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Development of an open access tool for design, simulated dispatch, and economic assessment of distributed generation technologies

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ABSTRACT

The design and deployment of DG systems requires an integrated assessment of the building and generator dynamics including the time-variant energy costs and emission factors. Static design optimizations are unable to consider the physical generator operating constraints, seasonal variability and non-coincidence in electric, heating, and cooling demands. This paper introduces the Distributed Generation Build-out Economic Assessment Tool (DG-BEAT) which combines building, utilities, and emissions databases with a library of simplified generator and building models in a user-friendly interface. Five control strategies are presented for the dynamic dispatch of distributed generation technologies at commercial buildings. The control approaches stem from the physical limitations of different generator types. Methods are also outlined for the dispatch of complementary technologies (e.g. energy storage) and accommodation of on-site renewables (e.g. solar PV) which could further improve the economic or environmental benefits of distributed generation. This paper details the methodology of sizing and dispatching distributed generation components, outlines eight databases that are employed to capture regional variations in pricing and building dynamics, and discusses the myriad of customizations available to provide a tailored analysis for a single building or national impact studies.

1. Introduction

Electric power generation in the United States is undergoing a transformation in pursuit of lower electrical costs, lower emissions, and improved reliability and sustainability. Distributed generation in the form of electrical generation on the user side of the meter can refer to a host of small-scale technologies that can enable higher efficiency, lower emissions, and lower costs. In this context, distributed generation (DG) does not refer to systems used exclusively for emergency backup power generation, but rather those systems designed to offset a portion of grid electricity purchases on a continuous basis. Commercial buildings represent the bulk of early-adopters of DG due to the high cost of energy for businesses, concerns for electric reliability, and bulk purchasing power [1–3]. The shift into on-site generation for businesses has been driven primarily by environmental concerns, generous incentive programs in some regions [4,5], and the increased reliability of redundant supply from on-site and centralized generation.

A variety of technologies including reciprocating combustion engines, micro-turbines, fuel cells, and solar power have been deployed at sites around the world. The capability to recover waste heat from on-site generation is an effective means of improving efficiency of these small scale system while simultaneously reducing emissions and costs. Additional features including electric and thermal storage, centralized cooling systems, and on-site renewables are often considered as additional elements in the design and deployment of these DG systems at commercial buildings.

The dispatch and control of the distributed energy resources is integrally linked with the optimal system design problem, and must be considered simultaneously. Within the dispatch problem, dynamic performance characteristics of generation and storage technologies, present constraints that cannot be neglected [6]. The work detailed herein outlines the methodology underling an analytical software tool for the design and deployment of most types of DG systems at commercial building installations. A focus on a user-friendly graphical user interface design is summarized in the 8-step process of Fig. 1. The steps include specifying the characteristics of the building where DG will be applied, selecting the DG system and complementary technologies, entering the local energy costs, and deciding upon a control strategy.

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Nomenclature

DER-CAM	Distributed Energy Resources Customer Adoption Model
DG	distributed generation
DG-BEAT	Distributed Generation Build-out Economic Assessment Tool
kW	kilowatt
MW	megawatt
NFCRC	National Fuel Cell Research Center
NPC	net present cost
NREL	National Renewable Energy Laboratory

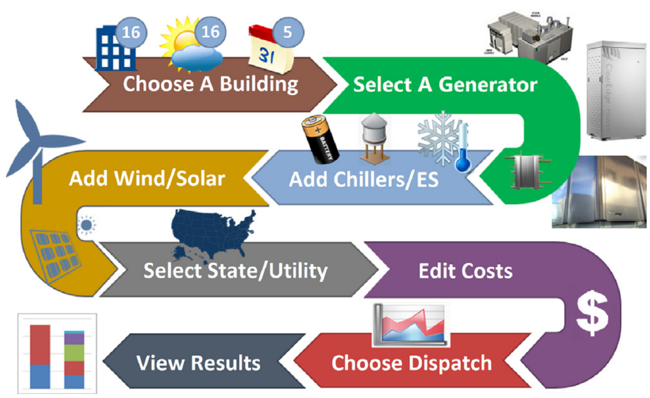

Fig. 1. Process of module specification for DG-BEAT software.

The open-access[1] software named the Distributed Generation Build-out Economic Assessment Tool or DG-BEAT packages previous research and development results and capabilities in building dynamics [7,8] and distributed energy resource dynamics and control [9,10]. Combined with detailed historical data on energy costs and emissions, DG-BEAT provides a powerful analysis tool for small stationary power installations. An included library of additional generator technologies (e.g. micro turbines, diesel generators, solar) are readily simulated and assessed for economic and emission benefits.

Previous analyses of the prospects for stationary power have tended to employ a simple market model that neglects the details of regional fuel and electricity price variations and the applicability of combined heat and power (CHP) integration with the dynamics of heat and power demand of a commercial building [11]. Some previous studies have evaluated a variety of building CHP systems (i.e. gas turbines, gas engines, diesel engines and phosphoric acid fuel cells) applied to four generic commercial buildings in Japan [12] or four commercial buildings in California [13].

The most comprehensive analysis tool available for distributed generation, DER-CAM, has been developed by Berkley Labs (LBNL) for more than 10 years [14–16] and provides some analyses that are similar to DG-BEAT in addition to analyses not addressed by DG-BEAT. The DER-CAM model provides multi-variable optimization of cost and emissions while simultaneously optimizing the system design using commercial DG systems.

DG-BEAT differs from DER-CAM in several keys areas of methodology and application. DG-BEAT was developed to investigate the impacts of system control rather than performing basic economic optimization. As such, it constrains the dispatch using physical characteristics such as off-peak performance curves, ramp rate constraints, and variable charging efficiencies. The design optimization used in DG-BEAT employs a full year of building load data with 15-min resolution. DG-BEAT applies one of the two algorithms (i.e. energy shifting or peak shaving) for utilizing either batteries or thermal energy. The flexibility and automation of DG-BEAT readily allow for comparative studies in addition to case studies. Specifically of interest during the development of this tool was the economic viability of specific DG technologies under both base-load and dynamic dispatch strategies while considering region specific weather impacts and energy costs.

DG-BEAT integrates multiple databases to accomplish these comparative studies including detailed 15-min demand profiles for 1280 simulated building types, state-specific hourly grid emission profiles for CO_2, SO_2, and NO_x [17], state specific wind and solar insolation profiles [18–21], a library of regional specific utility rate structures for electricity and natural gas, historical gas and electric rates by state for a variety of end-users [22,23], and a state-by-state building inventory of commercial buildings developed from a number of on-line sources.[2]

Section 2 will describe the simplified methodology for modeling the performance and dynamic response of distributed generation systems. Section 2 will detail many of the user-specified input parameters and outline options included for simulating and conducting comparative analysis on multiple case studies. Section 3 describes the algorithms used to dispatch the generation, energy storage, and complementary technologies to meet the electric, heating and cooling loads of a building. Section 3 also describes the method of dynamically sizing the generation under different design objectives. Section 4 provides a description of the building models and historical energy costs, unique datasets which bring additional validity to the analysis.

