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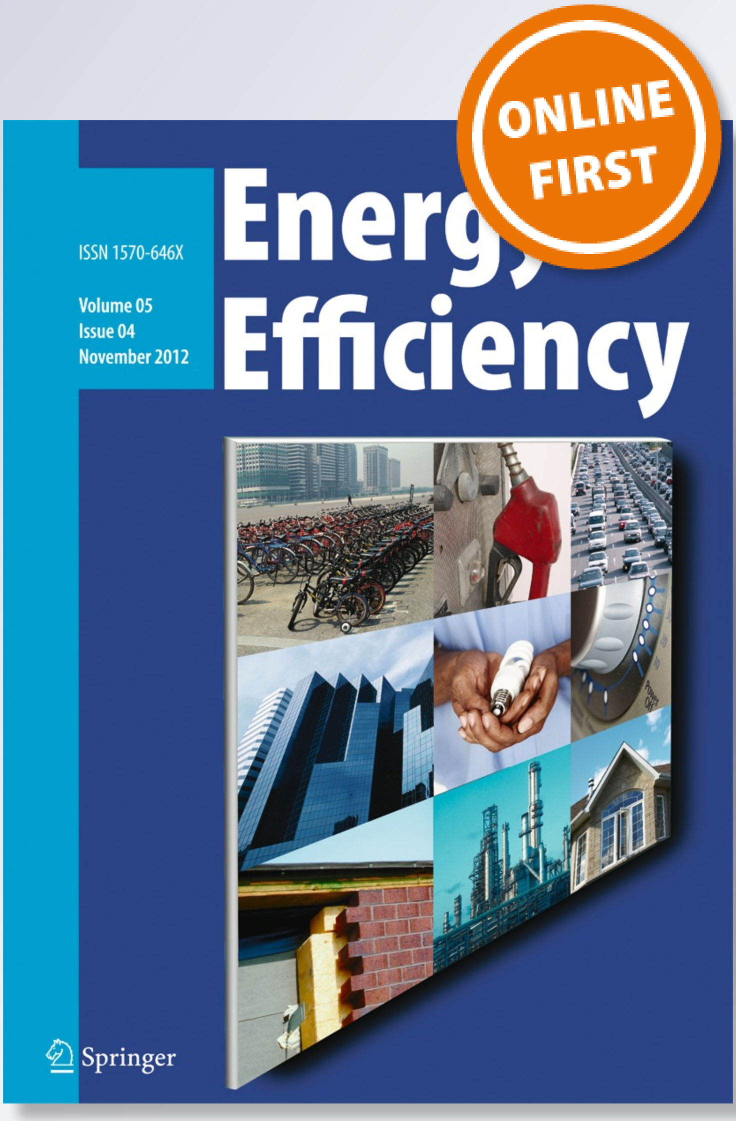
Energy Efficiency

ISSN 1570-646X

Energy Efficiency
DOI 10.1007/s12053-012-9182-6



Springer

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ORIGINAL ARTICLE

Bottom–Up Energy Analysis System (BUENAS)—an international appliance efficiency policy tool

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Received: 30 July 2012 / Accepted: 4 December 2012

Abstract The Bottom–Up Energy Analysis System (BUENAS) calculates potential energy and greenhouse gas emission impacts of efficiency policies for lighting, heating, ventilation, and air conditioning, appliances, and industrial equipment through 2030. The model includes 16 end use categories and covers 11 individual countries plus the European Union. BUENAS is a bottom–up stock accounting model that predicts energy consumption for each type of equipment in each country according to engineering-based estimates of annual unit energy consumption, scaled by projections of equipment stock. Energy demand in each scenario is determined by equipment stock, usage, intensity, and efficiency. When available, BUENAS uses sales forecasts taken from country studies to project equipment stock. Otherwise, BUENAS uses an econometric model of household appliance uptake developed by the authors. Once the business as usual scenario is established, a high-efficiency policy scenario is constructed that includes an improvement in the efficiency of equipment installed in 2015 or later. Policy case efficiency targets represent current "best practice" and include standards already established in a major economy or well-defined levels known to enjoy a significant market share in a major economy. BUENAS calculates energy savings according to the difference in energy demand in the two scenarios. Greenhouse gas emission mitigation is then calculated using a forecast of electricity carbon factor. We find that mitigation of 1075 mt annual CO_2 emissions is possible by 2030 from adopting current best practices of appliance efficiency policies. This represents a 17 % reduction in emissions in the business as usual case in that year.

Keywords Appliances · Energy demand forecast · Standards and labeling · Policy best practices · Appliance diffusion · Developing countries

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Introduction

A consensus has emerged among the world's scientists and many corporate and political leaders regarding the need to address the threat of climate change through emissions mitigation and adaptation. A further consensus has emerged that a central component of these strategies must be focused around energy, which is the primary generator of greenhouse gas emissions. Two important questions result from this consensus: "what kinds of policies encourage the appropriate transformation to energy efficiency" and "how much impact can these policies have"?

Appliance[1] efficiency alone will not solve the climate change problem, but it yields itself to market transformation policies whose success is well established. For example, appliance standards already written into law in the USA are expected to reduce residential sector consumption and carbon dioxide emissions by 8–9 % by 2020 (Meyers et al. 2003). Another study indicates that policies in all OECD countries will likely reduce residential electricity consumption in those countries by 12.5 % in 2020, compared to if no policies had been implemented to date (IEA 2003). Studies of impacts of programs already implemented in developing countries are rare, but there are a few encouraging examples. Mexico, for example, implemented its first Minimum Efficiency Performance Standards (MEPS) on four major products in 1995. By 2005, only 10 years later, standards on these products alone were estimated to have reduced annual national electricity consumption by 9 % (Sanchez et al. 2007). Finally, China has implemented MEPS and expanded the coverage of its voluntary energy efficiency label to over 40 products since 2005. In an impact assessment of the program, 11 products were included and shown to save a cumulative 1,143 TWh by 2020, or 9 % of the cumulative consumption of residential electricity to that year and reduce carbon dioxide emissions by more than 300 million tons carbon equivalent (Fridley et al. 2007).

BUENAS is an end use energy demand projection model developed by Lawrence Berkeley National Laboratory (LBNL). As the name suggests, BUENAS is a tool to model energy demand by various types of energy consuming equipment and aggregate the results to the end use, sector or national level. BUENAS is designed as a policy analysis tool which creates scenarios differentiated by the level of actions taken—generally toward higher energy efficiency. Impacts of policy actions towards market transformation are calculated by comparing energy demand in the "business as usual" case to a specific policy case. BUENAS shares elements with a variety of models,[2] including models of energy savings supporting the USDOE's appliance standards program. The characteristics that distinguish BUENAS are that it covers multiple countries, models energy demand at the technology level, and projects efficiency improvement based on specific targets judged to be achievable.

At the time the development of the BUENAS began, there were few examples of attempts to evaluate the potential impacts of appliance efficiency programs at a global level, although at least one study had considered the program-wide potential in the USA (Rosenquist et al. 2006)[3]. Since that time, a few serious attempts have been made, but these have generally focused on sector energy demand reductions (IEA 2010) or adoption of technology measures (McKinsey & Company 2009) without reference to specific efficiency policies.

Construction of the BUENAS model represents another example to estimate the global potential of appliance efficiency policies. The goals of this article are to:

1. Provide background on the objectives and scope of the BUENAS model
2. Detail the energy forecasting methodology and data inputs used by BUENAS
3. Describe the high-efficiency scenario and provide savings potential results.

Using the methodology and assumptions described below, we find that mitigation of 984 mt annual CO_2 emissions is possible by 2030 from adopting current best practices of appliance efficiency policies. This represents a 17 % reduction in emissions in the business as usual case in that year.

Modeling objectives

The main objective of the development of BUENAS is to provide a global model with sufficient detail and accuracy for quantitative assessment of policy measures such as appliance energy efficiency standards and labeling (EES&L) programs. In most countries where energy efficiency policies exist, the initial emphasis is on household appliances and lighting. Often,

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[1] Throughout this article, "appliance" is a generic term that includes energy-consuming equipment installed in residential and commercial buildings, lighting, and some discrete industrial equipment such as electric motors and distribution transformers. It excludes vehicles and equipment used as a component in industrial processes.

[2] See Mundaca et al. (2010) for a survey of energy-economy models used to evaluate efficiency policy.

[3] Since that time, additional studies of appliance efficiency potential in the USA have been performed (Rohmund et al. 2011; Lowenberger et al. 2012).

equipment used in commercial buildings, particularly heating, ventilation, and air conditioning (HVAC) is also covered by EES&L programs. In the industrial sector, standards and labeling generally cover electric motors and distribution transformers, although a few more types of industrial equipment are covered by some programs, and there is a trend toward including more of them.

The concept for BUENAS emerged from the example of the National Energy Savings (NES) component of analyses supporting US federal rulemakings on MEPS for residential and commercial equipment.[4] The NES analysis forecasts equipment sales and average annual unit energy consumption (UEC) of appliances either with or without a federal standard. Total national energy demand from the two scenarios is then compared to yield the energy saving potential of the standard. BUENAS was constructed in an attempt to replicate this type of analysis at a global scale, employing much less detail for any given appliance type in a given country.

We emphasize that, while the business as usual (BAU) scenario used in BUENAS represents a best estimate of future demand, the focus is on *energy savings* from policy, not on energy demand. In particular, BUENAS is not comprehensive and is not calibrated to agree with top–down estimates—it only includes appliance types for which savings potential can reasonably be assessed, on a country-by-country basis. Having said that, BUENAS covers a significant amount of total energy consumption for some sectors and fuels in some countries.

The bottom–up approach taken by BUENAS not only improves accuracy in many cases, it is necessitated by the nature of the policies commonly applied to appliances—EES&L. A first step in setting forth any such policy is to define the scope of covered equipment. For example, while "laundry equipment" may be a reasonable category for top–down modeling, actual EES&L programs act differently on clothes washers and dryers, and usually discriminate between electric and gas dryers. Furthermore, the energy demand and efficiency potential of top versus front-loading clothes washers is significant, so these two appliances are treated separately if input data allow and later aggregated as a single end use for reporting.

