## 3.6 A bottom-up approach for estimating latent and sensible heat emissions from anthropogenic sources

David J. Sailor*, Portland State Univ., Portland, OR; and A. Brooks, M. Hart, and S. Heiple
Portland State University, Portland OR

### 1. INTRODUCTION

As has been pointed out by various researchers (Ichinose et al., 1999; Torrance and Shum, 1975) the emission of waste heat from energy consuming activities plays a significant role in the development of the Urban Heat Island (UHI). Until recently, however, there have been relatively few studies of the urban climate that have explicitly included waste heat (anthropogenic heating) in their analyses (Ichinose et al., 1999 and Sailor and Fan, 2004). One reason for this is the relative difficulty in obtaining the necessary data for estimating spatial and temporal profiles of anthropogenic heating. While simplified methods have been introduced in the literature (e.g., Sailor and Lu, 2004) these approaches have limited spatial and temporal accuracy associated with numerous assumptions that are required in mapping available coarse-scale data to hourly city-scale profiles. As urban climate and air quality modelers continue to refine their spatial scales of analysis there is a growing need for improved methods for estimating urban waste heat emissions. As a starting point it is important to first estimate detailed profiles of energy consumption within the building and vehicle sectors. These data can then be propagated into corresponding estimates of latent and sensible heat emissions.

This paper presents a technique for estimating hourly and seasonal latent and sensible heat emission profiles from vehicles and the building sector at spatial scales down to the individual tax lot or parcel. The building energy component combines annual building energy simulations for prototypical buildings and commonly available geospatial data in a Geographical Information System (GIS) framework. The method for estimating emissions from the vehicle sector combines traffic data with GIS-based road link data. Hourly results for total anthropogenic latent or sensible heating can be extracted for any day and exported as a raster output at spatial scales as fine as an individual parcel (<100m). The target application for this "bottom-up" modeling approach is urban scale atmospheric modeling in support of urban heat island and air quality studies. In such applications the inclusion of high spatial and temporal resolution anthropogenic latent and sensible heating data represents a significant advancement.

### 2. METHODS: BUILDING SECTOR

To estimate anthropogenic emissions from the building sector we have used building energy simulation software in conjunction with a suite of prototypical building models. Prototype buildings were modeled using a comprehensive building energy simulation program (eQuest from the US Department of Energy).

Building simulations were validated by comparing aggregated annual Energy Use Intensities (EUIs [kWh/m$^2$/yr or kBtu/ft$^2$/yr ]) with survey data from existing buildings. Specifically, the U.S. Department of Energy maintains Residential and Commercial Building Energy Consumption Surveys (RECS, and CBECS). While these surveys are not applicable to specific cities, sample sizes are sufficient to assess building stock characteristics at regional and climate zone scales (EIA, 1999; 2001). As needed prototype simulation parameters were adjusted using information from similar relevant studies until all simulation prototype EUIs were within 10% of existing building types.

Existing buildings within a case study city were matched to building prototypes using GIS parcel (tax lot) data containing information on existing building type and building floor space for each tax lot. Total energy consumption for each existing building was calculated by multiplying the corresponding prototype's EUI by the actual building's floor space. Annual building energy consumption for the entire study area ($E_{city}$) was then calculated by:

$$E_{city} = \sum_{i=1}^{N} \left( A_i \sum_{j=1}^{M} EUI_j \cdot P_{ij} \right) \quad (1)$$

* *Corresponding author address:* David Sailor, Portland State Univ., MME Dept., Portland OR, 97207; e-mail: sailor@cecs.pdx.edu

where $A_i$ is the floor space for each existing building, $EUI_j$ is the energy usage intensity predicted for the building prototype category, N in the number of buildings, M is the number of prototype categories, and $P_{ij}$ is the matrix defining the mapping of buildings into each of the categories (if building i is in category j, $P_{ij}$=1.0, otherwise $P_{ij}$=0.0). This simulation process is illustrated in Fig. 1.