2. Model and interface description

The DG-BEAT interface was designed to be a user-friendly tool for building managers, distributed-generation stakeholders, and energy and environmental policymakers. Data visualization is a key aspect in applying perspective to results and allowing rapid feedback to the user with results automatically updated after any change in parameter selection. Behind the visual interface are a series of local electric utility rate structures and emission databases that eliminate guesswork when determining local costs and emissions impacts. Physical building and generator models, specialties of NREL and the NFCRC, are integrated into the tool through the insights and results of both the physical building models developed in Energy Plus [7,8] and the physical energy systems models [24] of the respective research centers. The control strategies are reflective of the dynamic limitations presented by different generators and complementary technology systems.

2.1. Component models

A library of 1280 building profiles generated using *Energy Plus* is used to represent the spectrum of commercial buildings in the United States. Each profile represents a year of detailed energy

[1] A simplified web-only version of the tool is available from http://fctac.nrel.gov/about.html, while access to the source code can be requested from the corresponding author at dustin.mclarty@wsu.edu.

[2] State building totals for restaurants and supermarkets are available from the USDA Food Environment Atlas, schools from the 2002 Census, office buildings from the Bureau of Labor Statistics, apartments from the National Multi-family Housing Council, hotels from http://www.factual.com/products/hotels, hospitals and clinics from the American Hospital Directory, retail stores from http://www.targetmap.com/viewer.aspx?reportId=2902, and warehouse data from a number of state and company specific websites.

Table 1
List of included generic building types, climates, and vintages for temporally resolved (15-min) demand profiles.

Building types	Locations	Vintages
Restaurant: full-service (sit down)	Miami (ASHRAE 1A)	ASHRAE 90.1-2010
Restaurant: quick-service (fast food)	Houston (ASHRAE 2A)	ASHRAE 90.1-2007
School: primary school	Phoenix (ASHRAE 2B)	ASHRAE 90.1-2004
School: secondary school	Atlanta (ASHRAE 3A)	ASHRAE 90.1-1989
Office: large office	Los Angeles (ASHRAE 3B-Coast)	Pre-1980 Construction
Office: medium office	Las Vegas (ASHRAE 3B-Inland)	
Office: small office	San Francisco (ASHRAE 3C)	
Hospitality: large hotel	Baltimore (ASHRAE 4A)	
Hospitality: small hotel/motel	Albuquerque (ASHRAE 4B)	
Health care: large hospital	Seattle (ASHRAE 4C)	
Health care: outpatient facility	Chicago (ASHRAE 5A)	
Retail: big-box, standalone retail store	Boulder (ASHRAE 5B)	
Retail: retail strip mall	Minneapolis (ASHRAE 6A)	
Retail: supermarket	Helena, MT (ASHRAE 6B)	
Mid-rise apartment building	Duluth, MN (ASHRAE 7)	
Unrefrigerated warehouse	Fairbanks, AK (ASHRAE 8)	

dynamics with electric, cooling and heating demands resolved at 15-min intervals. The electric load includes that of the HVAC system, which is removed or partially offset if a chiller system is included in the DG design. The electric profiles also include exterior lighting and refrigeration loads for specific buildings such as supermarkets or strip malls, which can be modified to include parking lots or integrated with the building cooling load when an external chiller is added. The analysis can aggregate any combination of buildings to simulate a campus or industrial complex. Table 1 identifies the 16 commercial building categories, ASHRAE climate regions, and vintages incorporated in the DG-BEAT library.

A library of existing generator and energy storage systems are available which can be customized by the user and saved with a variety of options specific to each system component including: size, peak efficiency, power ramp and slew rate, turndown efficiency, heat recovery potential, and minimum output threshold. Multiples of any system component are also permitted.

Sizing of the DG system can be done manually, or with one of the three building-specific sizing options. The options include (a) building specific sizing, which varies depending upon the control strategy but generally sizes a system large enough to meet 100% of the base load demand or up to 100% of the average summer peak load subject to control and turndown constraints ensuring zero export of power at any point during the year, (b) cost optimal sizing, which determines the capacity resulting in the greatest net present cost savings over the lifetime of the installation, and (c) emission optimal sizing, which determines the optimal system size for the reduction of GHG. These strategies for determining component capacity are presented mathematically in Table 4.

Fig. 2 illustrates the specification of a high efficiency DG system with a peak electrical efficiency of 60%. The per-kWh emissions increase as efficiency decreases at part load, as does the potential heat recovery despite an absolute reduction in emissions and heat at part-load. The NO_x and SO_2 emissions for this particular technology (e.g. high temperature fuel cell) are nearly zero, and not shown in the figure. Few DG systems are capable of spanning the complete range of power from zero to full load. Each generator is specified by

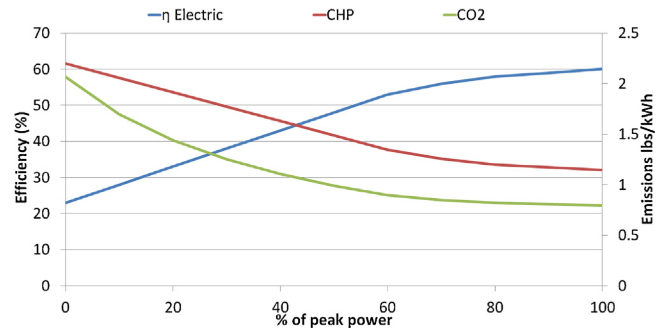

Fig. 2. Specification of FC performance and emissions characteristics.

a performance curve, a maximum turndown ratio, and a maximum slew rate. The heat recovery potential and emissions can also be specified with a performance curve.

Electric chillers are sized by a tonnage capacity, a percentage of the peak load, or in the case of absorption chillers by the available CHP heat. Chillers, like generators are specified by a performance curve, turndown ratio and slew rate. A sequence from most efficient to least efficient is utilized during the dispatch with priority given to absorption chillers when CHP heat is available.

Both thermal and electric energy storage options are included in DG-BEAT. Cold water storage capacity can be specified by a volume of water and thermocline temperature, by kWh, or by the number of hours needed to charge with the specified electric chiller capacity. An option exists to specify a storage loss term. Electric storage can specify one of four battery types (e.g. lead acid, lithium), three charging strategies (e.g. constant current, constant voltage), and a variety of inverting losses, charging constraints or discharging constraints. The size is specified by a total kWh or by the number of hours of peak shaving needed. Both chillers and energy storage devices can be automatically resized according to the three strategies described for the DG system above.

Options for solar power include fixed angle, single axis tracking and dual axis tracking systems. The surface area or rated power, the installation zenith, and various conversion efficiencies and losses can also be specified. A sub-hourly database of solar insolation and sun position specific to each state is used in Eq. (1) to determine the potential solar output throughout the year [21]. Similarly a wind installation can be specified by a rated power or a tower height and diameter, among other tunable parameter. Estimating the potential wind impact at a site utilizes a similar national database of 50, full year, hourly wind profiles selected from two larger NREL wind profile databases; the Eastern Wind Dataset and the Western Wind Dataset [18,19].