Comparison to other models

BUENAS is somewhat unique in the amount of detail on appliances it provides at the global level. However, it bears some similarity of purpose to other models, especially in the residential sector, and some discussions of its relation to other such models are useful. Happily, a recent article systematically compares such models and includes BUENAS as one of its examples (Mundaca et al. 2010). Mundaca et al. divide the world of "energy-economy" models into four main categories: (a) simulation, (b) optimization, (c) accounting, and (d) hybrid models. BUENAS is categorized as a "simulation" model, which provides "a descriptive quantitative illustration, which is based on exogenously determined scenarios" (p. 307).

Notwithstanding the features of accounting type models incorporated in BUENAS, the simulation characterization is accurate, since the BUENAS high-efficiency scenario is policy-driven rather than a result of consumer economic choice. This is in contrast to models such as MARKAL, MESSAGE, NEMS, or PRIMES (Seebregts et al. 2001; Messner and Strubegger 1995; USDOE 1995; Capros 2000), which assume that consumers act according to economic self-interest at least to some extent. On the other hand, BUENAS models well-defined efficiency targets generally determined by engineering rather than financial considerations. While such options are usually shown to be cost effective in the jurisdiction where they are mandated, it is not assumed that consumers will choose them in the absence of additional policy. In fact, the BUENAS business as usual scenario includes market failures and/or transaction costs that result in consumers not taking advantage of good investments because of lack of information, "principal agent" problems, or other barriers to adoption of efficient technologies. The reasons that energy end users may not pursue pure economic interest by investing in efficient equipment that provides a long-term benefit is the subject of considerable investigation and debate and is beyond the scope of this article. It is valuable, however, to clearly position BUENAS in this context. The working assumption of the BUENAS high-efficiency scenario is that well-designed and implemented policies will eliminate transaction costs and lower barriers and thus transform the

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[4] See for example USDOE (2011a). All analyses supporting US Department of Energy appliance rulemakings can be found at http://www1.eere.energy.gov/buildings/appliance_standards/.

market. In this way, the reliance on an exogenous policy construction is not a simplification in BUENAS, rather a design element appropriate to its purpose as a tool to evaluate policy instead of market effects.

Geographical and end use scope

BUENAS covers 11 countries individually and includes the 27 Member States of the European Union modeled as a single region. Countries currently included in BUENAS are Australia, Brazil, Canada, European Union, India, Indonesia, Japan, Republic of Korea, Mexico, Russia, South Africa, and the USA. Chinese appliance energy demand and efficiency potential has also been modeled in detail by LBNL (Zhou et al. 2011a). LBNL's China appliance model is a component of the China 2050 Energy Model (Zhou et al. 2011b), which includes all energy demand sectors.

Since the model covers most of the world's large economies, the fraction of global energy consumption represented by modeled countries is large. According to IEA data on total energy demand in 2005(International Energy 2006a), the countries covered account for 62 % of global final energy demand if China is not included. Including China, country energy coverage is 77 % of global energy demand. The breakdown of energy demand percentage by countries included in BUENAS is shown in Table 1.

BUENAS includes a wide range of energy-consuming products, including most end uses generally covered by EES&L programs around the world. End uses currently covered are:

- Residential sector: air conditioning, cooking + dishwashing, fans, lighting, refrigeration, space heating, standby, televisions, water heating, and laundry
- Commercial building sector: air conditioning, lighting, refrigeration, space heating, and laundry
- Industrial sector: electric motors and distribution transformers.

An earlier "regional" version of BUENAS (McNeil et al. 2008) estimated each end use listed above for every region, even in the absence of data. This version of the model made extensive use of proxy data; that is, the assumption that data for one country applies to the entire region and in some cases to multiple regions. In the current version of the model, the strategy prioritizes accuracy over comprehensiveness and therefore minimizes the use of proxy data with the consequence that significant gaps remain in the coverage. In fact, some of the end uses listed above are modeled for only one or two countries. A continuing effort will be made going forward to address these gaps as reliable country-specific data are made available. Table 2 summarizes the end use coverage in the current version of

Table 1 Energy consumption percentage by countries included in BUENAS

Region	% Energy	Country	% Energy
Pacific OECD	8	Australia	1.1
		Japan	4.6
		Korea	1.9
North America	23	United States	20.5
		Canada	2.4
Western + Eastern Europe	17	European Union	15.6
Former Soviet Union	9	Russia	5.7
Latin America	6	Mexico	1.5
		Brazil	1.8
Sub-Saharan Africa	3	South Africa	1.1
Middle East + No. Africa	5	–	–
Centrally-Planned Asia	16	China	15.0
South Asia—Other Pacific Asia	9	India	4.7
		Indonesia	1.6
Total	96	Total without China	62
		Total including China	77

Source: International Energy Agency (2006a), 2005 data

Table 2 BUENAS end-use/economy coverage

Sector	End Use Category	AUS	BRA	CAN	EU	IND	IDN	JPN	KOR	MEX	RUS	USA	ZAF
Residential	Air Conditioning	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Fans	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Laundry				🟦				🟦	🟦		🟦	
	Lighting	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Refrigerators & Freezers	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Space Heating			🟦	🟦			🟦				🟦	
	Standby	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Television	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Water Heating	🟦		🟦	🟦			🟦		🟦		🟦	
Commercial	Air Conditioning	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Lighting	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Refrigeration	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Industry	Distribution Transformers	🟦		🟦		🟦		🟦	🟦	🟦	🟦	🟦	
	Motors	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

the model by country/economy. Country abbreviations are defined by the International Standards Organization: Australia (AUS), Brazil (BRA), Canada (CAN), European Union (EU), Indonesia (IDN), India (IND), Japan (JPN), Republic of Korea (KOR), Mexico (MEX), Russia (RUS), United States of America (USA), and South Africa (ZAF).

The main objective of the development of BUENAS is to provide a global model with sufficient detail and accuracy for technical assessment of policy measures such as EES&L programs. In most countries where energy efficiency policies exist, the initial emphasis is on household appliances and lighting. Often, equipment used in commercial buildings, particularly HVAC, is also covered by EES&L programs. In the industrial sector, standards and labeling generally covers electric motors and distribution transformers, although a few more types of industrial equipment are covered by some programs, and there is a trend toward including more of them. In order to make a comprehensive estimate of the total potential impacts, development of the model prioritized coverage of as many end uses commonly targeted by EES&L programs as possible, for as many countries as possible. The model generally did *not* cover:

- Industrial processes
- 'Miscellaneous' end uses or end uses not typically included in EES&L programs.

Data regarding additional end uses is continually becoming available, particularly in the commercial and industrial sector, leading to an ongoing opportunity (and need) to expand and update BUENAS.

Energy demand forecast

BUENAS projects energy demand in order to calculate impacts of current, proposed or possible policies. National energy demand of each end use is constructed according to the following modification of the Kaya identity (Kaya 1989).

$$\text{Energy} = \frac{\text{Activity} \times \text{Intensity}}{\text{Efficiency}}$$

In this equation, *Activity* refers to the size of the stock, e.g., number of refrigerators or the air conditioned area of commercial buildings. *Intensity* is driven by the usage and capacity of each unit, such as the size of a water heater or the hours of use of a room air conditioner. Finally, *Efficiency* is the technological performance of the equipment, which can be affected by government policies.

BUENAS is implemented using the Long-Range Energy Alternatives Planning system (LEAP), developed by the Stockholm Environment Institute.[5] LEAP is a general-purpose energy accounting model in which the model developer inputs all data and assumptions in a format that is then transparent to other users.

BUENAS projects energy consumption by end use from 2005 (base year) to 2030. The strategy of the model is to first project end use activity, which is driven by increased ownership of household appliances, and economic growth in the commercial and industrial sectors. The total stock of appliances can be modeled either according to an econometric diffusion equation or according to unit sales projections if

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[5] For more information on LEAP, visit http://www.sei-us.org/software/leap.html

such forecasts are available. Electricity consumption or intensity of the appliance stock is then calculated according to estimates of the baseline intensity of the prevailing technology in the local market. Finally, the total final energy consumption of the stock is calculated by modeling the flow of products into the stock and the marginal intensity of purchased units, either as additions or as replacements of old units according to equipment retirement rates. The high efficiency or "policy" scenario is created by the assumption of increased unit efficiency relative to the baseline starting in a certain year. For example, if the average baseline UEC of new refrigerators is 450 kWh/year, but a MEPS taking effect in 2012 requires a maximum UEC of 350 kWh/year, the stock energy in the policy scenario will gradually become lower than that of the base case scenario due to increasing penetration of high-efficiency units under the standard. By 2030, the entire stock will generally be impacted by the standard.

The two main outputs of BUENAS are national-level final energy savings and carbon dioxide emissions mitigation. Final energy (electricity or fuel) savings is important because final energy demand is the driver of capital-intensive generation capacity additions and fuel imports. Final energy demand is also the quantity directly paid for by consumers. Carbon dioxide forms the majority of greenhouse gas emissions and is therefore the most important environmental impact of energy consumption. The model described in this article does *not* calculate financial impacts of efficiency policy due to the data requirements needed to include them. However, financial impacts are planned in future versions of the model. Primary energy inputs to electricity are also not considered, although carbon emissions are a rough proxy for them.

The legend of Fig. 1 shows the different component types of the model. These are:

1. *Data or assumption*—These are direct inputs to the model. In the case of data from other sources, the reference of the primary data source is listed. In cases where no data are available, assumptions are sometimes made.

