LBNL-180309

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

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**May 2015**

**This is a paper published in the ASHRAE Winter Conference, Chicago, 2015.**

Please cite this report as follows:
Lee, S.H., Hong, T., Sawaya G., Chen Y., Piette, M.A. DEEP: A Database of Energy Efficiency Performance to Accelerate Energy Retrofitting of Commercial Buildings. ASHRAE Winter Conference, Chicago, 2015. LBNL-180309.

# Acknowledgement

This work is part of an on-going project funded by the California Energy Commission under the Public Interest Energy Research (PIER) Program Award No. PIR-12-031. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. This research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy.

# DEEP: A Database of Energy Efficiency Performance to Accelerate Energy Retrofitting of Commercial Buildings

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## ABSTRACT

*The paper presents a method and process to establish a database of energy efficiency performance (DEEP) to enable quick and accurate assessment of energy retrofit of commercial buildings. DEEP was compiled from results of about 35 million EnergyPlus simulations. DEEP provides energy savings for screening and evaluation of retrofit measures targeting the small and medium-sized office and retail buildings in California. The prototype building models are developed for a comprehensive assessment of building energy performance based on DOE commercial reference buildings and the California DEER prototype buildings. The prototype buildings represent seven building types across six vintages of constructions and 16 California climate zones. DEEP uses these prototypes to evaluate energy performance of about 100 energy conservation measures covering envelope, lighting, heating, ventilation, air-conditioning, plug-loads, and domestic hot water. DEEP consists the energy simulation results for individual retrofit measures as well as packages of measures to consider interactive effects between multiple measures. The large scale EnergyPlus simulations are being conducted on the super computers at the National Energy Research Scientific Computing Center of Lawrence Berkeley National Laboratory. The pre-simulation database is a part of an on-going project to develop a web-based retrofit toolkit for small and medium-sized commercial buildings in California, which provides real-time energy retrofit feedback by querying DEEP with recommended measures, estimated energy savings and financial payback period based on users' decision criteria of maximizing energy savings, energy cost savings, carbon reduction, or payback of investment. The pre-simulated database and associated comprehensive measure analysis enhances the ability to performance assessments of retrofits to reduce energy use for small and medium buildings and business owners who typically do not have resources to conduct costly building energy audit. DEEP will be migrated into the DEnCity - DOE's Energy City, which integrates large-scale energy data for multi-purpose, open, and dynamic database leveraging diverse source of existing simulation data.*

## INTRODUCTION

Buildings consume 40% of the total primary energy in the United States. Reducing energy use in buildings by energy efficiency technologies is a key strategy to mitigate impact of global climate change. The building sector has the largest emission reduction potential from energy retrofit activities (UNEP, 2009). However, systematic retrofit information and impacts on building energy efficiency are difficult to obtain for users such as building owners, energy managers, architects, and engineers. In many cases, the industry stakeholders rely on simple assessments using rules-of-thumb or simplified tools for energy cost saving and retrofit costs. These approaches may lack accuracy in estimating energy savings and the economic performance of retrofits. In contrast, custom energy modeling by professionals is expensive and time consuming for the small buildings sector. Another barrier to information on retrofits is that most energy analysis tools are not freely available. Building owners of small and medium commercial buildings (SMB) usually lack resources to hire energy professionals to conduct a detailed analysis of potential energy savings from retrofits. Many energy professionals conduct detailed audits of ASHRAE Levels 2 and 3 (ASHRAE, 2011b) by performing building energy simulations to evaluate energy savings and identify cost-effective retrofit measures. Easy-to-use, readily accessible retrofit assessment tools are needed to support SMB owners to enable wise decisions about energy savings and economic benefits from the investment in energy efficiency retrofits.