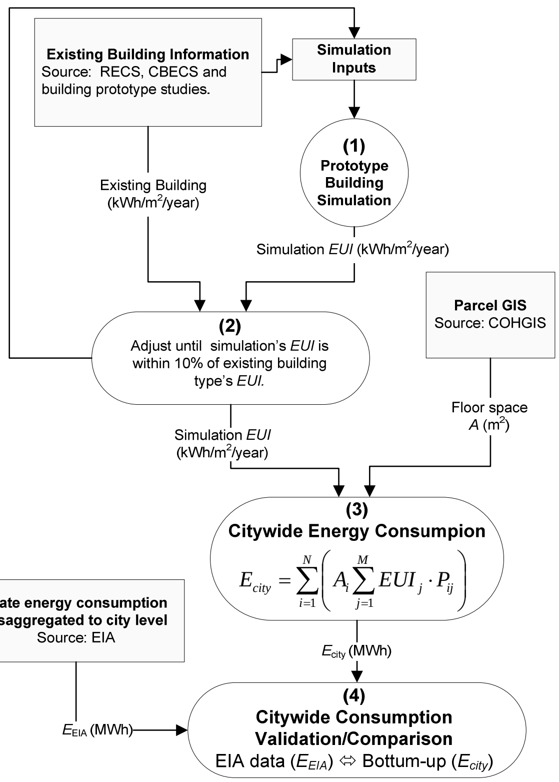


**Figure 1**. Building energy simulation and model validation procedure.

After prototype simulation and validation, hourly load outputs from the simulations were used to calculate diurnal energy consumption profiles for each building prototype. Diurnal consumption profiles $Q_p(h)$, also known as load shapes, were calculated by taking the average consumption for each hour over a specific day of week and time duration, usually a season or month. Prototype diurnal profiles were then matched to existing buildings using the parcel GIS. Diurnal energy consumption for existing buildings was estimated by multiplying corresponding prototype consumption profiles by building floor space. The resulting profiles allow for hourly estimation of energy consumption at the parcel scale.

In addition to producing building energy consumption estimates, the building energy simulation model also produces output for total heat rejection from the building's heating and air conditioning system. Depending upon the type of air conditioning installed (e.g., direct expansion refrigerant with air-cooled coils vs. an evaporation-based cooling tower) the heat rejection will be partitioned into sensible and latent components.

In order to use the resulting parcel-level profiles as input to an atmospheric model, anthropogenic sensible and latent heat rejection at the parcel level is aggregated up to the atmospheric model's spatial resolution. This is achieved by first overlapping the atmospheric model's grid on the parcel GIS, and then sorting buildings by the grid cells in which they are located and by their building type.

It is also important to note that much of the building's thermal load is associated with environmental loading (solar radiation passing through windows, infiltration, and conduction of heat through the building envelope). As a result the total heat rejection from the building can be larger than the total building energy consumption. It is not uncommon for the summertime environmental load to be of the same order of magnitude of the energy consumption, resulting in a heat rejection that is double the energy consumption. Conversely, in winter, much of the environmental load and building energy consumption contributes to maintaining the building internal air temperature at a level above the outdoor ambient conditions. As a result, the total wintertime heat rejection from a building is generally less than the building energy consumption.

### *2.1 Case Study: Houston TX*

The method just described has been applied to the city of Houston Texas as a case study. The Commercial Building Energy Consumption Survey (CBECS) has 18 predefined building types for the commercial building stock in the climate zone containing Houston. After assessing the total contribution of energy consumption of each building type, building categories were combined and reduced to eleven types. Building types which did not represent a significant amount of consumption were grouped together into a general building category. Retail and office buildings, accounting for 48% of commercial energy consumption in Houston, were divided based on floor space, into large and small buildings (Large ≥

2,323 m$^2$ or 25,000 ft$^2$). Building types were further grouped by primary heating fuels (electric or non-electric). Because fuels other than electricity and natural gas are less than 5% of commercial energy consumption for Houston, and because these other fuels typically have the same end-uses as natural gas, they were not modeled explicitly - their net energy consumption was simply added to natural gas consumption estimates (NG+). Building age is also a significant factor affecting consumption, but could not be differentiated because of sample size limitations in CBECS. The prototype definition process resulted in 22 commercial building prototypes (Fig. 2).

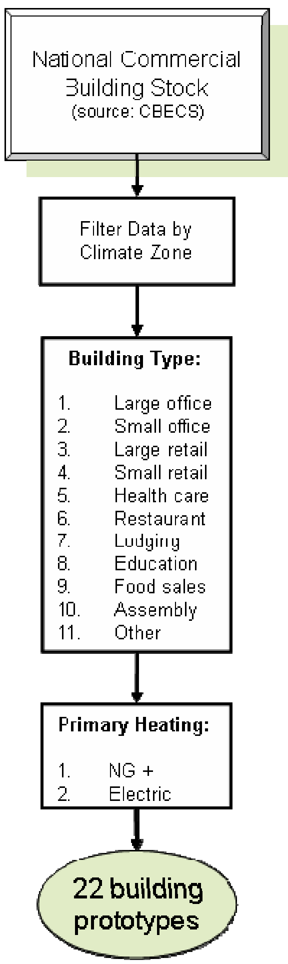


**Figure 2**. Summary of the commercial building prototype definition process.

Residential buildings are categorized as either multi-family residential (MFR) or single-family residential (SFR). Based on past prototypical building studies, residential buildings were also sorted by year of construction (pre-1980 vs. post-1979). After vintages had been defined, buildings were then sorted by primary heating fuel type. As was done for the commercial sector, residential sector energy consumption associated with fuel types other than electricity and natural gas was simply added to the natural gas consumption estimates (NG+). The residential prototype definition process resulted in 8 building prototypes as shown in Fig. 3.

