainty provided by a DOE expert is explicitly taken into consideration, as shown in Figure 5-3-1 and 5-3-2.

Figure 5-3-3. PV Generation Cost in US Commercial Sector for 2050


【Reference Scenario】 **【DOE Program Scenario】**

In the commercial sector, as depicted in Figure 5-3-3, PV generation cost[6] is anticipated to reach nearly 0.25 US$ per kWh around 2020 in reference case, and 0.20 US$ per kWh in DOE program case, both at 50th percentile probability. On the other hand, retail electricity price in commercial sector will hover around 0.08 US$ per kWh.

Figure 5-3-4 represents the PV generation in building sector at both reference and DOE program scenario. The algorithm in this PV prediction is that total electricity demand is allocated into the electricity supply from utility and from aggregate PV generation through logit function. In the reference scenario, the share of PV generation in electricity demand is projected to be 5%, and in DOE program scenario, 16%. In those amounts, electricity purchase in building sector is forecast to be curtailed, and self-sufficiency in end-use energy supply is expected to be enhanced. As is in this calculation, successful rooftop PV development based on current DOE funding will greatly assist the achievement of Zero Net Energy Building Policy now under discussion by DOE. Additionally, Figure 5-3-5 shows the relation between PV generation and the corresponding probability density in the reference scenario, which suggests that the magnitude of uncertainty in PV adoption increases as it approaches 2050.

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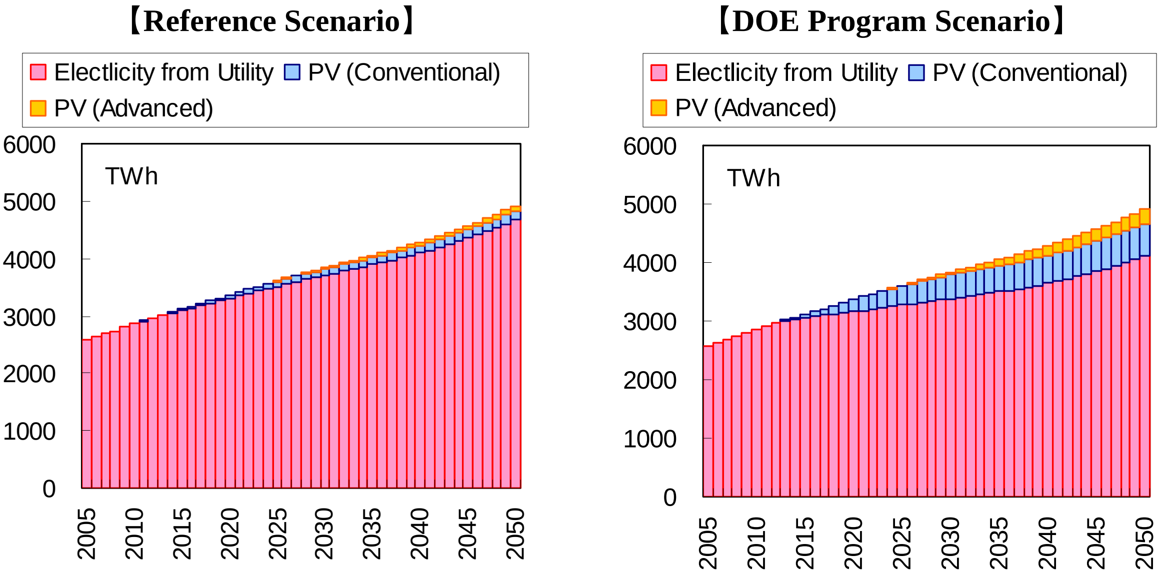
[6] PV generation cost is calculated in a following way.

$$\text{PV generation cost [\$/kWh]} = \frac{PV\ \ System\ \ Cost}{Capacity\ \ Factor} \bullet \frac{i(1+i)^n}{(1+i)^n - 1}$$

Figure 5-3-4. PV Generation in US Building Sector for 2050



* "PV(Conventional)" assumes monocrystalline silicon, multicrystalline silicon. "PV(Advanced)" assumes Copper-Indium Selenide(CIS), Gallium arsenide (GaAs) multijunction, Light-absorbing dyes (DSSC).

Figure 5-3-5. Probability Density of PV Generation in US Building Sector for 2050 (Reference Scenario)