Using simulations for energy assessment has drawbacks for small projects. In general, simulations require experiences and expertise to characterize building equipment and systems. The time and effort to configure simulation models to define and run a set of parametric simulations can require from hours to many days of effort depending on the complexity of level of detail in a building energy analysis. Previous research has described the method by which quick and preliminary information of the energy performance of buildings from simulations performed on-demand by the user can be replaced with pre-simulated tools using a large scale set of simulations performed ahead-of-time by experts and packaged to answer a specific class of analysis questions (Roth et al., 2012). Although a pre-simulation approach comes with drawbacks, such as excessive simulation requirements and the use of prototypes to represent actual buildings, it provides an immediate but reliable energy assessment replacing "just in-time simulation". ASHRAE's Standard 90.1 and Advanced Energy Design Guides (ASHRAE, 2014) are canonical examples and success stories of this approach, leveraging the expertise of a few to create robust easy-to-follow prescriptive rules for commercial building in U.S. More recently, pre-simulation has been successfully deployed in online interactive tools like DOE's 179D easy calculator (DOE, 2014) , Energy Impact Illinois' EnCompass (Energy Impact Illinois, 2013), CEC's EnergyIQ (LBNL, 2013), and LBNL's COMBAT tool (Pan, Xu, & Li, 2012).

The DOE's 179D energy calculator has been supporting the tax deduction program of the Section 179D of Energy Policy Act (IRS, 2005), which determines eligibility for the federal tax deduction for energy efficiency improvements to commercial buildings. It is based on pre-simulated data to determine qualification for both the partial and interim compliance pathways avoiding a high cost of simulation for small building owners. EnCompass serves to find a best-fit baseline energy model from the pre-simulated database and presents the energy data with energy saving opportunities and retrofit recommendations. The pre-simulated database (using EnergyPlus) stores 278,000 energy models representing energy data for large office buildings in Chicago. EnergyIQ provides a list of retrofit recommendations and associated energy savings. The analysis is based on a large batch mode analysis using data from 65,000 eQUEST pre-simulation runs that represent retrofit measure-building combinations integrating 50 energy conservation measures (ECM) in a subset of the California commercial buildings. COMBAT uses prototype buildings for different commercial building types in China. The prototype model using EnergyPlus was applied to a large number of ECMs in major Chinese cities, creating a pre-simulated database. The pre-simulated results account for energy performance interactions among retrofit measures. The use of the pre-simulated database allows users to avoid time-consuming inputs of the baseline buildings as well as detailed descriptions of ECMs. Furthermore there is no constraint of time needed for real-time energy simulations.

We present a method and process to develop a large-scale pre-simulation database called **DEEP – Database of Energy Efficiency Performance** with an aim to provide a quick and preliminary retrofit assessment for small and medium-sized office and retail buildings in California. The energy data for DEEP are compiled from results of a large scale, about 35 million, EnergyPlus simulations. DEEP covers building technologies for various building types, vintages, and climate zones. It can help guide building retrofits to reduce energy use and carbon emissions by providing readily available energy saving of retrofit measures for commercial buildings. DEEP will be made available to the public via a web application to enable industry wide adoption. The large-scale EnergyPlus simulations are made possible by using the national super computers that enable parallel simulations using hundreds of thousands of cores. It would take tens of years to complete such simulations on current desktop computers. DEEP serves as a data bank on energy savings for screening and evaluation of retrofit measures for commercial buildings. The establishment of the pre-simulation database is a part of the Small and Medium Building (SMB) Efficiency Toolkit project, funded by California Energy Commission (CEC) under the Public Interest Energy Research (PIER) Program.

## TECHNICAL ASPECTS

### SMB Prototypes in California

The prototype building models represent seven types of small and medium-sized office and retail buildings in all 16 climate zones in California (CEC, 2014a) at six vintages (year built). The prototype building models are EnergyPlus input files, which were developed based on several sources of information. These include,

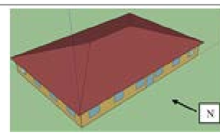
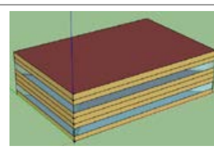
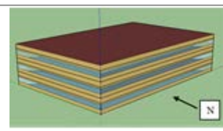
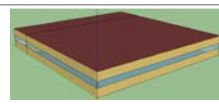
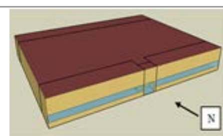
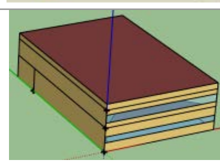
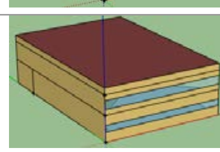
- Small office, medium 3-story office, and medium office:
  - Title 24 California building energy efficiency program: Non-Residential Alternative Calculation Method (ACM) reference (CEC, 2013)
- Medium 2-story office and small retail:
  - Database for Energy Efficiency Resources (DEER) 2011 Version 4.01 e(CEC, 2014b), prototype buildings used for Title 24-2013
- Mixed-use 2-story and 3-story building:
  - First floor: Title 24 ACM reference, a large store unit of the strip mall
  - Second and third floor: Accompanying office space matching to the first floor