Table 2 presents the calculation of wind [20] and solar generation [25]. The air density is calculated as a function of elevation using a polynomial fit of the international standard atmosphere with units of $kg\,m^{-3}$. The wind and solar installations can be automatically re-sized using one of the two options: (a) scaling the renewable energy installation with the annual electric energy demand of the building/s, or (b) scaling the renewable energy installations with the non-renewable generation capacity.

Table 2
Expressions for the determination of solar and wind generation.

Feature	Equation
Solar power	$P_{solar} = P_{rated}\frac{Irrad_{direct\ normal}}{1000} \cdot \cos(Zenith - Tilt_{PV}) \cdot \cos(Azimuth_{sun} - Azimuth_{PV}) \cdot \eta_{conversion}$
Air density	$\rho = 1.1798 - 1.3793 \times 10^{-4} \cdot Elevation + 5.667 \times 10^{-9} \cdot Elevation^2$
Wind power	$P_{wind} = \eta_{conversion} \cdot 0.5\rho\frac{\pi D_{turbine}}{4} \cdot WindSpeed^3$

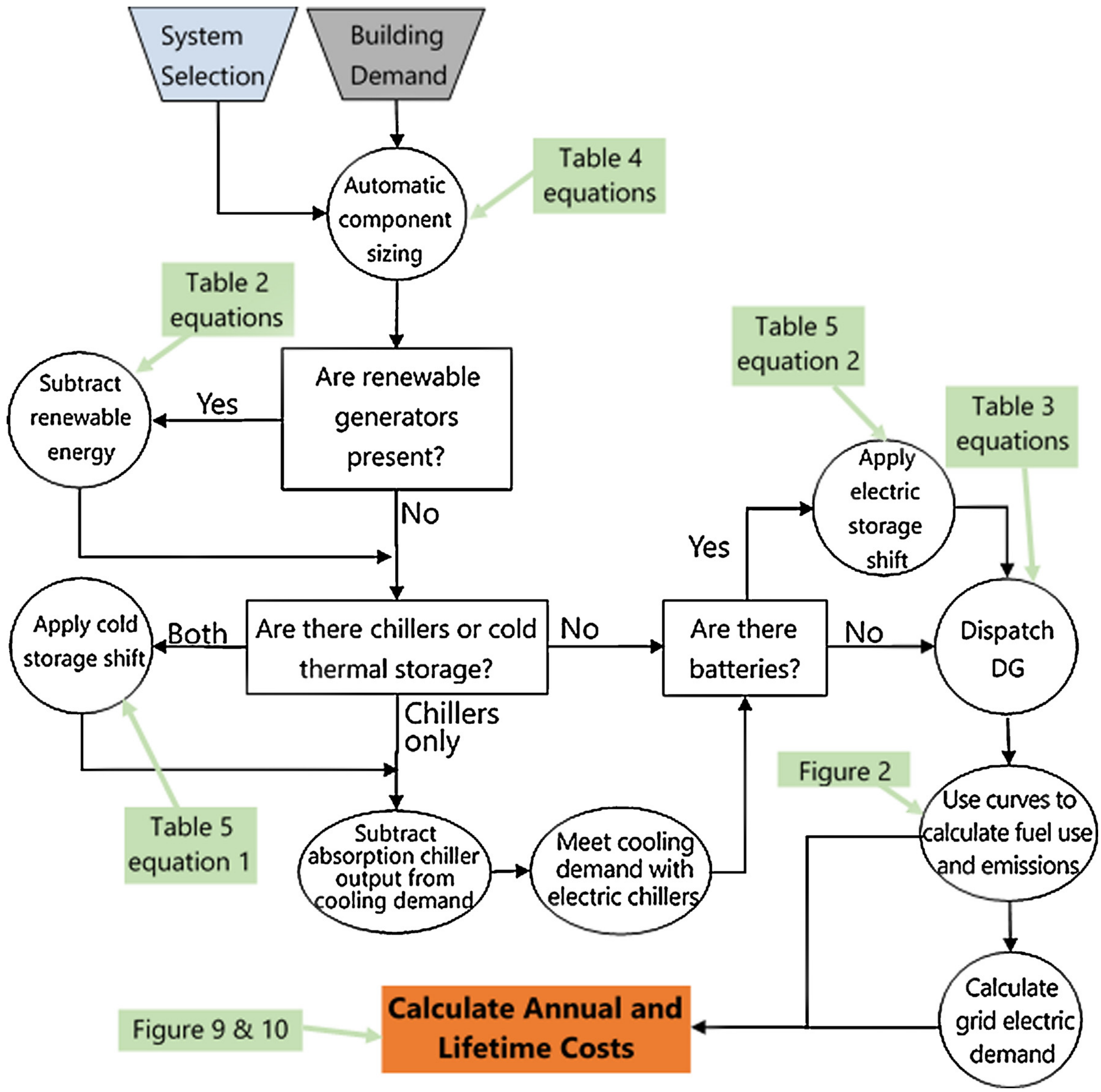

Fig. 3. Process diagram for DG-BEAT analysis with reference to equations used in this text.

The financial component of the tool includes the variable energy costs of electric/gas utilities, the equipment costs, and the financing terms. The electric utility plays an important role in determining the operating strategy of the distributed generation systems by specifying the constraints regarding the sellback of excess power onto the grid. Whether sellback is permitted, and the rate at which sellback is compensated will have a significant impact on the outcome of the financial analysis, particularly when also using rooftop solar generation. Additional details on utility rate structures and the method of projecting future rate increases is presented in Section 4.

2.2. Analysis methods

Fig. 3 illustrates a flow process diagram for the analysis of a distributed generation system in the current tool. After the DG system components have been specified and the appropriate building or campus energy demands defined, the component sizing equations of Table 4 are implemented. The time-resolved renewable energy production is removed from the building or campus demand using historical data for solar insolation or wind speed at the selected site and using the equations of Table 2. If chillers or cold thermal storage are present the cooling demand is met first, and the resulting electric load is added to the electric demand that must be met.

Cold thermal storage uses the first set of equations from Table 5 for shifting demand to off-peak hours. If there is any electric energy storage it is used for peak shaving (Table 5) and the resulting charge/discharge profile is added to the electric demand to be met by the remaining DG systems. Next the electric and CHP generators are dispatched according to the user selected control strategy and the equations of Table 3. The fuel used by the DG is determined from the efficiency curves of Fig. 2. The final costs are determined using the local utility rate structures and fuel costs. Seasonal fluctuation in fuel costs and annual increases in energy costs over the lifetime of the system are determined with Figs. 9 and 10.

Several additional meta-analysis features included in the software can provide insights into building or regional differences in DG economics or the potential co-benefits of different balance of system configurations. The comparative study features include: (a) real building demand validation which utilizes a California Energy Commission (CEC) dataset of real-world buildings with combined heat and power (CHP) installations, (b) multi-building simulation

Table 3
Expressions for determination of distributed generation (DG), thermal energy storage (ES) and battery electric storage (BS) dispatch using individual generator characteristics, building load profiles, and grid energy charges.