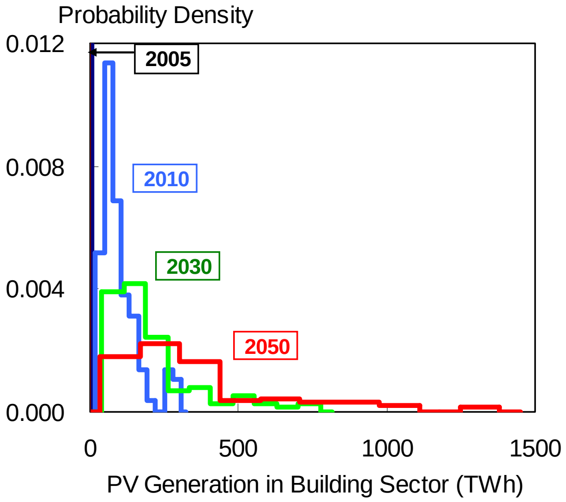
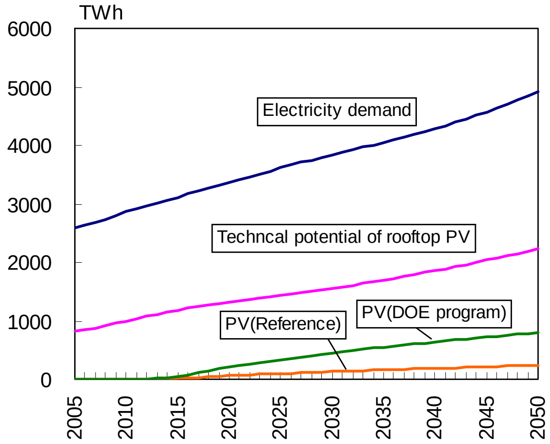


Figure 5-3-6 and 5-3-7 represent PV generation and the technical potential of rooftop PV generation in the building sector. Figure 5-3-6 describes the statistical probability of PV generation derived from future uncertainty of PV cost and efficiency. Maximum deployment potential of building rooftop PV is derived from Navigant Consulting "PV Grid Connected Market Potential under a Cost Breakthrough Scenario" 2004. According to this literature, 65% of total roof space in commercial sector and 22% of total roof space in residential sector are assumed to be technically available to install PV. However, the maximum PV generation in the U.S. building sector is estimated to potentially supply less than half of total electricity demand in the building sector. In the reference scenario, PV generation is likely to accomplish 10% of the technical potential, and in DOE program case, nearly 40% of that potential.

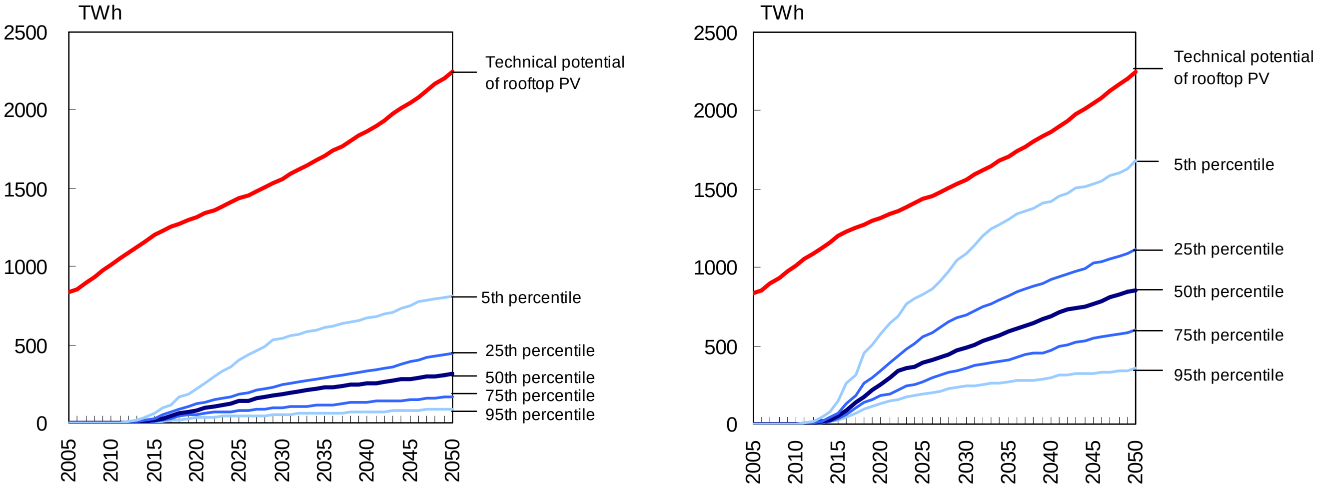
Figure 5-3-6. PV Generation in US Building Sector in comparison with Technical Rooftop Potential for 2050



(Note) "Reference" scenario only considers baseline industrial R&D effort. "DOE program" scenario incorporates currently planning DOE R&D activity. Illustrated electricity demand is calculated under Reference Scenario.

Figure 5-3-7. PV Generation in US building Sector with Probability Distribution for 2050

【Reference Scenario】 【DOE Program Scenario】



6. Conclusions

Anticipating how current R&D should be directed to robustly meet the climate change challenge, especially given wide uncertainty about our evolving energy system, creates a formidable modeling challenge. USDOE is attempting to respond through the creation of an uncertainty based forecasting tool. The buildings aspect of this tool will be a mixture of innovation and tradition. Floorspace forecasting is based on a regression of macro variables against historic floorspace requirements. Downstream of this calculation, the model attempts to use building service requirements rather than energy-based metrics of services as the basis of equipment adoption and energy use forecasts. These service requirements are in turn connected to the composition of the existing building stock. Actual equipment choice is constrained within a common Template that applies to all sectors. The goal is to represent decision-making such that active, passive, and on-site energy conversion options are evenhandedly considered in a way that might allow for radical rethinking of building design and therefore R&D objectives and investments.

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