The prototype building models are modified to comply with the requirements of historical versions of Title 24, which the DEER prototype buildings have defined input parameters for each vintage. The prototype models used in Non-Residential ACM for Title 24 are based on the DOE Prototype Building Models. Further details of the prototype building design and system are provided from functional specification document (LBNL, 2014c). Added to the prototype building models, upgrades made to the building systems are considered to establish baseline building models that better represent actual buildings with asset changes during the buildings' life cycle. Most buildings in California were built decades ago; many building owners might have replaced building systems such as lighting, cooling, heating, electrical appliances, and windows with the same efficiency levels of the Title 24 standards at the time of upgrades. Therefore, the pre-simulation energy models consider this upgrade to enhance the value of pre-simulated database providing more-realistic representation of existing buildings. The available upgrade options cover:

- Lighting systems:
  - Upgraded to T8 lamps, meeting the requirements of Title 24-2005
  - Upgraded to T5 lamps, meeting the requirements of Title 24-2013
- Glazing systems:
  - Windows upgraded to meet Title 24-2005 requirements
  - Windows upgraded to meet Title 24-2013 requirements
- Cooling systems:
  - Rated efficiency upgraded to EER 10.5, meeting Title 24-2005 requirements
  - Rated efficiency upgraded to EER 11.5, meeting Title 24-2013 requirements
- Heating systems
  - Rated efficiency upgraded to 0.9 (AFUE 90, for condensing furnace or boilers)

In this paper, prototype buildings represent the system specifications of vintages without upgrades; while the baseline buildings represent buildings with upgrades applied to the prototype buildings. Table 1summarizes key features of the prototype building models, used for the whole building energy simulations.

Table 1 Description of the prototype and baseline buildings

<table>
<tr><th colspan="7">Baseline Buildings</th></tr>
<tr><th colspan="6">Prototype Buildings</th><th rowspan="2">Upgrades</th></tr>
<tr><th colspan="2">Building types</th><th>Gross floor area ($m^2$ / $ft^2$)</th><th>Forms</th><th>Climate zones</th><th>Vintages</th></tr>
<tr><td rowspan="3">Office</td><td>Small<br>1-story</td><td>511 / 5,500</td><td></td><td rowspan="7">CZ 1: Arcata<br>CZ 2: Santa Rosa<br>CZ 3: Oakland<br>CZ 4: Sunnyvale<br>CZ 5: Santa Maria<br>CZ 6: Los Angeles<br>CZ 7: San Diego<br>CZ 8: El Toro<br>CZ 9: Pasadena<br>CZ10: Riverside<br>CZ11: Red Bluff<br>CZ12: Sacramento<br>CZ13: Fresno<br>CZ14: China Lake<br>CZ15: El Centro<br>CZ16: Mount Shasta</td><td rowspan="7">Before 1978<br>1978-1992<br>1993-2001<br>2002-2005<br>2006-2008<br>2009-2013</td><td rowspan="7">Lighting<br>Cooling<br>Heating<br>Windows</td></tr>
<tr><td>Medium<br>2-stories</td><td>929 / 10,000</td><td></td></tr>
<tr><td>Medium<br>3-stories</td><td>4,982 / 53,628</td><td></td></tr>
<tr><td rowspan="2">Retail</td><td>Small</td><td>743 / 8,000</td><td></td></tr>
<tr><td>Medium</td><td>2,294 / 24,962</td><td></td></tr>
<tr><td rowspan="2">Mixed-use</td><td colspan="2">Retail at the 1st floor, office at the 2nd Floor<br>(929 / 9,996)</td><td></td></tr>
<tr><td colspan="2">Retail at the 1st floor, office at the 2nd and 3rd Floors<br>(1,394 / 14,494)</td><td></td></tr>
</table>