Description	Equations
System ramping characteristic	$RR = \sum_{n=1}^{\#\,of\,DG\,sys} DG_{ramp\,rate_n} DG_{size_n}$
Base load dispatch	$DG_t = \min\{demand_t\}\ \forall t \in year$
Load following dispatch	$DG_t = demand_t$ Constrained by: $\lvert DG_t - DG_{t-1} \rvert < RR$ &: $DG_{size}/DG_{turndown} \le DG_t \le DG_{size}$
Diurnal dispatch (repeated daily) *each 24 h day has 96 time segments	$\left\{ \begin{array}{l} t_{on} \\ t_{off} \end{array} \right. \rightarrow \min \left\{ \sum_{t=1}^{96} (demand_t - DG_t) \cdot Price_{grid} \right\}$ $DG_t = \begin{cases} \min\limits_{t<t_{on}-r_{on}} (demand_t), & 1 < t < t_{on} - r_{on} - 1 \\ demand_{t_{on}} - ramp_t, & t_{on} - r_{on} < t < t_{on} - 1 \\ \min\limits_{t_{on}<t<r_{off}} (demand_t), & t_{on} < t < t_{off} \\ demand_{t_{on}} - ramp_t, & t_{off} + 1 < t < t_{off} + r_{off} \\ \min\limits_{t_{off}<t} (demand_t), & t_{off} + r_{off} + 1 < t < 96 \end{cases}$ where: $r_{on} = \frac{\min\limits_{t_{on}<t<t_{off}} (demand_t) - \min\limits_{t<t_{on}} (demand_t)}{RR}$ &: $r_{off} = \frac{\min\limits_{t_{on}<t<t_{off}} (demand_t) - \min\limits_{t_{off}<t} (demand_t)}{RR}$ Constrained by: $(ramp_{t+1} - ramp_t) \le RR$ &: $DG_t \le demand_t\ \forall t$
Weekend dip dispatch (repeated weekly)	Same process as diurnal dispatch with $1 \le t \le 672$
Emissions control dispatch (repeated daily)	Similar procedure to Diurnal Dispatch except the function minimized is the following: $\left\{ \begin{array}{l} t_{on} \\ t_{off} \end{array} \right. \rightarrow \min \left\{ \sum_{t=1}^{96} (demand_t - DG_t) \cdot CO_{2_{grid}} + \sum_{t=1}^{96} DG_t \cdot CO_{2_{DG}} \right\}$

which compares the results across the 16 commercial building varieties or the 16 climate zones, (c) a sensitivity analysis which can determine an installations sensitivity to a variety of features including financial parameters, component sizes, control algorithms, or utility structures, (d) a fleet analysis which identifies and sorts buildings according to how amenable they are to DG installations among a user defined list of buildings, and (e) a national market survey which analyzes a single building or all varieties across the lower 48 states. These analyses apply a brute force approach by individually simulating all of the specified building and distributed generation configurations.

2.3. Data and results visualization

The primary interface presents the user with three information areas. The first area describes the system currently being considered, and allows modification of that system. The second area is a visualization of the building energy demands, the output of the dispatched generation, and the impact any energy storage technology has in shifting energy demand. The final area presents a summary of the analysis results. A more detailed summary of the simulation results is easily accessed by pressing the 'Results' button. This presents a summary of the simulation parameters, an economic comparison to the grid only alternative, and an emissions summary. Results using the presently incorporated, wind, solar, building, climate, emissions, and energy cost data sets are specific to commercial building applications in the lower 48 states. In many instances a particular US commercial building and climate may readily stand as a proxy for a non-US site installation. In other cases, users may input data for energy demands and cost that would allow the same analysis techniques to be performed for any potential DG site.

The results of the economic analysis are sub-divided into energy costs, demand charges, fuel costs, operations and maintenance costs, and financing costs. A variety of options exist to modify building or economic parameters, re-optimize the size of the system components, or change the dispatch algorithm used. Results are refreshed and updated in real time as changes are made. The results and a summary of the system can be exported to excel for archiving or comparative analysis with other software tools. Results for the additional meta-analysis tools are presented in separate windows with features specific to the type of analysis conducted (i.e. sensitivity, fleet, national survey). The multi-building analysis results window supports trend identification by allowing any characteristic parameters to be plotted against one another.

3. Dispatch methodology and capacity determination

Beneath the surface functionality and design options of DG-BEAT are dispatch algorithms which incorporate all applicable constraints to rapidly determine the operating profile with 15-min resolution for the entire year. This section outlines the dispatch algorithms used to determine the operation of the generators, chillers, and energy storage as well as a systematic method of determining component capacities from the building load profiles. Control strategies for DG systems are typically quite simple in that they are usually used for either base load (i.e. operated at fixed power setting) or for emergency backup generation. Some systems operate on a prescribed schedule (e.g. higher power and lower power settings), while emerging technologies may be capable of fully dynamic load following operation to reduce costs or emissions.

Five different control strategies were devised to span this spectrum of dispatch strategies. The control options include: (a) base load, fixed power operation, (b) weekend dip, a scheduled

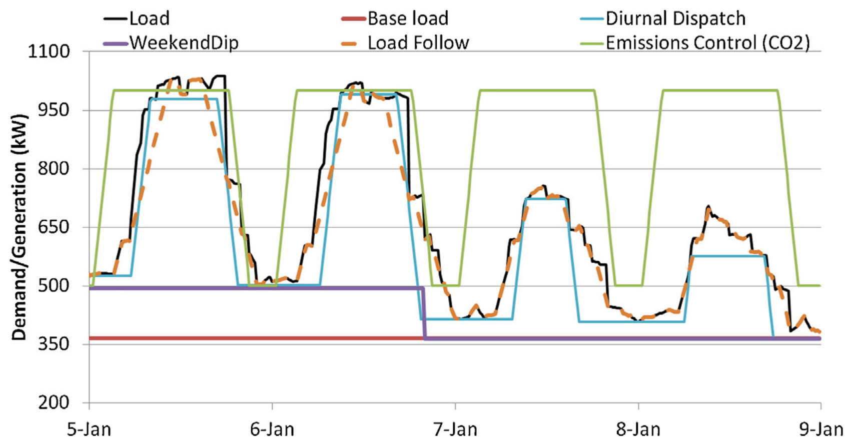

Fig. 4. Example electric dispatch profiles for two weekdays and two weekend days at a Los Angeles area hospital.

operation with full load on weekdays and part-load on weekends/holidays, (c) diurnal dispatch, a dynamic daily scheduling in which the system is designed to meet the bulk of the on-peak hour demand with a single power set-point, and operate at reduced power during the off-peak hours, (d) a fully dynamic load following dispatch subject only to the ramp rate constraints specified for the generator and other equipment, and (e) an emissions control algorithm developed to minimize the net GHG emissions attributable to the building using historical grid emissions as a reference.