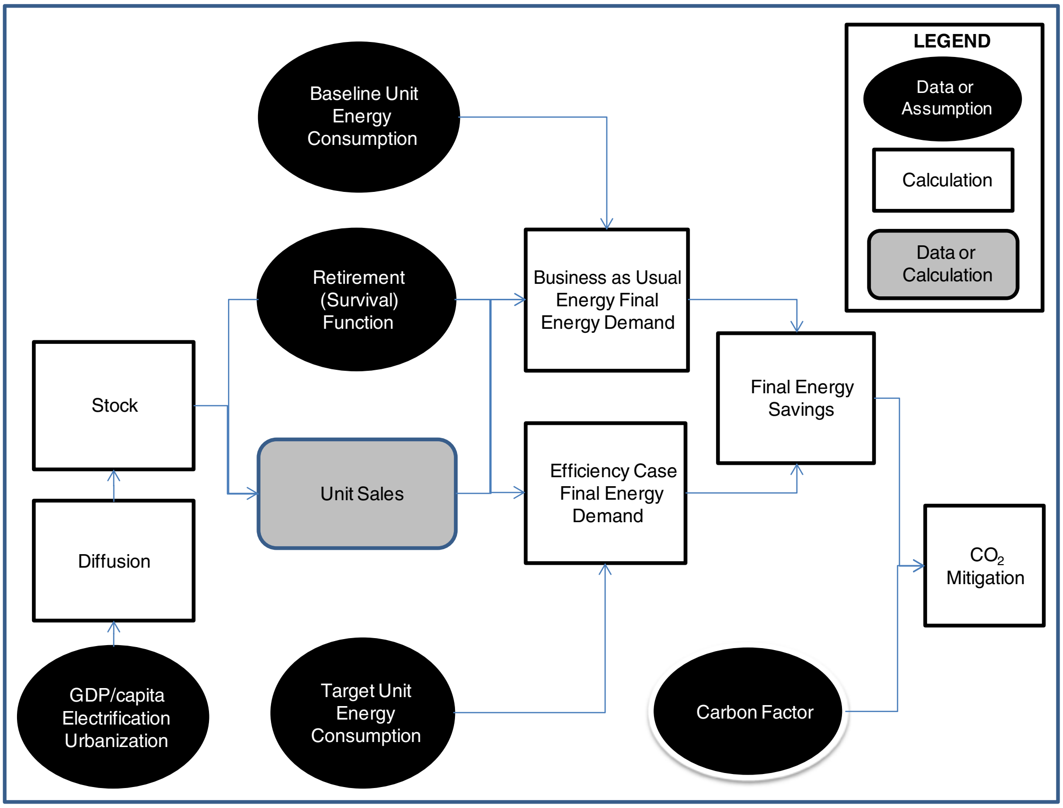

Fig. 1 Flowchart of BUENAS calculation. Note: Stock and Diffusion can be entered directly into the model as data, but this is rare

2. *Calculation*—These are computations governed by the equations in the previous section. These are either built into LEAP, or are user-defined.
3. *Data or calculation*—This can be either a direct data input or a calculation. The main example of this is the projection of unit sales. When available, these data are input directly in the model. If no such data are available, sales are modeled from stock as an intermediate result. Stock in turn can be a direct input or from a model of appliance ownership (diffusion).

Residential sector model

BUENAS calculates final energy demand according to unit energy consumption of equipment sold in previous years:

$$E_{\mathrm{BAU}}(y) = \sum_{\mathrm{age}} \mathrm{Sales}(\mathrm{y} - \mathrm{age}) \times \mathrm{UEC}_{\mathrm{BAU}}(\mathrm{y} - \mathrm{age}) \times \mathrm{Surv}(\mathrm{age})$$

- $E_{\mathrm{BAU}}(y)$ = final energy demand in the business as usual scenario in year y
- Sales(y) = unit sales (shipments) in year y
- UEC(y) = unit energy consumption of units sold in year y
- Surv(age) = probability of surviving to *age* years.

When unit sales (shipments) are not given as direct data inputs then BUENAS derives them from increases in stock and replacements:

$$\mathrm{Sales}(\mathrm{y}) = \mathrm{Stock}(\mathrm{y}) - \mathrm{Stock}(\mathrm{y} - 1) + \sum_{\mathrm{age}} \mathrm{Ret}(\mathrm{age}) \times \mathrm{Sales}(\mathrm{y} - \mathrm{age})$$

- Stock(y) = number of units in operation in year y
- Ret(age) = probability that a unit will retire (and be replaced) at a certain age.

Survival function and retirement function are related by:

$$\mathrm{Surv}(\mathrm{age}) = 1 - \sum_{\mathrm{age}} \mathrm{Ret}(\mathrm{age})$$

Three different methods are used to estimate the total stock of a particular residential end use. For each region and end use, the highest accuracy method is chosen for which sufficient data are available. In order of decreasing accuracy, the methods are:

1. Stock based on historical and projected flows of products (unit sales)
2. Stock from historical and projected ownership rates—sales derived from stock increases and replacement rates
3. Stock from econometric modeling driven by macroeconomic trends—sales derived from stock increases and replacement rates.

Stock is rarely given directly as input data. Instead, if sales data are not available, BUENAS uses appliance diffusion (ownership) rates:

$$\mathrm{Stock}(\mathrm{y}) = \mathrm{Diffusion}(\mathrm{y}) \times \mathrm{HH}(\mathrm{y})$$

- Diffusion(y) = number of units (owned and used) per household in year y
- HH(y) = Number of households in year y.

In turn, diffusion rates are generally not given by input data, but are projected according to a macroeconomic model:

$$\mathrm{Diffusion}(\mathrm{y}) = \frac{\alpha}{1 + \gamma \times \exp[\beta_1 \times \mathrm{I}(\mathrm{y}) + \beta_2 \times \mathrm{U}(\mathrm{y}) + \beta_3 \times \mathrm{E}(\mathrm{y})]}$$

- $I(y)$ = household income (GDP per household) in year (y)
- $U(y)$ = urbanization rate in year (y)
- Elec(y) = electrification rate in year (y)
- $\alpha,\gamma,\beta_1,\beta_2,\beta_3$ = model parameters (described in McNeil and Letschert 2010).

The determination of diffusion coefficients for all modeled equipment types is shown in Table 3.

In the case of fans, cooling degree days are used as a driving variable of ownership. Air conditioner ownership is also highly climate dependent. To model this, the diffusion equation for air conditioners is multiplied by a *climate maximum* parameter ranging from 0 to 1. Climate maximum is given by the following equation, as determined in (McNeil and Letschert 2010)

$$\mathrm{ClimateMaximum} = 1.0 - 0.949 \times \exp(-0.00187 \times \mathrm{CDD})$$

This equation utilizes the climate parameter *cooling degree days* (CDD), which integrates total

Table 3 Residential diffusion model parameters

Points of light			$\ln \gamma$	β_{Inc}	β_{Elec}	β_{Urb}
α	40	Coefficient	2.204	−3E−05		
Observations	42	Standard error	0.18	3.0E−06		
R^2	0.71	t-Stat	12.45	−10.00		
Refrigerators			$\ln \gamma$	β_{Inc}	β_{Elec}	β_{Urb}
α	1.4	Coefficient	4.84	−1.3E−05	−3.59	−2.24
Observations	64	Standard error	0.197	4.82E−06	0.27	0.59
R^2	0.92	t-Stat	24.508	−2.77	−13.42	−3.78
Televisions			$\ln \gamma$	β_{Inc}	β_{Elec}	β_{Urb}
α	3	Coefficient	3.701	−2.5E−05	−2.39	
Observations	46	Standard error	0.134	4.96E−06	0.31	
R^2	0.85	t-Stat	27.584	−5.07	−7.66	
Room air conditioners			$\ln \gamma$	β_{Inc}	β_{Elec}	β_{Urb}
α	ClimateMax	Coefficient	4.843	−6.9E−05		
Observations	24	Standard error	0.503	9.82E−06		
R^2	0.69	t-Stat	9.635	−7.04		
Fans			$\ln \gamma$	β_{Inc}	β_{Elec}	β_{CDD}
α	3	Coefficient	0.798	9.79E−07	−1.13	3.41E−04
Observations	11	Standard error	0.968	4.82E−06	0.98	1.34E−04
R^2	0.79	t-Stat	0.824	0.20	−1.15	2.55
Standby power devices			$\ln \gamma$	β_{Inc}	β_{Elec}	β_{Urb}
α	12	Coefficient	1.266	0.00		
Observations	20	Standard error	0.508	0.00		
R^2	0.40	t-Stat	2.492	−3.43		

hours in a year during which outdoor temperatures exceed a reference defined as a cooling threshold. Cooling degree days are the main climate parameter determining cooling load, though other factors, such as humidity, are also important. Country specific parameters, including activity, and efficiency scenarios are given in the following sections.

In the residential sector, UEC is almost always taken from a direct data source, or is an assumption. The exception is air conditioning consumption, which is modeled to be both climate and income dependent. The model describing business as usual room air conditioner energy demand is determined in (McNeil et al. 2008) as follows:

$$\mathrm{UEC(y)(kWh)} = 0.0276 \times \mathrm{I(y)} + 1.46 \times \mathrm{CDD} - 1,332$$

In cases where the air conditioner model would predict extremely high air conditioner consumption, UEC is set to a maximum of 3,500 kWh/year.

Commercial sector modeling

Sales data are scarce for most commercial end uses. In this sector, BUENAS models commercial floor area and end use intensity, since these data are more readily available from national statistics.

Commercial floor space projection

The "commercial" sector refers to all buildings that are not used as residences, or part of industrial facilities (also called "tertiary" or "service" sector). For the purposes of modeling, the commercial sector is distinguished from the residential sector in several important ways. First, buildings and end use equipment can vary greatly in size, from a room air conditioner used in a corner market to large chillers used in the largest office buildings. Second, data on these buildings and on the equipment installed in them is generally sparser than for residences. Finally, residential end uses tend to be the first target of efficiency programs with commercial end uses targeted later. Such programs are an important source of insight into the consumption and further savings potential of upcoming programs.

$$E_{\mathrm{BAU}} = \sum_{\mathrm{age}} \mathrm{Turnover}(\mathrm{y}-\mathrm{age}) \times \mathrm{uec}_{\mathrm{BAU}}(\mathrm{y}-\mathrm{age}) \times \mathrm{Surv}(\mathrm{age})$$

- Turnover(y) = equipment floor space coverage added or replaced in year y
- uec(y) = energy intensity (kWh/m^2) of equipment installed in year y (lower case used to distinguished from unit energy consumption, UEC).

Much of the focus of commercial building modeling is on the projection of commercial floor space. While current floor space estimates are available for some countries, in general projections are not. The strategy for determining floor space is to separately model the percentage of employment in the tertiary sector of the economy and the floor space per employee engaged in this sector. Service sector share (SSS) is multiplied by the total number of employees which is determined by:

- *Economically active population* $P_{EA}(y)$ from the International Labor Organization projected to 2020 and extrapolated thereafter (ILO 2007)
- *Unemployment rate* $R_U(y)$ from the International Labor Organization (ILO 2007) till 2005, and projected to 2005 regional average by 2020.