**Energy Conservation Measures**

The pre-simulation database is established based on baseline building models implementing energy efficiency measures that consider applicable local climate conditions for building systems including envelope, lighting, heating, ventilation, and air conditioning (HVAC), plug-loads, and domestic hot water. Currently, about 100 measures are implemented, as shown in Table 2. The measure database includes detailed description of technical specification and modeling methods. The measures are compiled from various data sources including Advanced Energy Retrofit Guide for offices and retails (PNNL & PECI, 2011a, 2011b), DEER (CEC, 2014b), Small HVAC System Design Guide (CEC, 2003), Advanced Energy Design Guide for Small Commercial Buildings (ASHRAE, 2011a), Home Energy Saver Measures database (LBNL, 2014b).

There are two sets of measures. One incurs higher capital costs, and sometimes involves the replacement of equipment or building components to improve performance. The other includes no-cost/low-cost measures involving minimal cost investment, and achieving energy savings by the implementation of more efficient operation and maintenance practices. Examples include adjusting temperature set-points to minimize mechanical heating and cooling, and scheduling equipment maintenance to optimize operation conditions. In addition to the technical details, the measure database provides cost data for materials and labor. The cost data enriches the energy efficiency analysis with various economic metrics such as total costs and payback years for a retrofit. The economic analysis reflects the local conditions of costs using the RSMeans location factor to adjust the measures cost. The full list provided in measure data compilation report (LBNL, 2014a).

Table 2 A sampled list of energy conservation measures

| Category | Component | Measure Description |
|---|---|---|
| Indoor Lighting | Lamp Replacement | Replace T12 with T8 lamp and ballast; same troffer. |
| Indoor Lighting | Lighting Retrofit | Retrofit existing T12 or T8 lighting to T5 |
| Indoor Lighting | Lighting Retrofit | Use troffer retrofit kit to convert from fluorescent to LED |
| Indoor Lighting | Lamp Replacement | Replace halogen with LED for Display lighting |
| HVAC - cooling | Roof Top Air Conditioners | Replace RTU with higher-efficiency unit, SEER 12.5 |
| HVAC - cooling | Roof Top Air Conditioners | Replace RTU with higher-efficiency unit, SEER 14 |
| HVAC - heating | Gas furnace upgrade | Replace gas furnace with higher-efficiency unit AFUE 92 |
| HVAC - heating | Gas furnace upgrade | Replace gas furnace with higher-efficiency unit AFUE 95 |
| HVAC | Economizer | Install economizer on existing HVAC system |
| Building Shell | Envelope | Install air sealing |
| Plug Loads | Efficiency upgrades | Replace equipment with more energy efficient version |
| Plug Loads | Plug load controller | Install smart plug strip |
| Building Shell | Roof | Roof insulation (R24.83) If re-roofing is desired, tear off old roof, add foam insulation, and re-roof. |
| Building Shell | Roof | Cool roof - apply reflective roof coating |
| Service Hot Water | Gas storage | Replace existing hot water heater with efficiency 0.93 |
| Building Shell | Wall | Wall Insulation (R15) - blown fiberglass in wall. |
| Building Shell | Wall | Wall Insulation (R19) - blown fiberglass in wall. |
| Building Shell | Wall | Wall Insulation (R21) - blown fiberglass in wall. |
| Building Shell | Window | Specifications: Clear, high VT, high SHGC, Reinforced vinyl Framing |
| Building Shell | Window | Specifications: Reflective, low VT, low SHGC, Reinforced vinyl Framing |
| Building Shell | Window | Specifications: Tint, moderate VT, moderate SHGC, Reinforced vinyl Framing |
| Building Shell | Ceiling | Ceiling Insulation (R30) - If re-roofing is not required or desired, fasten fiberglass blankets/batts to ceiling beneath roof |
| Building Shell | Ceiling | Ceiling Insulation (R38) - If re-roofing is not required or desired, fasten fiberglass blankets/batts to ceiling beneath roof |

**Control of Parametric Runs**

There is a need for an automated control tool to manage large-scale simulations to conduct parametric runs for various energy efficiency retrofits. There are existing tools that can be used for parametric runs to explore alternative design options. OpenStudio Parametric Analysis Tool (NREL, 2014) and jEPlus (Zhang, 2009) serve a parametric shell to define parameter values for different design options and call EnergyPlus to conduct multiple simulations in an automated way. However, they are designed for small-scale simulation tasks to optimize a building design for low energy, and are suboptimal for organizing simulations tasks of large scale stock analysis.