Table 3 provides a mathematical description of how these different control strategies are implemented to determine the dispatch, DG_t, of the different distributed generators. In systems with multiple generators, priority is given to the system with the lowest operating cost. The capacity of each DG component, DG_{size}, must correspond with the control strategy, and in cases with energy storage some iteration is required to optimize generator and energy storage component capacities for a particular building. The capacity and dispatch can be constrained by both the building demand, $demand_t$, and the generator characteristics such as ramp rate, $DG_{ramprate}$, and turndown capacity, $DG_{turndown}$, defined as the ratio of maximum to minimum output for a particular generator.

Fig. 4 presents a sample dispatch using each of these strategies, while Table 4 details the expressions used to determine component capacities from the building profile. Generally the system is sized as large as possible without violating a zero-export constraint at any point during the year. The size of any generator can be specified manually to be either, smaller, larger, or a specific ratio of the size determined with the equations of Table 4.

These expressions were developed in order to readily facilitate the comparison of DG installations with different operating characteristics at different buildings in different climates. Comparing systems in which capacity was determined directly from the building characteristics avoids any bias resulting from a fluke compatibility of a specific building with a specific existing commercial system. The results are thus able to indicate a difference in economic viability as a result of the amenability between building and generator dynamics. Existing commercial systems can readily be compared by manually selecting each components capacity. The capacities of balance of system components (e.g. chillers, heaters, energy storage) can be determined manually or scaled according to the generator and building dynamics using additional expressions which are omitted for brevity.

Table 4
Expressions for determination of DG system capacity using individual building load profiles.

Sizing method	Equations
Base load	$DG_{size} = \min_t(demand_t) \quad \forall t \in year$
Weekend dip *each day has 96 time segments	$Summer\ Week_{1-672} = \sum_{week \in summer} \frac{demand_{1-672,\ week}}{\#\ of\ summer\ weeks}$ $DG_{size} = \min_{9 \le t \le 664}(demand_t)$
Diurnal dispatch, load following, and emissions control	$Summer\ Day_{1-96} = \sum_{\substack{day \in summer \\ day \in weekday}} \frac{demand_{1-96,\ day}}{\#\ of\ summer\ weekdays}$ $DG_{size} = \max_{1<t<96}(Summer\ Day_t)$
Optimal cost sizing	$DG_{size} \rightarrow \max\{NPC_{no\,DG} - NPC_{with\,DG}(DG_{size})\}$ $\min(demand_t) < DG_{size} < \max(demand_t)$
Optimal emissions sizing	$DG_{size} \rightarrow \max\{CO_2\ Emissions_{no\,DG} - CO_2\ Emissions_{with\,DG}(DG_{size})\}$ $\min(demand_t) < DG_{size} < \max(demand_t)\ \forall\, t \in year$
Additional constraint without grid sellback	$TD = \sum_{n=1}^{\#\ of\ DG\ sys}(DG_{size_n}) / \sum_{n=1}^{\#\ of\ DG\ sys}(DG_{size_n}/DG_{Turndown_n})$ $\sum_{n=1}^{\#\ of\ DG\ sys}(DG_{size_n})/TD \le \min_t(demand_t) \quad \forall t \in year$

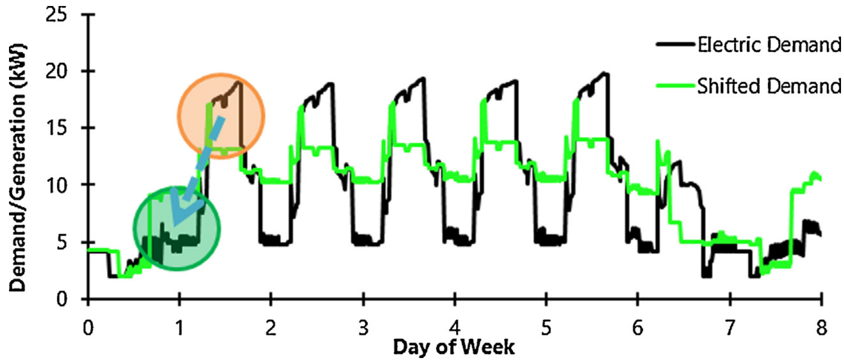

Fig. 5. Sample thermal energy storage dispatch shifting on-peak loads to previous off-peak hours.

The comparison between different buildings and between different balance-of-system components at a single building utilizes a calculation of NPC for the buildings energy related demands over the lifetime of the DG installation. The net present cost for a building with DG depends upon a range of factors including the electricity and fuel price structures, the change in prices over the plant lifespan, the installation cost of the DG system, the operation and maintenance costs over the plant lifetime, the size of the DG and balance of system components, and the dispatch strategy selected. The last two sizing options include an optimization which isolates the impact of the DG systems capacity on either net present cost or emissions. It is also important to note that under the common real-world constraint of DG systems not being allowed to export power onto the grid, the system capacities are constrained by the minimum annual load and the ability to turn down to this output. The dispatch strategies do not currently permit a generator to shut off freely as repeated re-starts are undesirable for most systems.

The generator dynamics are not the only factor that constrains the operation. Electric utilities often strictly regulate the interconnection with the grid stipulating when and under what circumstances power can be exported. It is unusual for commercial buildings to receive full retail pricing for exported power, thus any excess generation is worth less than generation used on-site. Large installations of several MW-size, such as a university campus, may have the opportunity to generate additional revenue in ancillary service markets, but that is beyond the scope of the utility pricing schemes that are currently considered in the DG-BEAT tool. Many utilities do not allow even incidental export of power, thereby constraining generation to below on-site demand. In such zero-export markets the weekend-dip and diurnal dispatch strategies may offer a cost effective method of increasing self-generation with minimal load variations for the distributed energy system.

Energy storage can serve to decouple generation from the building demand in two ways. Thermal storage is inexpensive to scale, and is traditionally sized to shift an entire day's worth of cooling demand to the previous night. Depending upon options selected within the DG-BEAT interface, refrigeration loads may or may not be included in the cooling demand that can be met by the thermal storage. Electrical energy storage is more expensive and used primarily for peak shaving in order to minimize demand charges. DG-BEAT utilizes two algorithms to dispatch the charging and discharging of energy storage. The first algorithm, illustrated in Table 5 and Fig. 5, uses cold water storage to shift on-peak cooling loads to the previous off-peak hours. Details of this algorithm can also be found in [9].

This method can be seen to effectively level weekday demands despite a morning spike which occurs off-peak and is not subject to high demand charges. Cold water storage can save energy by operating chillers at night when lower ambient temperatures improve chiller efficiency, and save energy costs by shifting demand to reduced rate periods. Fig. 5 demonstrates how thermal storage could strongly benefit a DG installation operating on a weekly schedule.

Table 5
Description of algorithms for deployment of thermal energy storage and battery electric energy storage.