SSS is modeled as a function of GDP per capita in terms of purchasing power parity (PPP). SSS data are available from the World Bank for a wide range of countries and for different years. The relationship between SSS and GDP per capita is modeled in the form of a log-linear equation of the form

$$\mathrm{SSS}(\mathrm{y}) = \mathrm{a} \times \ln[\mathrm{I}(\mathrm{y})] + \mathrm{b}$$

The parameters a and b are determined to be 0.122 and −0.596, respectively. More detail about the data used to determine these parameters can be found in (McNeil et al. 2008).

Using these components, the number of service sector employees N_{SSE} is given by

$$N_{\mathrm{SSE}}(y) = P_{\mathrm{EA}}(y) \times [1 - R_U(y)] \times \mathrm{SSS}(\mathrm{y})$$

Floor space per employee, denoted $f(y)$ is, like SSS, assumed to be a function of per capita income only. The relationship assumes a logistic functional form:

$$f(y) = \frac{\alpha}{1 + \gamma \times \exp[\beta' \times i(y)]}$$

In this equation, the maximum value α is set to 70 m^2 per employee, which was larger than any of the observed data. The variable I denotes GDP per capita, and β'' and γ were determined to be -9.9×10^{-5} and 6.04, respectively. More detail about the data used to determine these parameters can be found in (McNeil et al. 2008).

Turnover is driven by increases in floor space, and replacement of existing equipment occupying floor space.

$$\mathrm{Turnover}(\mathrm{y}) = \mathrm{F}(\mathrm{y}) - \mathrm{F}(\mathrm{y}-1) + \sum_{\mathrm{age}} \mathrm{Ret}(\mathrm{age}) \times \mathrm{Turnover}(\mathrm{y}-\mathrm{age})$$

- $F(y)$ = total commercial floor space in year y.

Commercial end use intensity

Generally, it is difficult or nearly impossible to model commercial end use intensity according to stock flows of specific equipment types due to data limitations. Therefore, end use intensity estimation takes an aggregate approach. End-use intensity is composed of *penetration*, *efficiency*, and *usage*. Penetration takes into account the effect of economic development on increased density of equipment expressed in Watts per square meter and is assumed to be a function of GDP per capita only. Relative efficiency is estimated from specific technologies and usage is given by hours per year. Savings between the high-efficiency and the business as usual case arise from percentage efficiency improvements.

Lighting efficiency is estimated as the fraction in the stock of lighting types: T12, T8, and T5 fluorescent tubes, incandescent lamps, compact fluorescent lamps, halogen lamps, and other lamps. In addition, relative efficiency of fluorescent lamp ballasts contributes to overall lighting efficiency. Assumptions for lighting energy intensity and the subsequent calculation of penetration are provided in McNeil et al. (2008). The result is a model of penetration according to a logistic function

$$p\left(\mathrm{W}/\mathrm{m}^2\right) = \frac{\alpha}{1 + \gamma \times e^{\beta \times I(y)}}$$

The variable $I(y)$ denotes GDP per capita, and α, β, and γ are found to be 16.0, -7.78×10^{-5}, and 3.55, respectively.

Space cooling energy intensity is of course a strong function of not only climate but also economic development. Its dependence on cooling degree days (CCD) is assumed to be linear. The dependence on GDP per capita, which we call "availability," takes a logistic form:

$$\mathrm{Int}\left(\mathrm{kW/m^2}\right) = \frac{\alpha}{1+\gamma\times e^{\beta\times \mathrm{I(y)}}}\times(\mathrm{a}+\mathrm{b}\times\mathrm{CCD})$$

In order to separate the effect, the climate dependence is determined from US data, where availability is assumed to be maximized. Once modeled in this way, the climate dependence can be divided out of final energy intensity data to yield availability as a function of GDP per capita. The parameters for space cooling intensity determined in this way are:

$$\alpha = 1.8, \beta = 0.00011, \gamma = 8.83; a = 9.7193, b = 0.0123$$

Space cooling efficiency is determined according to estimates of market shares of room air conditioners, central air conditioners and chillers, prevailing baseline technologies and feasible efficiency targets (see McNeil et al. 2008)

Due to a scarcity of data for commercial refrigeration, space cooling *penetration* is assumed to have the same shape as lighting, that is, the availability of space cooling increases as a function of per capita GDP in the same proportion as for lighting, but with a different coefficient of proportionality A.

$$\mathrm{Int}\left(\mathrm{kWh/m^2}\right) = \frac{\mathrm{A}}{1+\gamma e^{\beta \mathrm{I(y)}}}$$

The penetration curve is then calibrated to data from the USA, which has a refrigeration intensity of 9.94 kW/m^2. The resulting value of A is 10.61 kW/m^2. In the high efficiency scenario, an improvement of 34 % is assumed to be possible (Rosenquist et al. 2006) in all countries.

Industrial model

The main industrial type of equipment modeled by BUENAS is electric motors, which are thought to account for around half of the industrial electricity consumption in most countries. Motors modeled range from 1 to over 250 HP and are used in both manufacturing and lighter industry or commercial applications. They generally exclude smaller motors used as components in other equipment. In addition to motors, distribution transformers are categorized as industrial equipment although these are sometimes categorized as commercial sector equipment depending on their application.

Industrial motors model

When sales data and unit energy consumption are not available for industrial motors, they are modeled as a function of industrial value added GDP:

$$E(y)_{\mathrm{BAU}} = \mathrm{GDP(y)_{IND}}\times\varepsilon\times\mathrm{p}$$

- $\mathrm{GDP}(y)_{\mathrm{IND}}$ = GDP value added of industrial sector in year (y)
- ε = electricity intensity per unit of industrial GDP
- p = percentage of electricity from electric motors

Electricity demand and savings potential for electric motors is treated in the same way for all regions except for the European Union, for which a motor stock projection is provided in the Ecodesign preparatory study (de Ameida et al. 2008). The model for industrial motor activity used in BUENAS is somewhat simplistic. For all countries outside of the EU, total electricity consumption of motors as a fraction of industrial electricity is used as the activity variable, according to the following formula:

$$\mathrm{Elec(y)} = \mathrm{GDPVA_{IND}(y)}\times\varepsilon\times\mathrm{p}$$

In this equation, $\mathrm{GDPVA_{IND}}$ is the value added to GDP from the industrial sector. The variable ε is the electricity intensity of the industrial sector, that is, the amount of electricity consumed for each dollar of industrial value added. This variable is taken from historical energy consumption data (from IEA) and divided by $\mathrm{GDPVA_{IND}}$ from the World Bank in the base year. Multiplying ε and $\mathrm{GDPVA_{IND}}$ for the base year simply gives back reported industrial electricity consumption in that year and, since ε is assumed constant, industrial electricity consumption in the projection simply grows at the same rate as $\mathrm{GDPVA_{IND}}$. The fraction p is the percentage of industrial electricity passing through motors. Multiplying the three variables together then gives motor electricity consumption in each year through 2030.

Distribution transformers model

For some countries, per-unit sales of each category of distribution transformers is forecast and unit energy losses can be used to directly calculate energy losses and savings due to efficiency. Most often, however, these data are not available. In that case, BUENAS models distribution transformer simplistically according to exogenous national electricity demand forecasts provided by (EIA 2008). Since virtually all of the electricity used in all sectors eventually passes through at least one distribution transformer, losses through transformers in each year *y* are given by the following equation:

$$\mathrm{Losses(y)} = (1 - \mathrm{eff}) \times \mathrm{Demand(y)}$$

In this equation, *eff* is the efficiency of transformers, including both load and no-load losses averaged over the load profile. Demand(*y*) is the total national electricity demand and Losses(y) is the electricity lost through all distribution transformers. Finally, in cases where neither unit level data nor electricity forecasts are available, distribution transformers are omitted.

Efficiency scenarios

The BAU forecast scenario modeled by BUENAS combines activity forecasts with intensity as modeled or determined by data inputs or assumptions. The base year for the BAU forecast is 2010. BUENAS generally assumes that baseline efficiency is constant or "frozen" at 2010 values over the forecast period and that there are no major technology or product class shifts in that time. Some exceptions include:

- Equipment forecasts from the USA, which are taken from other studies and often include projections of baseline efficiency improvement and product class shifts
- Phase out of incandescent lamps, which is expected to gradually occur over the forecast period even in the BAU case
- Evolution of product classes towards split room air conditioners and frost-free refrigerators in India.

Of course, the BAU forecast is itself not expected to remain constant over time. For instance, ongoing regulations are continually improving appliance efficiency in major economies. Although these are known, for practical reasons, we chose not to continually update the baseline, instead choosing to create a separate scenario quantifying the impact of recent regulations (Kalavase et al. 2012).

A second scenario modeled by BUENAS considers the potential impacts of regulations in the near to medium term. This scenario includes efficiency improvements judged to be ambitious but achievable for all countries[6]. There are many possible ways of defining global potential, including cost effectiveness, removal of a certain fraction of low-efficiency models from the market, or adoption of best available technology. Due to data limitations, the most practical approach has been to rely on an evaluation of best practices. The best practice (BP) scenario assumes that all countries achieve stringent efficiency targets by 2015, where 'stringent' is interpreted in the following way:

1. Where efficiency levels are comparable globally: the most stringent standard issued by April 1, 2011 anywhere in the world.
2. Where they are comparable only within regions or testing regime: the most stringent comparable standard issued by April 1, 2011.
3. In the case where an obvious best comparable standard was not available, an efficiency level was set that was deemed to be aggressive or achievable, such as the most efficient products in the current rating system.

In addition, the best practice scenario assumes that standards are further improved in the year 2020, by an amount estimated on a product-by-product basis. This scenario either assumes that the same level of improvement made in 2015 is repeatable in 2020 or assumes that a specific target, such as current "best available technology," is reached by 2020. Some of the policies available to achieve high efficiency targets include:

- *Minimum Efficiency Performance Standards* (*MEPS*)—Equipment is required to perform at the level of efficiency determined by the standard. Products failing to demonstrate compliance are banned from the market.
- *Comparative labels*—Comparative labels provide information to the consumer about efficiency level of all products, and boost the efficiency of the

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[6] In this scenario, "achievable" means that it would be feasible to implement a policy by that time. The definition does not take into account the lead times between policy announcement and implementation, which can be several years in some countries.

market by generating consumer preference towards more highly-rated models.