DEEP includes the energy simulation results of the prototype buildings, the baseline buildings, and retrofits from individual measures as well as packages of measures. The total number of simulations reaches about 35 million, covering:

- Prototype buildings (7 building types, 6 vintages, and 16 climate zones): 672
- Baseline buildings with upgrades allowing combinations: 24,256
- Retrofits (applied to the baseline buildings) from 100 individual measures: 2,492,800
- Retrofits (applied to the baseline buildings) from packages of measures with an exhaustive combination of a dozen selected measures (with more attractive energy savings or energy cost reductions): 32,853,536

Figure 1 illustrates the process for the large scale simulations. The process starts with preparing seed Input Data Files (IDF) which are unique per building type. Next, control files elaborately manage the generation of IDFs reflecting parameters for different vintages, climate zones, and retrofit measures. When generating IDFs, Design Day data (DDY) are embedded for each climate location. This enriches the simulation results considering HVAC system capacity may be reduced due to the decrease of peak cooling and heating loads from retrofits. Then, the codes generate IDFs and link the climate zone specific EnergyPlus Weather (EPW) files for simulations.

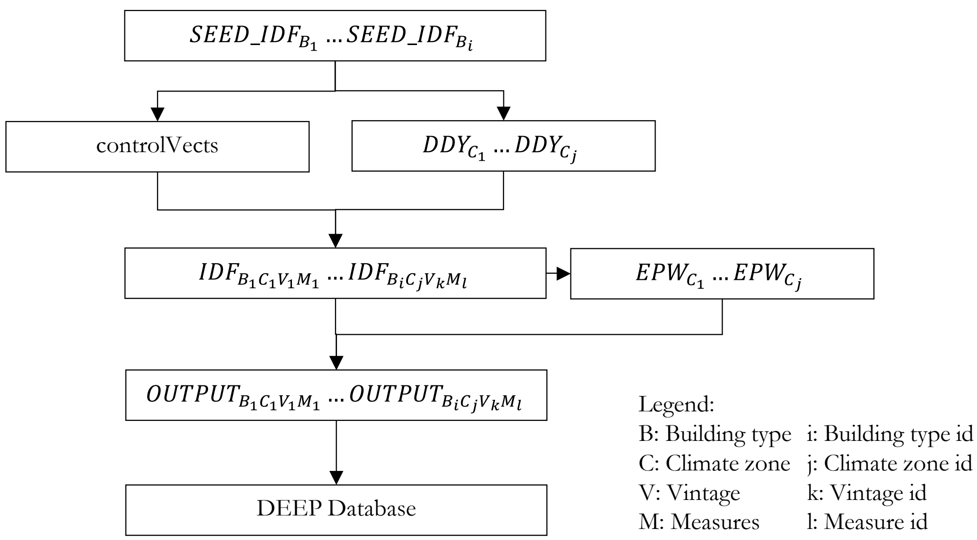



Figure 1 DEEP Database Establishment Process

**Parametric Runs using the NERSC clusters**

A challenge to establish DEEP lies in a scale of simulation runs and its inherited time and cost in the current computing environment. An individual simulation run takes couple of minutes, depending which building type and features, on a typical computer. If we use a desktop computer with four cores, it takes about 13,139 days (36 years) to run 35 million simulations. It is almost impossible to complete the proposed jobs with a normal affordable computing environment. To overcome this we used the supercomputing clusters, Hopper system at LBNL from the National Energy Research Scientific Computing (NERSC) Center. NERSC is one of the largest facilities in the world devoted to providing computational resources for research accelerating scientific discovery through computation.