Description	Equations
Thermal energy storage (ES) (repeated daily)	$\left\{\begin{matrix} DG_t \\ ES_t \end{matrix}\right. \rightarrow$ $\min \left\{ \sum_{t=1}^{96} (demand_t - DG_t - ES_t) \cdot Price_{grid} \right\}$ Constrained by: $(DG_t + ES_t) \le demand_t$ $ES_t \le 0 \,\forall\, t \in \textit{off-peak}$ & $ES_t \ge 0 \,\forall\, t \in \textit{on-peak}$ $\sum_{\textit{off-peak}} (ES_t) \le ES_{capacity}$ DG_t is determined simultaneously according to the selected dispatch
Battery electric storage (BS) (repeated daily)	$\left\{\begin{matrix} DG_t \\ BS_t \end{matrix}\right. \rightarrow$ $\min \left\{ \sum_{t=1}^{96} (demand_t - DG_t - BS_t) \cdot Price_{grid} \right\}$ Constrained by: $(DG_t + ES_t) \le demand_t$ $-BS_{charge\,rate} \le BS_t \le BS_{discharge\,rate} \,\forall\, t \in \textit{off-peak}$ $\sum_{t=1}^{n} (BS_t) \le BS_{capacity} \forall n \le 96$ $\sum_{t=1}^{96} (BS_{discharging}) = \eta_{round\text{-}trip} \sum_{t=1}^{96} (-BS_{charging})$

The second algorithm presented in Table 5 focuses on peak shaving rather than energy shifting. The algorithm lowers the peak threshold while remaining subject to the battery capacity and discharge constraints. Fig. 6 illustrates the impact battery storage might have in reducing the demand dynamics and meeting the shoulder loads as the DG system is ramped up and down. Blue shaded areas highlight periods when the battery is discharging to support the DG in meeting the building load while orange shaded areas indicate the battery is recharging. The battery effectively reduces the midday peak by as much as 10%, and reduces the severity of morning and evening ramps. This deployment of battery energy storage would effectively support the diurnal dispatch strategy.

Battery electric storage will typical increase the net generation required due to round trip inefficiencies, but the additional energy requirement may be partially offset by the improved operating efficiency of the DG system. The algorithm utilized in DG-BEAT

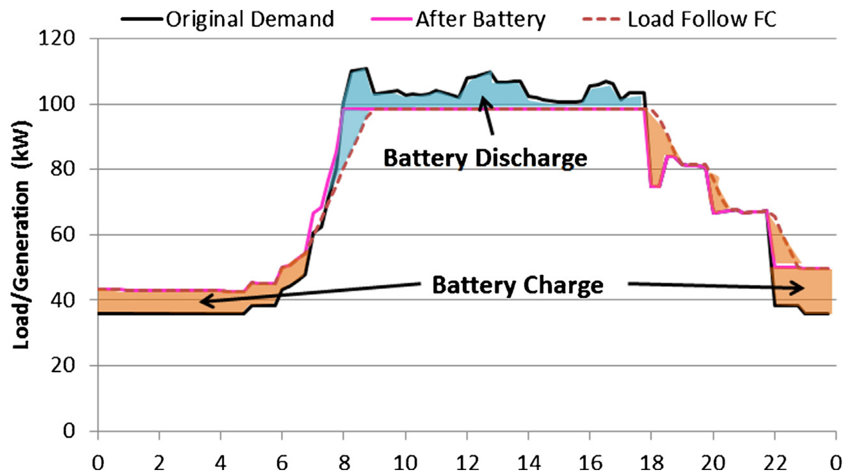

Fig. 6. Sample battery dispatch acting in peak-shaving mode.

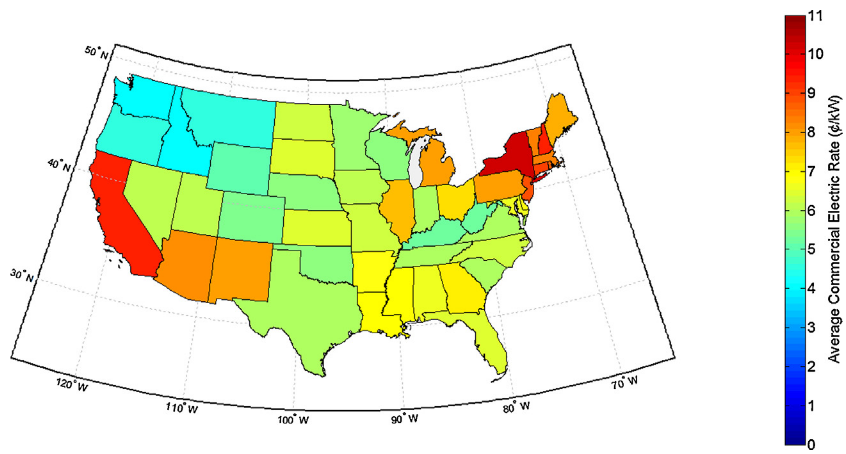

Fig. 7. Average annual electric rate for commercial users [22].

does not apply any predictive load forecasting, but rather has complete knowledge of the building demands. This simplification improves simulation speed considerably, closely approximates what an advanced predictive control strategy might achieve, and is preferred for the purposes of this design and evaluation tool. If one were to implement an active control strategy for any particular DG installation the control outcome could approximate the results achieved by this dispatch strategy.

4. Description of energy costs and commercial building databases

Once the DG system has been appropriately dispatched, the remaining challenge is to determine the potential economic and environmental benefit. With building electric and heating profiles as inputs the annual gas and electric bills are calculated using region specific utility rates. Figs. 7 and 8 provide an overview of the average

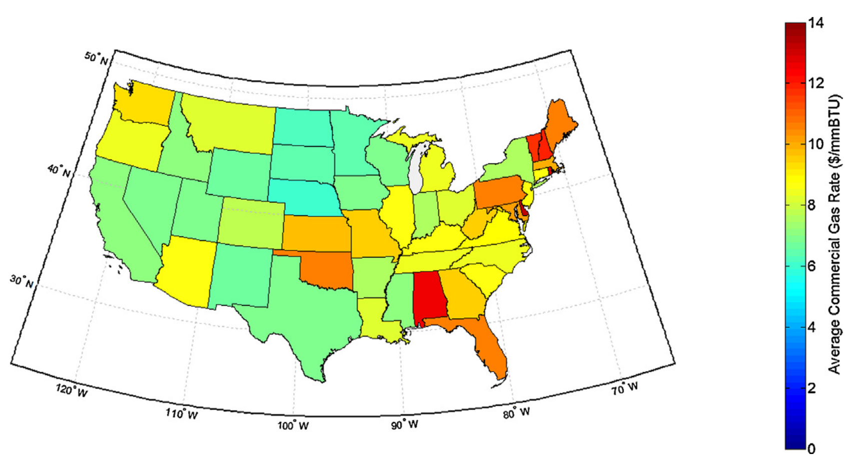

Fig. 8. Average annual natural gas prices for commercial users [23].