- *Endorsement labels*—Endorsement labels represent a "seal of approval" issued by the government or an independent entity. Only those models of very high efficiency are awarded the label. These labels improve the average market efficiency by raising the market share of the highest performing equipment.

These program types are discussed in detail elsewhere (see Wiel and McMahon 2005), and we do not discuss them further here. It is worth noting, however, that, due to the complexity of the number of regions, sectors and end uses considered, we make the simplifying assumption that the entire market reaches the efficiency target in the implementation year—an assumption that corresponds to the implementation of a MEPS program, although other programs could achieve the same result if they were able to move the market average to the same level.

Table 4 summarizes the references and assumptions used in modeling the *best practice scenario*. The following variables are shown:

End use	Appliance type covered by the regulation
Units	Metric used to define efficiency level (energy consumption or direct efficiency metric)
ISO	International Standards Organization three-letter country code
Standard year	Year that regulation takes effect
$\mathrm{UEC}_{\mathrm{BC}}$	Unit Energy consumption in the *business as usual case*[7]
Reference	Source of unit energy consumption data
$\mathrm{UEC}_{\mathrm{BP}}$	Unit energy consumption in the *best practice scenario*
% Imp	Percentage improvement between *business as usual* case and *recent achievements* scenario
Assumptions/ definition	Definitions provided by regulatory documents or assumptions made regarding best practice in developing the scenario

The most detailed and data-intensive analyses of the potential impacts of standards and labeling programs take cost effectiveness into account in an integral way, often defining the optimum policy in terms of "economic potential," that is, the market transformation that maximizes net economic benefits to consumers.[8] These benefits can be quantified by a variety of different metrics, including least life cycle cost, cost of conserved energy, or benefit to cost ratios. Due to data constraints, this type of analysis was not possible here. Inclusion of costs that will allow this type of analysis is anticipated in future versions of the model. Instead, the BP scenario emphasizes the setting of realistic, achievable goals. While cost effectiveness is not considered explicitly, the degree to which the transformation of the market to a new technology is achievable is implicitly dependent on the cost effectiveness of the technology.

Two specific corrections are not taken into account in these scenarios. First, we do not assume improvement in efficiency in the absence of a program. While in some cases the 2010 baseline is higher than the current level (due to already scheduled standards), between 2010 and 2020, we assume that the baseline efficiency is constant. Historically, there is generally (but not always) a gradual trend towards higher efficiency from market forces alone, but this increase tends to be small in comparison to the increase propelled by EES&L programs. On the other hand, the targets that we specify in the high efficiency scenario are already known to exist and to be cost effective in some markets. More often than not, markets overshoot the targets due to learning by manufactures in the time between promulgation and implementation of standards.[9] These two effects are very difficult to predict, especially for a wide range of regions and end uses. Unpredictably high efficiency in the base case and policy case also tend to compensate for one another. In fact, it can be argued that they are both effects of the same learning process in the manufacturing industry and should therefore, at least on average, tend to cancel each other out.

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[7] While efficiency is generally assumed to be constant in the business as usual case, unit energy consumption can change over time according to usage trends.

[8] Examples of these are analyses of potentials for the USA (Rosenquist et al. 2006) and IEA countries (IEA 2003).

[9] There are other reasons as well. For example, evidence suggests that manufacturers in Mexico outperformed MEPS in that country in order to produce products competitive in the wider North American Market—see Sanchez et al. (2007).

Table 4 References and definitions of best practice scenario

End use	Units	ISO	Standard year	UEC$_{BC}$	Reference		UEC$_{BP}$	Reference		% imp.	Assumptions/ definition
Refrigerators	kWh/year	USA	2014	577.1	DOE Final Rule	(USDOE 2011b)	481	DOE Final Rule	(USDOE 2011b)	20	Ratio from 2014 Standard
Refrigerators	kWh/year	MEX	2015	369.0	IIE 2005	(Sanchez et al. 2007)	295.2		(Sanchez et al. 2007)	25	
Refrigerators	kWh/year	CAN	2015	577.1	assumed equal to US		481.2			20	
Refrigerators	kWh/year	EU	2014	279	Ecodesign	(EC 2008)	232	A+	(EC 2008)	40	EU A++ Level
Refrigerators	kWh/year	RUS	2015	597	Same size as Europe, Level C		232			40	
Refrigerators	kWh/year	ZAF	2015	597	Same size as Europe, Level C		232			40	
Refrigerators	kWh/year	IDN	2015	328	Assumed equal to India		323	5 Star Phase 1		49	India 5 Star Phase 2
Refrigerators	kWh/year	BRA	2015	597	Same size as Europe, Level C		232	A+		40	EU A++ Level
Refrigerators	kWh/year	IND	2015	327.7	McNeil AND Iyer 2009	(McNeil and Iyer 2009)	323	5 Star Phase 1		49	Indian Labeling Program 5 Star Phase 1
Refrigerators	kWh/year	AUS	2015	412	Australian TSD (3E)	(Energy Efficient 2008)	323	6 Star Ref	(Energy Efficient 2008)	35	Australian Labeling Program, 10 Star
Refrigerators	kWh/year	JAP	2015	519.04	Top Runner Target		429.0	Next Top Runner, 21 % more efficient (2005–2010 improvement)		21	Ratio from 2015 Standard
Refrigerators	kWh/year	KOR	2015	519.04	Top Runner Target		429.0			21	
RAC	EER	USA	2014	2.87	DOE Final Rule	(USDOE 2011c)	3.65	Top Runner		27	
RAC	EER	CAN	2015	3.18	4E Benchmarking		3.58			13	
RAC	EER	MEX	2015	2.78	4E Benchmarking		3.42			23	
RAC	SEER	EU	2012	3.17	Ecodesign, MEPS 2012 Scenario-personal communication	(EC 2009a)	3.95	Ecodesign, MEPS 2012 Scenario-Personal communication Philippe Riviere		24	
RAC	SEER	RUS	2015	3.17	Assumed equal to EU		3.95			24	
RAC	EER	IND	2015	2.63	CLASP Impact Study		3.23	Top Runner		23	
RAC	EER	IDN	2015	2.53	Assumed equal to India		3.23			27	
RAC	EER	AUS	2015	2.90	4E Benchmarking		3.33			15	
RAC	EER	ZAF	2015	2.78	Assumed equal to Mexico		3.42			23	
RAC	EER	BRA	2015	2.78	Assumed equal to Mexico		3.42			23	
RAC	EER	JAP	2015	2.88	Assumed equal to Korea		3.23			12	
RAC	EER	KOR	2015	2.88	4E Benchmarking		3.2			12	

Table 4 (continued)

End use	Units	ISO	Standard year	UEC_{BC}	Reference		UEC_{BP}	Reference		% imp.	Assumptions/ definition
LCD	kWh/year	USA	2012	102.5	LBNL Technical Study	(Park et al. 2011)	96.2	Super Efficiency Scenario, Cost Effective Target DBF + Dimming	(Park et al. 2011)	5.00	Standard 5 % more efficient than baseline in every year
LCD	kWh/year	MEX	2012	71.4	LBNL Technical Study	(Park et al. 2011)	60.6		(Park et al. 2011)	5.00	
LCD	kWh/year	CAN	2012	82.0	LBNL Technical Study	(Park et al. 2011)	77.0		(Park et al. 2011)	5.00	
LCD	kWh/year	EU	2012	64.6	LBNL Technical Study	(Park et al. 2011)	60.9		(Park et al. 2011)	5.00	
LCD	kWh/year	RUS	2012	69.1	LBNL Technical Study	(Park et al. 2011)	63.2		(Park et al. 2011)	5.00	
LCD	kWh/year	ZAF	2012	72.0	LBNL Technical Study	(Park et al. 2011)	64.8		(Park et al. 2011)	5.00	
LCD	kWh/year	IDN	2012	72.0	LBNL Technical Study	(Park et al. 2011)	64.8		(Park et al. 2011)	5.00	
LCD	kWh/year	BRA	2012	70.2	LBNL Technical Study	(Park et al. 2011)	67.2		(Park et al. 2011)	5.00	
LCD	kWh/year	IND	2012	70.5	LBNL Technical Study	(Park et al. 2011)	60.6		(Park et al. 2011)	5.00	
LCD	kWh/year	AUS	2012	70.5	LBNL Technical Study	(Park et al. 2011)	63.6		(Park et al. 2011)	5.00	
LCD	kWh/year	JAP	2012	70.8	LBNL Technical Study	(Park et al. 2011)	67.5		(Park et al. 2011)	5.00	
LCD	kWh/year	KOR	2012	70.5	LBNL Technical Study	(Park et al. 2011)	63.6		(Park et al. 2011)	5.00	
Stand by	kWh/year	USA	2015	17.2	Ecodesign	(EC 2007a)	3.6	Ecodesign	(EC 2007a)	402	0.1 W standard
Stand by	kWh/year	MEX	2015	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Stand by	kWh/year	CAN	2015	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Stand by	kWh/year	EU	2013	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Stand by	kWh/year	RUS	2015	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Stand by	kWh/year	ZAF	2015	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Stand by	kWh/year	IDN	2015	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Stand by	kWh/year	BRA	2015	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Stand by	kWh/year	IND	2015	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Stand by	kWh/year	AUS	2015	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Stand by	kWh/year	JAP	2015	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Stand by	kWh/year	KOR	2015	17.2	Ecodesign	(EC 2007a)	3.6		(EC 2007a)	402	
Water heater	kWh/year	USA	2015	2491	DOE, TSD 2010		2305	DOE, FR 2010		90	
Water heater	kWh/year	CAN	2015	2491	Assumed equal to US		2305	DOE, FR 2010-assumes same % imp		90	Heat Pump, DOE FR 2010
Water heater	kWh/year	EU	2013	2161			1799			EER=2.35	

Table 4 (continued)