We setup the simulation environment on the NERSC to perform gigantic simulation runs. The settings include installing required applications such as EnergyPlus and Ruby, developing codes for assigning simulation parameters for retrofit measures, generating IDFs, allocating simulation jobs, and consolidating simulation outputs to a CSV (comma separated value) file which later gets imported into DEEP. There are many processing steps to obtain the energy results data from the initial inputs, consisting of seed IDFs, EPW files, and supplementary IDF object files. The controlVect files define objects with lists of values that are systematically perturbed to generate a number of IDF specifications to represent energy models for prototype buildings of different types, vintages, and climates allowing various retrofit measures. These controlVect functions determine the values of any specified IDF file objects such as fan efficiencies, construction materials, and window performance.

The first processing step to generate the multitude of IDF inputs for EnergyPlus is to generate the full set of perturbed input vectors. The controlVect file is a Ruby code file containing data structures specifying the IDF objects to output. The input generation code parses this file, assembles the seed IDF files integrating DDY file to make climate region specific, and then assembles a set of input vectors, each of which contains values for each IDF object to be modified. The next step takes the input vectors, reads the seed IDF files, and outputs an IDF file for each simulation to be executed. Both of these execute in parallel on shared memory architectures. Once the input files are constructed, it launches the EnergyPlus simulations. The challenge is to distribute the simulations widely enough to obtain the output set in a reasonable amount of time. There are several components that manage this aspect. The simulation management system consists of a setup program, a node level program (that is run on each cluster node) and a core level program (which runs once for each EnergyPlus simulation). The development of the simulation environment at NERSC requires MPP hours for testing codes and debugging, and optimizing the simulation speed. MPP represents for Massively Parallel Processing, a type of computing that uses many separate CPUs running in parallel to execute a single program. The computing requires 1.5 million MPP hours that can cover the simulation runs for DEEP. Using NERSC to perform 35 simulation runs, the executing time is estimated to be about 240 clock hours (10 days) that include generating IDFs, simulation running, and consolidating outputs times.

## SUMMARY

By leveraging the computing resources of NERSC clusters, we have established the pre-simulated database that integrates data for retrofit technology and its impact on building energy performance. DEEP with comprehensive retrofit measures enhances the value proposition of a retrofit assessment which promotes and accelerates a voluntary retrofit action to reduce energy use for small and medium size commercial buildings with owners typically do not have the resources or expertise to conduct a more costly building energy audit. The retrofit analysis includes energy performance data for the baseline building (prototype building with upgrades) and queried measures based on the user's retrofit investment criteria of maximizing energy savings, energy cost savings, carbon reduction, or payback of investment. The strength of DEEP includes a wide coverage of building types, vintages, climate zones, and a large set of energy conservation measures, as well as the energy performance considering not only individual measures but also interactive effects between multiple individual measures. Looking up the pre-simulated database with referencing the measure database enables a quick and reliable retrofit analysis providing:

- Monthly energy consumption in site energy (electricity and natural gas)
- Monthly energy consumption breakdown into systems such as lighting, cooling, heating, domestic hot water, electric equipment, fan, pump, and etc.
- Peak electrical demand and time of the year
- HVAC system capacities
- Energy costs, retrofit investment costs and payback years

DEEP is producing a web-based retrofit toolkit for small and medium commercial buildings in California, and potentially can be expanded to other regions. DEEP will be implemented in a web application to provide real-time energy retrofit feedback which identifies most cost-effective retrofit measures. In the future, DEEP will feed into DEnCity, DOE's Energy City (Roth et al., 2012), which is a planned public resource to support design and retrofit of energy efficient buildings. DEnCity integrates large-scale energy data for multi-purpose, open, and dynamic database leveraging diverse source of existing simulation data, which will help building owners, designers and engineers to improve energy efficiency of buildings. A future paper will present retrofit analysis results from several pilot applications of DEEP and the web-based toolkit as part of the CEC funded PIER project.

## ACKNOWLEDGEMENTS

This work is part of an on-going project funded by the California Energy Commission under the Public Interest Energy Research (PIER) Program Award No. PIR-12-031. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. This research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy.

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