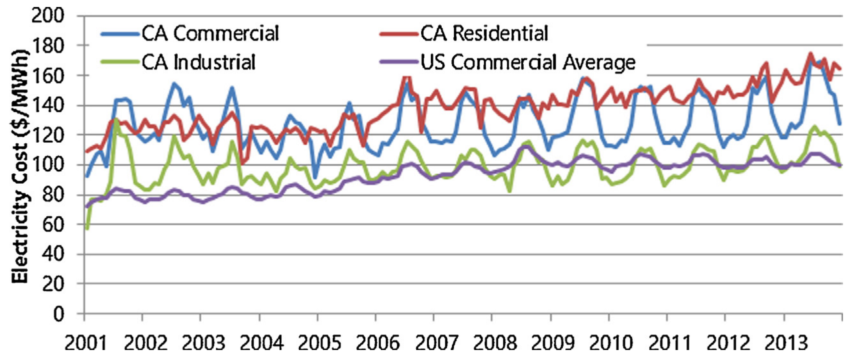

Fig. 9. Long-term and seasonal variation of electric costs by user for California [22].

electric and gas prices paid by commercial users throughout the country in 2013. The highest electric rates are concentrated in the northeast and southwest, while gas rates are considerably higher in the eastern United States. These maps can provide a snapshot identification of states that are more amenable to DG, such as California with high electric rates and low gas rates, but they do not capture the hourly or seasonal energy cost variations. For that we must look into time-of-use pricing and future energy cost projections, which are included in the DG-BEAT tool. Sometimes these dynamic rate structures can make DG cost effective when average rates may not appear to make it so. Accounting for the dynamics of DG dispatch and the dynamics of rate structures is a key feature of DG-BEAT.

Demand for electricity varies considerably each day and between seasons. Summer electricity demand is typically higher, by as much as 30%, due to high air conditioning loads. Meeting these daily and seasonal peak demands requires additional peak generation and transmission capacity that is underutilized most of the year. Peaking generators are less efficient and cost considerably more to operate than base load generation leading to higher electricity prices during peak periods. Utilities incentivize peak demand reduction, particularly for large commercial installations, through direct subsidies, demand response programs, and penalizing rate structures. Higher summer rates and demand charges based upon the highest peak energy use during any particular billing cycle are commonplace strategies to discourage excessive summer electricity use. Nearly all rate structures include some form of additional summer/weekday charges in the form of higher electric energy rates or demand charges. Gas utility rates for commercial users typically employ a declining block rate structure with some seasonal variation of rates.

Many electric utility companies are now offering or mandating time-of-use rate structures for commercial users. These rate structures charge different tariffs at different times of day, typically dividing a summer day into on-peak, mid-peak, and off-peak periods. The addition of self-generation, departing load charges, and possible electric energy sell-back from DG systems further complicate the electric rate calculations. States with limited excess generating or transmission capacity, such as California, apply markedly higher seasonal rates than the national average for commercial and industrial users. Residential rates are largely isolated from these additional tariffs by rule, as shown in Fig. 9, placing additional pressure on utilities to regulate peak summer demands within the commercial and industrial sectors.

The DG-BEAT tool has stored historical data for monthly electrical and gas rate structures for each state extending back to 2001 and 1989 respectively. Figs. 9 and 10 illustrate these historical trends for the state of California. When performing an economic analysis for an energy installation it is important to consider the local variations in future energy costs. DG-BEAT calculates future energy cost by extrapolating the long term annual trend line and adding in the seasonal variation of this historical data to create a state-specific energy cost projection. User specified energy cost projections can also be implemented. Buildings subject to time-of-use rates and demand charges will not pay precisely the state average cost per kWh for electricity. In these cases the electric and gas rate projections are taken as escalators to the current rates and applied as a scalar factor to the future calculated energy costs.

A library of seasonal and time-of-use rate structures from more than 25 electric utilities is provided along with infinite customization of rate structures within DG-BEAT. Real-time-pricing is an option that is increasingly becoming available to large consumers, but was omitted from DG-BEAT due to a lack of available data. The details of other specific tariffs and riders are omitted from the description in this paper since these charges would typically apply to the building with or without a distributed generation system.

Fig. 10 highlights why California comprises a unique opportunity for distributed generation. Over the past 5 years commercial gas rates in California have been nearly half of the national average with very low seasonal variation. While on the other hand, as

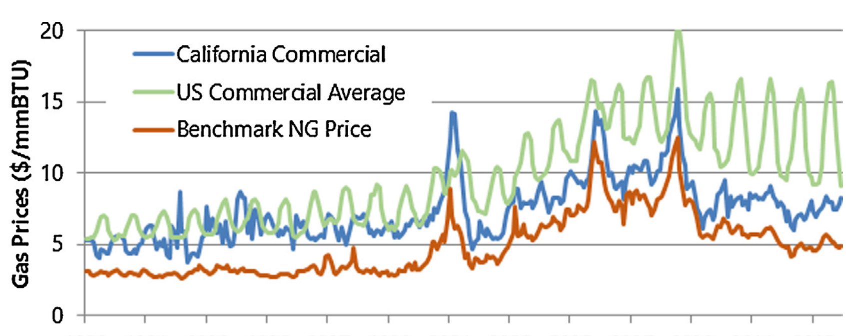

Fig. 10. Long-term and seasonal variation of gas costs by user for California [23].

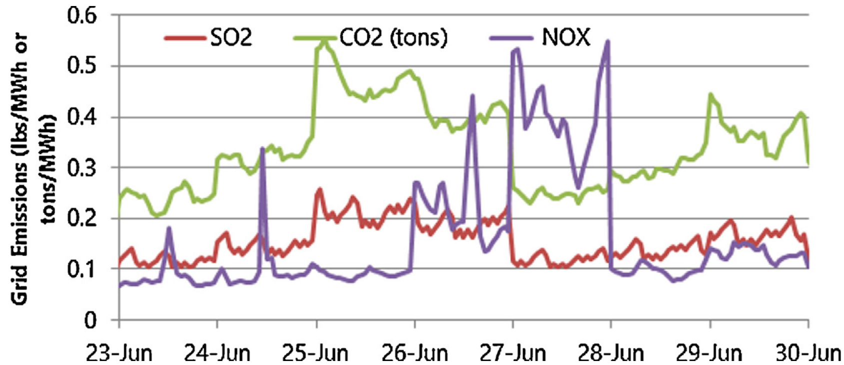

Fig. 11. Temporally resolved California grid emission factors [17].

shown in Fig. 9, California businesses pay 40% more than average for electricity with very high rates in the summer.

Another key distinguishing feature of DG-BEAT is its ability to temporally resolve regional emission profiles. Data compiled from the United States Environmental Protection Agency (EPA) was used to generate hourly state and regional emission profiles for CO_2, SO_2, and NO_x, as shown in Fig. 11 for example, for one week in California. The EPA's Air Markets Program Data available at http://ampd.epa.gov/ampd/ combines emissions monitoring at large stationary power plants in the lower 48 states from several emissions monitoring programs including the Clean Air Interstate Rule, Acid Rain Program, and the expired NO_x Budget Trading Program [17].