End use	Units	ISO	Standard year	UEC$_{BC}$	Reference		UEC$_{BP}$	Reference		% imp.	Assumptions/ definition
					Useful energy from Ecodesign study, efficiency from USDOE rulemaking			Efficiency target same as US FR, 2010			Heat Pump, DOE FR 2010
Electric water heater	kWh/year	AUS	2015	3603	McNeil et. al 2008	(McNeil et al. 2008)	3262	McNeil et. al 2008		10	Ratio from 2015 Standard
Gas storage water heater	GJ/year	USA	2015	16.8	DOE, FR 2010		16.3	DOE, FR 2010		24	Condensing, DOE FR 2010
Gas storage water heater	GJ/year	MEX	2014	20.90	CONUEE		18.81	CONUEE		11	Ratio from 2015 Standard
Gas storage water heater	GJ/yr	CAN	2015	16.8	assumed equal to US		16.3	DOE, FR 2010-assumes same % imp		24	Condensing, DOE FR 2010
Gas storage water heater	GJ/year	AUS	2015	15.37	Global model Baseline + Savings from Syneca report	(Syneca 2007)	13	Syneca Consulting, 5 star std		19	Ratio from 2015 Standard
Gas instantaneous water heater	GJ/year	USA	2015	11.3	DOE, FR 2010		11.1	DOE, FR 2010		16	Condensing
Gas instantaneous water heater	GJ/year	AUS	2015	11.3	US baseline		9.2	Syneca Consulting, 6 star std		22	Ratio from 2015 Standard
Incandescent lamps	% IL	USA	3 tier	Phase out by 2020	LBNL Assumption		Phase out by end of 2014	EISA		67	100Lm/W LEDs (CFLs 60Lm/W)
Incandescent lamps	% IL	CAN	3 tier	Phase out by 2020	LBNL Assumption		Phase out by end of 2014			67	
Incandescent lamps	% IL	Others	3 tier	Phase out by 2030	LBNL Assumption		Phase out by end of 2014	Ecodesign Directive		67	
Fluorescent ballast	%	USA	2015	80 %	Harmonization Report		87.80 %		(EC 2009b)	4	BAT from Harmonization Report
Fluorescent ballast	%	CAN	2015	78 %	Global Model		87.80 %		(EC 2009b)	4	
Fluorescent ballast	%	MEX	2015	80 %	Assumed equal to US		87.80 %		(EC 2009b)	4	
Fluorescent ballast	%	EU	2017	80 %	Harmonization Report	(Waide 2010)	87.80 %		(EC 2009b)	4	
Fluorescent ballast	%	RUS	2015	78 %	McNeil et. al 2008	(McNeil et al. 2008)	87.80 %		(EC 2009b)	4	
Fluorescent ballast	%	ZAF	2015	78 %	McNeil et. al 2008	(McNeil et al. 2008)	87.80 %		(EC 2009b)	4	
Fluorescent ballast	%	IDN	2015	70 %	McNeil et. al 2008	(McNeil et al. 2008)	87.80 %		(EC 2009b)	4	

Table 4 (continued)

End use	Units	ISO	Standard year	UEC_{BC}	Reference		UEC_{BP}	Reference		% imp.	Assumptions/ definition
Fluorescent ballast	%	BRA	2015	78 %	McNeil et. al 2008	(McNeil et al. 2008)	87.80 %		(EC 2009b)	4	
Fluorescent ballast	%	IND	2015	70 %	McNeil et. al 2008	(McNeil et al. 2008)	87.80 %		(EC 2009b)	4	
Fluorescent ballast	%	AUS	2015	80 %	Assumed equal to EU		87.80 %		(EC 2009b)	4	
Furnace	GJ/year	USA	2015	34.7	Final Rule 2011	(Energy Efficient 2008)	32.3	Final Rule 2011	(Energy Efficient 2008)	28.5	Condensing
Furnace	GJ/year	CAN	2015	79	Energy Use Datahandbook 2008	(NRCAN 2011)	73	assumed equal to US, scaled		8	Ratio from 2015 Standard
Furnace fan	kWh/year	USA	2015	285.32	Final Rule 2011	(Energy Efficient 2008)	265.3	Scales with Fuel Consumption of NWGF		8	
Furnace fan	kWh/year	CAN	2015	643	assumed equal to US, scaled		598	assumed equal to US, scaled		8	
Central AC	kWh/year	USA	2016	3234.8	Final Rule 2011	(Energy Efficient 2008)	2,915	Final Rule 2011	(Energy Efficient 2008)	11	
Central AC	kWh/year	CAN	2015	1,698	Energy Use Datahandbook 2008	(NRCAN 2011)	1,630	Same % Improvement as US		4	
Central AC	kWh/year	AUS	2015	432	Energy Use in Australia in the residential sector 1986-2020	(CONUEE 2009)	414			4	
Freezer	kWh/year	USA	2014	529.3	Final Rule 2011	(USDOE 2011d)	347	Final Rule 2011	(USDOE 2011d)	52	
Freezer	kWh/year	EU	2014	233.4	Ecodesign	(EC 2008)	223	Ecodesign Directive	(EC 2008)	5	

Emissions mitigation

BUENAS calculates carbon dioxide mitigation from final energy savings:

$$\Delta \mathrm{CO_2(y)} = \Delta \mathrm{E(y)} \times \mathrm{f_c(y)}$$

- $\Delta CO_2(y)$ = CO_2 mitigation in year y
- $\Delta E(y)$ = Final Energy Savings in year y
- f_c = carbon conversion factor (kg/kWh or kg/GJ) in year y

Final energy savings

BUENAS calculates final energy savings (electricity or fuel) by comparing *efficiency case* (EFF) energy demand and *business as usual* (BAU) energy demand:

$$\Delta E(y) = E_{\mathrm{BAU}}(y) - E_{\mathrm{EFF}}(y)$$

- $E(y)$ = final energy demand in year y.

Data inputs

Much of the development of BUENAS consists of gathering and refining data inputs. In particular, the scope of the model is currently primarily limited by data availability. Nevertheless, the current state of the model represents a significant accumulation of appliance energy and market data in a single database. This section summarizes data inputs. Where no data are available, inputs are modeled as described in the previous section.

GDP per capita, electrification, and urbanization Macroeconomic parameter data, either historical or forecast, are provided by the World Bank and United Nations agencies, based on data supplied officially from national agencies.

Unit sales or stock The number of units of appliances sold (and in the stock) in each year originate from a number of sources. The most common of these are the models used by countries to evaluate the impacts of their own efficiency programs.[10] Other sources include industry reports and market research firms. A summary of sources of unit sales or stock data is given in Table 5.

Baseline unit energy consumption Annual energy consumption of appliances arises from a combination of appliance size, efficiency and usage patterns. Like unit sales, this parameter is often available from efficiency program studies or from the efficiency metrics definitions of countries with EES&L programs. Estimates and algorithms for UEC are less frequently found in the energy literature. A summary of sources of baseline unit energy consumption data is given in Table 6. Cases where unit energy consumption was generated by assumption are indicated with an "A."

Target unit energy consumption Target energy consumption is derived according to known performance achievements in other countries as described above, assuming the same usage and capacity characteristics as the BAU scenario.

Retirement (survival) function The retirement function gives the probability that equipment will fail or be taken out of operation after a certain number of years. Retirement functions data are given for some equipment types by national analyses and follow common functional forms, such as normal (Gaussian) or the Weibull distribution, which is commonly used to model equipment failure. Often, however, there are no data available to describe the particularities of the distribution. In those cases, BUENAS uses a normal distribution as a default. The mean value of this distribution, or average lifetime, is taken from the literature. In some cases, particularly in the US studies, lifetimes were derived or tested by comparing historical sales and stock data. In general, however, lifetime estimates depend on anecdotal reports from industry experts and are subject to considerable uncertainty.

Carbon factor The carbon factor is the constant of proportionality between final electricity consumption and carbon dioxide emissions. Carbon factor is a result of plant efficiency, transmission, and distribution losses and the generation fuel mix. Carbon factors in the base year 2005 are taken from (Price et al. 2006). The projection of carbon factor is derived using the base year data, and scaling by the trend of IEA's World Energy Outlook (WEO) 2006 (International Energy 2006b), which takes into account expected improvement in plant efficiency, reduction of transmission and distribution losses, and

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[10] The most common of these are the Technical Support Documents used in the development of US federal appliance standards and Preparatory Studies used to support the European Commission's Ecodesign standards.

Table 5 Sources of unit sales or stock data

Product	Country/economy									
	AUS	BRA	CAN	EU	IND	JAP	KOR	MEX	RUS	USA	ZAF
Boilers			(NRCAN 2011)	(VHK 2007a)						(USDOE 2008)	
Central air conditioners	(DEWHA 2008)		(NRCAN 2011)					(CONUEE 2009)		(USDOE 2011e)	
Clothes dryers										(USDOE 2011a)	
Clothes washers				(EC 2007b)				(CONUEE 2009)			
Commercial clothes washers										(USDOE 2010a)	
Cooking equipment										(USDOE 2009a)	
Direct heating equipment										(USDOE 2010b)	
Dishwashers				(EC 2007b)							
Distribution transformers			(USDOE 2007)		(McNeil et al. 2005)					(USDOE 2007)	
Electric motors				(de Ameida et al. 2008)				(CONUEE 2009)			
Fans					[Prayas Energy Group 2010]					(USDOE 2005)	
Freezers				(USDOE 2011f)						(USDOE 2011b)	
Furnace Fans										(USDOE 2011e)	
Furnaces			(NRCAN 2011)							(USDOE 2011e)	
Lighting				(EC 2009c)						(Bickel 2009)	
Pool heaters										(USDOE 2010c)	
Refrigerators	(Energy Efficient 2008)			(EC 2008)				(CONUEE 2009)		(USDOE 2011b)	
Room Air conditioners	(DEWHA 2008)		(NRCAN 2011)	(EC 2009a)						(USDOE 2011c)	
Standby power				(EC 2007a)						(Meier 2001)	
Televisions	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)
Water heaters				(VHK 2007b)				(CONUEE 2009)		(USDOE 2010d)	

Table 6 Sources of unit energy consumption data

Product	Country/Economy										
	AUS	BRA	CAN	EU	IDN	IND	JAP	KOR	MEX	RUS	USA	ZAF
Boilers			(NRCAN 2011)	(VHK 2007a)							(USDOE 2008)	
Central air conditioners	(DEWHA 2008)		(NRCAN 2011)						(USDOE 2011e)		(USDOE 2011e)	
Clothes dryers				(EC 2010a)							(USDOE 2011a)	
Clothes washers				(EC 2010b)				(EC 2007b)	(Sánchez et al. 2006)			
Commercial clothes washers											(USDOE 2010a)	
Cooking equipment											(USDOE 2009b)	
Direct Heating equipment											(USDOE 2010b)	
Dishwashers				(EC.(EC 2010c). Commission Regulation (EU) No 1016)								
Distribution transformers			(USDOE 2007)			(McNeil et al. 2005)					(USDOE 2007)	
Electric motors	(Brunner 2006)	(Garcia et al. 2007)	(de Ameida et al. 2008)	(de Ameida et al. 2008)	(Brunner 2006)	(Brunner 2006)	(Brunner 2006)	(Brunner 2006)	(de Ameida et al. 2008)	(Brunner 2006)	(de Ameida et al. 2008)	(Brunner 2006)
Fans	(Sathaye et al., forthcoming)	(Sathaye et al.	forthcoming)	(Sathaye et al.	forthcoming)	(Sathaye et al.	forthcoming)	(Sathaye et al.	forthcoming)	(Sathaye et al.	forthcoming)	(Sathaye et al.
Freezers				(EC(EC 2009d). COMMISSION REGULATION (EC) No 643/2009 of 22 July 2009)							(USDOE 2011b)	
Furnace Fans			(USDOE 2011e)								(USDOE 2011e)	
Furnaces			(NRCAN 2011)								(USDOE 2011e)	
Lighting	(Waide 2010)	A	(Waide 2010)	(EC 2009e)	A	(Waide 2010)	(EC 2009e)	(EC 2009e)	(Waide 2010)	(EC 2009e)	(Waide 2010)	A
Pool heaters											(USDOE 2010c)	
Refrigerators	(Energy Efficient 2008)	A	(USDOE 2011b)	(EC(EC 2009d). COMMISSION REGULATION (EC) No 643/2009 of 22 July 2009)	(McNeil and Iyer 2009)	(McNeil and Iyer 2009)	(METI 2010)	(METI 2010)	(Sánchez et al. 2006)	A	(USDOE 2011b)	A
Room AC (Window)			(NRCAN 2011)									
Room AC (Split)	(CLASP 2011)	(McNeil et al. 2008)	(NRCAN 2009)	(EC 2009a)	(McNeil et al. 2008)	(Tathagat and Anand 2011)	(McNeil et al. 2008)	(McNeil et al. 2008)	(Sánchez et al. 2006)	A	(USDOE 2011c)	(McNeil et al. 2008)
Standby Power	(Energy Efficient 2008)	(NRCAN 2011)	(CONUEE 2009)	(EC 2007a)	(DEWHA 2008)	(Letschert et al. 2011)	(Freedonia 2004)	(de Ameida et al. 2008)	(Park et al. 2011)	(Sathaye et al., forthcoming)	(USDOE 2009c)	(USDOE 2011g)

Table 6 (continued)

Product	Country/Economy											
	AUS	BRA	CAN	EU	IDN	IND	JAP	KOR	MEX	RUS	USA	ZAF
Televisions	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)	(Park et al. 2011)
Water heaters	(Syneca 2007)		(USDOE 2010d)	(VHK 2007b)					(Sánchez et al. 2006)		(USDOE 2010d)	

reduced dependence on fossil fuels for electricity generation. The analysis does not consider the difference between average and marginal carbon which, while more accurate, are difficult to forecast given the available data. Finally, while in principle there is a feedback relationship between decreased electricity demand as a result of efficiency improvement and carbon intensity of electricity production, these effects are difficult to quantify without a dedicated power-sector model, which BUENAS does not contain. These effects therefore remain out of the scope of the current study.

Results

By summing up the energy demand estimates modeled by equipment included in Table 2, it is possible to evaluate the energy demand by BUENAS as a fraction of sector within each economy. These estimates are shown in Table 7.

Differences between the sum of energy demand in BUENAS and top–down estimates from national statistics arise primarily from end uses that are not included in the model. However, differences may also indicate over- or underestimates in BUENAS. These two effects are difficult to disentangle in bottom–up modeling. Finally, the top–down estimates are also subject to uncertainty, as evidenced by significant differences between sources. For these reasons, the table should be understood as a rough guide of the level of coverage of the model instead of an exact measure. In some cases, top–down data were not available at a level of detail necessary to make a meaningful comparison.

Table 7 shows that BUENAS coverage in residential electricity is the highest of the three sectors, with BUENAS demand accounting for over half of the top–down estimate. Sector totals are weighted by sector energy for each fuel where these data are available. Residential gas coverage is significant only for Australia, Canada, Japan and the USA, where sufficient data were available to model space heating and/or water heating. Commercial sector electricity coverage is lower than residential sector electricity coverage, but high for some countries where space cooling is important because BUENAS includes this end use (in addition to lighting, which is usually the main commercial building end use). Commercial building gas coverage is zero for all countries except for the USA due to lack of available data for commercial space heating and water heating. Finally, in the industrial sector,

Table 7 Percentage of final energy in BUENAS by country, sector and fuel in 2005

Sector	Fuel	AUS (%)	BRA (%)	CAN (%)	EU (%)	IND (%)	IDN (%)	JAP (%)	KOR (%)	MEX (%)	RUS (%)	USA (%)	ZAF (%)	Total (%)
Residential	Electricity	56	105	27	N/A	100	N/A	53	69	69	36	59	N/A	60
	Gas	32	0	92	N/A	N/A	N/A	72	0	N/A	0	65	N/A	44
	Total	46	58	62	57	N/A	7	61	23	N/A	4	62	N/A	50
Commercial	Electricity	36	50	27	N/A	56	N/A	38	22	72	22	64	N/A	52
	Gas	0	0	0	N/A	N/A	N/A	0	0	N/A	0	54	N/A	36
	Total	29	44	13	21	N/A	33	27	18	N/A	9	60	N/A	37
Industrial	Electricity	N/A	58	37	N/A	54	N/A	102	59	44	40	79	N/A	64
	Gas	N/A	0	0	N/A	N/A	N/A	0	0	0	0	0	N/A	0
	Total	N/A	38	17	18	N/A	18	73	45	15	9	22	N/A	21

Final, or "delivered" energy does not include electricity input energy or losses in transmission or distribution. Percentages of "primary" energy inputs would therefore be significantly different

Sources: DEWHA (2008), Andrew Dickson and Thorpe (2003), Brazilian Federal Government Ministry of Mines and Energy (2006), NRCAN (2011), Eurostat (2011), Center for Data and Information on Energy and Mineral Resources (2007), EDMC (2007), Australia Retail Appliance (2011), EIA (2011), EIA (2010), and EIA (2008)

electricity coverage is moderate while gas is not covered in BUENAS. This is to be expected since motors, which are covered, generally account for a significant portion of industrial electricity. A significant amount of electrical energy in industry comes from heavy industry processes such as electric arc furnaces in the steel sector. These types of industrial processes are not covered in BUENAS. Likewise, most of the nonelectric fuel use in industry comes from heavy industrial heating processes, which are out of the scope of BUENAS.

In some instances, the comparison of BUENAS to top–down estimates exposes some apparent overestimations in the model. Examples of these are residential electricity in India and Brazil and industrial electricity in Japan. While much of residential electricity in Brazil and India is concentrated in end uses covered by BUENAS (lighting, refrigeration, and air conditioning), the total should of course not exceed 100 % of the actual reported consumption. This could be due to an overestimate of energy demand in one or more of the end uses. It should be pointed out, however, that there is significant variation in reported electricity consumption in India, due to significant "non-technical losses" (electricity theft) in the residential sector in India. In addition, BUENAS models demand, not consumption. These two approaches differ by up to 20 % in India due to chronic shortages. These two effects may also explain the apparent overestimate by BUENAS. The overestimate of industrial electricity in Japan is likely due to overestimation of energy consumption of motors in that country. This difference may be the subject of a calibration in subsequent versions of the model.

Table 8 shows savings in 2030 for the *best practice scenario* for countries included in Table 2. The best practice scenario is the best estimate for what is feasibly achievable from appliance efficiency policies. There is necessarily some subjectivity and incompleteness in these results, but they are meant to be indicative of the scale of the potential and the breakdown by end use. Because of the discrepancy in end use coverage between countries, per-country totals are not easily comparable, and therefore, we omit them here.

As Table 8 shows, overall potential emissions reductions for the scope of equipment covered are about 1075 Mt of CO_2. The results also show that a significant percentage of electricity and gas would be saved in the best practice scenario. Savings are compared to demand in 2030. Electricity savings is most pronounced in the residential sector, where savings of 35 % are projected. Electricity savings are similar, at 23 % in the commercial sector. In general, savings are much smaller for fuels. This is because some major space heating and water heating technologies are not yet included in the model and because space heating in particular is already a relatively high efficiency end use.[11] Similarly, savings from industrial motors are small in percentage terms.

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[11] Due to the large footprint of space heating, however, savings in absolute terms from this end use can be very large.

Table 8 Energy and emissions demand and savings potential in 2030—best practice scenario

Sector	End use	2030 demand			2030 savings			2030 percent reduction		
		Electricity TWh	Gas PJ	CO_2 mt	Electricity TWh	Gas PJ	CO_2 mt	Electricity TWh (%)	Gas PJ (%)	CO_2 Mt (%)
Residential	Air conditioning	842		462	235		142	28		31
	Fans	146		100	77		54	53		53
	Lighting	371		195	111		55	30		28
	Refrigerators & freezers	466		201	148		56	32		28
	Space heating	129	11236	776	0	639	38	0.2	6	5
	Standby	198		97	189		93	95		95
	Television	140		66	13		6	9		10
	Laundry	147		76	35		20	24		26
	Water heating	413	3922	322	195	615	98	47	16	31
Sub total		2,852	15,158	2,296	1,003	1,254	563	35	8	23
Commercial	Lighting	1324		611	322		147	24		24
	Refrigeration	357		155	90		39	25		25
	Air conditioning	884		409	198		88	22		21
Sub total		2,679		1,434	610		274	23		19
Industry	Distribution transformers	612		323	270		141	44		44
	Motors	4,395		2,141	190		97	4		5
Sub total		5,007		2,465	459		238	9		10
Grand total		10,538	15158	6,195	2,073	1,254	1075	20	8	17

Discussions and conclusions

Table 8 shows significant percentage energy reductions for the end uses that are addressed in the model. It is reasonable to assume that this level of improvement is unlikely to occur without directed policies, or a sharp rise in energy prices that drives the market for efficiency. On the other hand, the definition of the best practice scenario ensures the feasibility of the targets, since there is a clear demonstration that they are achievable. In fact, these targets are likely to be conservative, since they do not incorporate technological learning.[12]

Significance of impacts

In absolute terms, it is difficult to gauge the significance of the CO_2 savings represented in Table 8. These results benefit from some comparison. For example, these results can be compared to reductions that the International Energy Agency deems sufficient to stabilize global CO_2 concentration at 450 ppm (IEA 2010). Emissions projections in the IEA's WEO are divided into emissions related to power generation and emissions from transport and "on site" consumption in the buildings and industrial sector. Most of the savings covered by BUENAS is in the form of electricity, which accounts for 1005 Mt of the 1075 Mt total, or 93 %. Annex A of the WEO report projects power-related emissions in 2030 to be 4,816 Mt in the current policies scenario (CPS) compared to 1,434 Mt in the 450 scenario. The difference between these two scenarios implies a policy-driven mitigation of 3,382 Mt in the power sector, or about two thirds of the total mitigation of 5,073 Mt.