Typical analyses may consider the regional differences in the carbon intensity of grid electricity, but this fails to accurately capture the carbon intensity of a building that relies upon mixed sources of on-site and grid power that vary on an hourly basis. Take for example a base loaded DG system in a region with substantial wind power. Despite operating with a lower carbon intensity than the average grid emissions of the region, the DG system may not reduce emissions. The DG may completely displace the night-time grid use, when the proportion of wind power is highest, and displace only a portion of the daytime energy use when the grid has more fossil fuel combustion. The net impact would then be an increase in carbon emissions. The DG-BEAT tool offers the ability to compare the hourly DG emissions to either the net grid emission factor (e.g. including renewables) or only the displaced combustion portion of the grid.

When determining the regional or national impacts of a generation technology, the time-of-day and season in which the energy is delivered has a tremendous impact on the emission reductions. DG-BEAT offers the ability to quickly estimate the actual annual emissions impact of a solar or wind project. Users can calculate emission reductions relative to the total state energy mix of fossil and non-fossil energy resources, or relative to the state fossil fuel combustion generation only. The second method of comparison that DG-BEAT includes is similar to the EPA method of using the annual non-baseload CO_2 emission rate, except it is spatially and temporally resolved. Nuclear, large hydro, and large renewable installations would be classified as baseload generation.

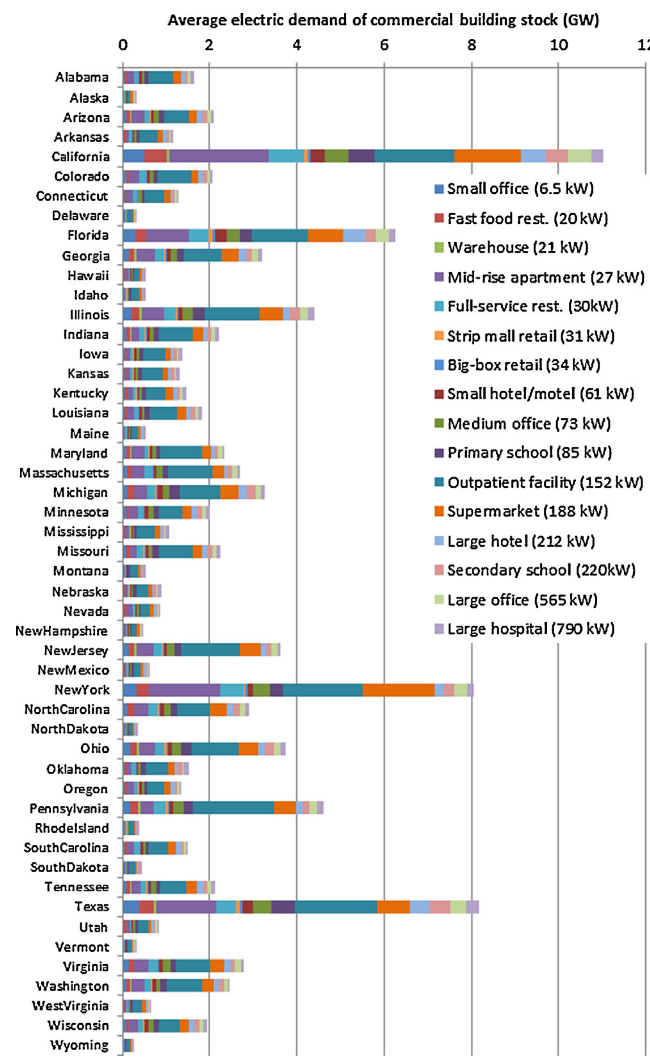

Fig. 12. Distribution of US commercial building stock.

4.1. US commercial building inventory

Another core feature of the DG-BEAT tool is the database of commercial building energy profiles and inventory of the US commercial building stock. The 16 building varieties introduced in Table 1 are unevenly distributed throughout the country. Fig. 12 summarizes this distribution among the states in terms of average annual electric demand (shown in parentheses for each building type). States with large populations such as California, Florida, New York, and Texas dominate the national market, while rural states and states with large incentives for clean technology, such as Connecticut and Delaware, comprise a small proportion of the building stock. The data of Fig. 12 combines the annual energy use of the simulated commercial building profiles with the number of commercial buildings in each category and state. The building inventory database was constructed from a number of online sources and represents a best-available representation of the commercial building sector of the US.

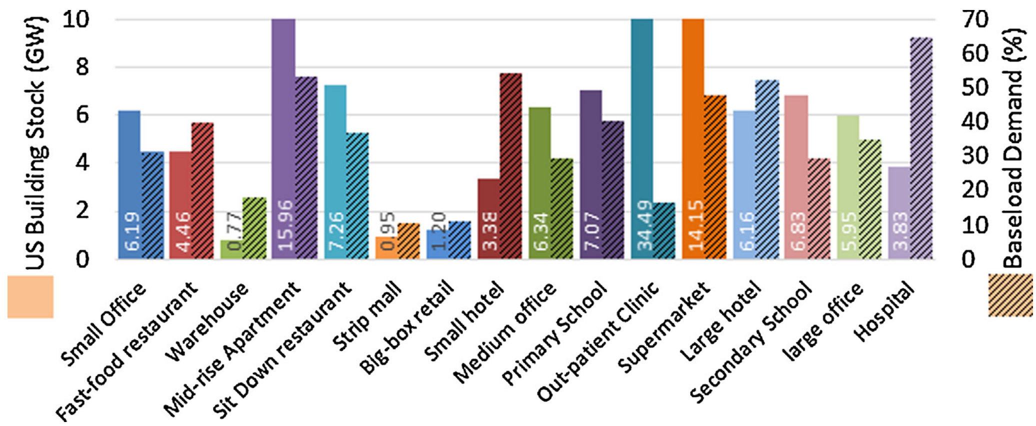

Fig. 13. Distribution of electric load among US commercial building stock and base load demand as proportion of average electric load organized in order of ascending peak electric load.

An initial estimate of a building's compatibility with distributed generation can be garnered from the building characteristics. Fig. 13 presents the net capacity of the US commercial building stock (solid bars) and the portion of base load electric demand (hashed bars) for the 16 building types arranged by peak electrical demand. The buildings range in scale from a small 9 kW office to a 900 kW hospital. The building types most suitable for DG have a large market size, a large capacity, and a substantial base load. These building characteristics allow for a high utilization of the distributed generation system. A high utilization defrays the initial installation cost, and enables the system to undercut the cost of local electric rates. Fig. 13 identifies supermarkets, hotels, and hospitals as large commercial building classes that may be particularly well-suited for on-site generation, and have in fact been the sites of most early DG installations.

5. Summary and conclusions

The newly developed and open-source software, DG-BEAT, provides a novel analytical tool for designing and evaluating distributed generation installations. The integration of multiple databases with a user-friendly interface places specific and accurate analysis in the hands of stakeholders and supports informative decision making by businesses and policymakers alike. The inclusion of regional utility costs and building energy use profiles enables location specific economic analyses for distributed generation systems. The ability to integrate detailed building energy dispatch with accurate economic forecasting and detailed temporally and spatially resolved emissions inventories, while retaining the flexibility to study a wide variety of generators and DG components, makes DG-BEAT a valuable tool for the comparative study of these systems.

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