The 1005 Mt of electricity savings from BUENAS is 30 % of the WEO power sector savings. This is very significant contribution to the target, especially since BUENAS is extensive in scope, but not comprehensive. In conclusion, we believe that the BUENAS best practice scenario analysis represents a relatively specific and achievable set of policy targets that would contribute significantly to the magnitude of greenhouse gas mitigation that could have a real impact on climate change.

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[12] Due to learning, higher efficiency levels are likely to be achievable, but the baseline may also be more efficient.

Discussion of scenario definition

As mentioned above, the BUENAS best practice scenario is used not only because it provides specific examples of achievable targets but also because it does not require cost data, which are scarce. This situation is unsatisfactory in the long term because of the understandable emphasis on the cost of climate change mitigation by policymakers, business leaders, and consumer advocates. This concern becomes increasingly acute with the aggressiveness of the targets, since "disruptive" efficiency technologies may come with a considerable price tag, at least initially. For this reason, a cost-based scenario is highly desirable, in order to establish the *economic potential* of efficiency policies.

It is well-established that technology costs continually decrease with time as a function of cumulative production and increasingly apparent that energy efficiency technology is also subject to this *experience curve* effect. Therefore, a cost-based analysis is also useful in exploring the time evolution of technology development.

Finally, given that the efficiency scenario considers policy actions a few years in the future but extends over decades, it is reasonable to look as far forward as possible in terms of innovative technologies. In general, this implies considering technologies that are demonstrated as effective, but have not necessarily been mass-produced or commercialized. Often, the cost for these technologies is high or difficult to project because they have not yet entered the marketplace in a significant way. The consideration of technically feasible but yet-to-be-commercialized efficiency options gives rise to the *technological potential* of policies, which may be considered as an upper-bound to the potential.

Discussion of uncertainty

A well-established methodology exists for establishing the uncertainties in a mathematical model, given reliable estimates of uncertainties in the inputs. Unfortunately, errors are generally not well defined for most model inputs in BUENAS. Therefore, a robust quantification of uncertainties is not possible. Instead, this discussion presents the general level of uncertainty of key variables and their impact on the final results. There are two general categories of uncertainties associated with BUENAS inputs:

- Errors in determination of "data-driven" parameters
- Uncertainties forecast parameters due to difficulty in predicting the future

In principle, the first of these could be reduced or eliminated with sufficient data, while the second are "irreducible" to the extent that the future is difficult to predict. Parameters that are "data-driven" include energy efficiency and product class market shares, usage patterns, lifetimes, and sales. Critical forecast variables include sales growth rates, population and household size, economic growth, and evolution of baseline efficiency.

The following sections describe the general level of uncertainty in the most important input variables and assess their effect on energy and savings calculations. We characterize levels of uncertainty as "low" (0–5 %), "moderate" (5 %–15 %), or "significant" (>15 %). Even these categories, however, are just estimates.

Evaluation of the uncertainty on a given parameter and the impact of that uncertainty on final results is determined by an understanding of the sources of data and the degree to which energy savings estimates scale with the value of the variable. For example, market parameters such as sales or stock values, when provided by actual statistics can have a relatively low uncertainty. However, the impact on final results from these is classified as moderate because data are not always available and because energy demand and therefore energy savings are directly proportional to these parameters. On the other hand, data are scarce for equipment lifetime distributions (significant uncertainty), but lifetime has only an indirect impact on equipment sales in many countries, where market growth is driven by growth in ownership.

Data-driven variables

Historical sales In many cases, the sales forecast is driven off of current or historical sales using a growth rate, calibrated to long-term diffusion rates. In this case, future sales scale directly with historical sales. When these data are available, the uncertainty on them is generally low, but the impact on the final results is moderate.

Lifetime The equipment lifetime impacts sales through replacement rates when sales are forecasted using saturation modeling. It impacts sales only indirectly when sales are forecasted using historical growth rates or are taken from secondary sources, which generally have access to high-quality data. Therefore, while the uncertainty on lifetime is significant, the overall impact of lifetime on the sales forecast is moderate.

Base year efficiency distribution In countries and appliance groups with existing standards or labeling programs, the uncertainty on this parameter is low because the distribution is close to the minimum, and/or the market shares are known. Where no standards or labels exist, the uncertainty on base year efficiency distribution is moderate. Because efficiency directly impacts UEC, the resulting uncertainty in these two cases is low or moderate, respectively.

Usage The dependence of UEC on usage varies greatly among end uses. End uses that are highly dependent on usage include lighting, air conditioning, water heating, and space heating. For these equipment types, the uncertainty and impact on UEC are significant.

Forecast parameters

Shipments growth rates In cases where historical sales are trended forward, the assumed growth rate has a direct effect on stock and turnover. The uncertainty and impact of this variable is significant.

Population and household size Demographic parameters have a direct effect on sales when a diffusion model is used. These trends are modeled carefully and probably have only moderate uncertainty over the forecast period. The overall affect on uncertainty of results is low.

GDP growth rate The GDP forecast affects the projection of commercial floor space, appliance diffusion, and industrial motor energy. GDP growth rates are assumptions and are associated with a significant level uncertainty. The impact of GDP growth on energy forecast is moderate to significant, depending on the country and appliance group.

Urbanization and electrification Like population and economic growth, these parameters affect sales when a diffusion model is used. These trends are modeled carefully and probably have only moderate uncertainty over the forecast period. The overall effect on uncertainty of results is low.

Efficiency and product class trends Appliance markets are constantly evolving, with changes in product classes and technology types driven by consumer preferences and technological innovations. In the case of major white goods, these changes can be gradual

Table 9 Summary of level of uncertainty and impact of results by variable

Variable	Level of uncertainty	Impact on results
Data-driven variables		
Historical sales	Low	Moderate
Lifetime	Significant	Moderate
Base year efficiency distribution	Low to moderate	Low to moderate
Usage	Significant for some equipment types	Significant for some equipment types
Field consumption variability	Moderate	Moderate
Rebound effects	Moderate	Moderate
Forecast parameters		
Shipments growth rates	Significant	Significant
Population and household size	Moderate	Low
GDP growth rate	Significant	Moderate to significant
Urbanization and electrification	Moderate	Low
Efficiency and product class trends	Moderate to significant	Moderate to significant
Electricity carbon factor	Moderate	Moderate

and incremental, whereas in electronics, for example, changes can be extremely rapid, making anticipation of trends difficult even a few years in the future. The uncertainty of these parameters is therefore moderate to significant. Obviously, the impact of these changes can be wide ranging and can dramatically impact energy consumption. The overall effect on the results is therefore also moderate to significant.

Electricity carbon factor Electricity carbon dioxide emissions are calculated as the product of electricity demand and an *electricity carbon factor* taken from IEA base year data forecasted according to trends in the *World Energy Outlook* (International Energy 2006b). The projection of electricity carbon factors is based on expectations of the carbon intensity of new generation capacity. The uncertainty of this projection can be characterized as moderate. Since emissions are directly proportional, they can also be characterized as moderate.

Field consumption variability Efficiency for many equipment types modeled in BUENAS is estimated according to ratings determined according to standardized test procedures. Differences between rated and actual installed (field) consumption due to variable ambient conditions and use patterns have long been known to exist and have been recently studied (see for example Greenblatt et al. 2012). The uncertainty from this variability is moderate and has a moderate impact on estimates of energy demand and savings.

Rebound effects Rebound effects' refers to the increase in usage of energy that is a direct impact of increased efficiency. *Macroeconomic* rebound effects refer to the general increase in economic activity due to reductions in consumer energy expenditures. *Direct* rebound effects refer to increases in appliance usage due to a perceived or actual reduction in expenditures as a result of efficiency. Neither effect is included in BUENAS, although there are plans to include them in future versions. Estimates of rebound effects are variable and often controversial, but we characterize them as moderate, with a moderate impact on savings results.

In conclusion, there are significant areas where the accuracy of results produced by BUENAS could be improved through various means, primarily through better data. On the other hand, there will always be uncertainties in forecasting, and these are likely to be significant. In fact, overall, the forecast parameters identified in Table 9 more often have a "significant" effect on the results. This aspect of the modeling should be taken into account when considering opportunities for increasing model precision.

Acknowledgments Development of the BUENAS model has taken place over several years and has benefitted from a great number of colleagues, including those at LBNL, in the international energy policy community, and among our sponsors. From LBNL, the authors would like to acknowledge Nicholas Bojda and Puneeth Kalavase, who contributed to recent updates and quality assurance. For their contributions to and review of the analysis, we thank Gregory Rosenquist, Won Young Park, Nakul Sathaye, Nihar Shah, Amol Phadke, Jayant Sathaye, and James McMahon from LBNL. In addition, we received invaluable insight from international colleagues, including Tanmay Tathagat, Jun Young Choi, Lloyd Harrington, Itha Sánchez, Margarito Sánchez, Anibal de Almeida, and Philippe Rivière. Special thanks go to Kevin Lane and Louis-Benoit Desroches for their careful review. We also acknowledge our sponsors and project managers, including Christine Egan, Yamina Saheb, Frank Klinckenberg and Allison Fan of CLASP, John Mollet of the International Copper Association, and Gabrielle Dreyfus of the US Department of Energy. Finally, we are particularly indebted to Stephen Wiel for planting the seed that grew into BUENAS.

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