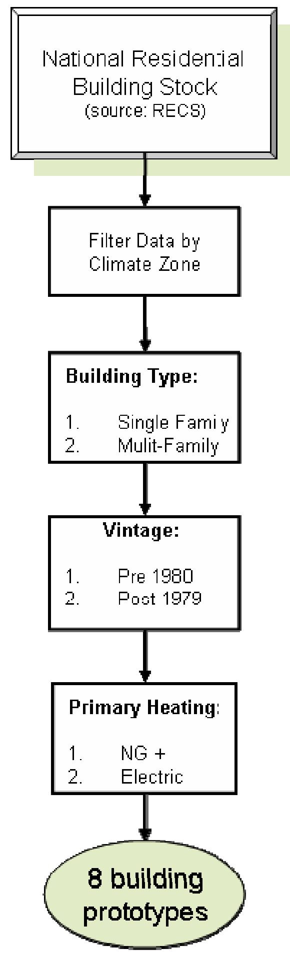


**Figure 3.** Summary of the residential building prototype definition process.

### *2.2. Building Energy Simulations*

Using the prototype definitions in Huang et al., 1991 as a starting point we derived additional building inputs where new information was available. Huang's study reported building prototype information for older and newer vintages. Because we did not differentiate between building vintages for the commercial sector, Huang's vintage input values were averaged based on total vintage floor space within Houston.

The goal for each building prototype definition was to balance the accuracy of modeled energy consumption profiles with level of detail and complexity of the simulation process. We used DOE-2 in conjunction with eQUEST for all building simulations (both available from and documented by the U.S. Department of Energy at www.DoE2.com). eQUEST has an extensive library of default values for building characteristics for several building types. Default values supplied within eQuest were used for building features that had a minor impact on energy consumption (i.e., hot water tank insulation, interior finish, door types).

In defining prototypes we used many of the building prototype simulation practices established in Huang et al., 1991. Building physical features, such as walls and windows were equally distributed along the four building faces to avoid directional bias errors. Building internal complexities were simplified by using a well established technique that separates internal areas into five zones - four perimeter zones and one core. Building insulation and other envelope values were estimated taking into account that many buildings are not at current building standards. Therefore, building codes were not directly applied to define building characteristics. Instead, we used envelope values from Huang's study that were estimated from historic building codes, building conditions and human comfort levels.

Building schedules are a major determinant of load shapes. The ELCAP study concluded for commercial buildings within the Pacific Northwest, that time alone can explain approximately 70% of hourly load variation Reiter, 1986). Occupancy, internal loads, HVAC operating schedules, and DHW use are some of the many building characteristics that are modeled in building energy simulation programs using schedules (assumed hourly profiles). Internal load shapes, such as lighting, office equipment and cooking, not only contribute to the building load, but also affect space conditioning loads by supplying "free heating" to conditioned spaces (Huang and Brodrick, 2000). A literature review by Abushakra et al., 2004) examined existing typical internal load shapes from monitored commercial buildings and methods to develop them without end-use hourly load data. Although the review covered most commercial building types, it focused on office buildings. In the present work, reported internal load shapes were used where readily available. Lighting load shapes were based on office building profiles developed by ASHRAE (Abushakra et al., 2001).

The National Renewable Energy Laboratory has created the Building America Benchmark Definition NREL, 2005 for Residential buildings. This benchmark was based on building industry knowledge and other end-use studies such as ELCAP. It developed building energy simulation inputs that are representative of "standard" building use. The Department of Energy's Building Energy Data Book (DOE, 2006) and the Huang and Franconi, 1999 study were used to define characteristics of prototypical residential buildings. We used these parameters in conjunction with the Building America Benchmark to develop internal load shapes, end-use intensities and occupancy and HVAC schedules. As illustrated in Fig 4, the final prototype models had a simple square geometry for the commercial sector and a rectangular geometry with attached garage for the residential sector.

## 3. METHODS: TRANSPORTATION SECTOR

In order to estimate anthropogenic heat and moisture emissions from the transportation sector we used a comparatively simpler approach than was needed for the building sector. First, we estimated city-wide hourly traffic. The U.S. Department of Transportation has estimates of vehicle distance traveled per capita for all major U.S. cities. Keeping with the case study of Houston, it is estimated that the average person in Houston drives 59.4 km per day (USDoT, 2003). To estimate the total vehicle travel in Houston, we simply multiplied this value by the greater metropolitan population of Houston (~4.2 million in 2000). These 24.9 million vehicle km driven per day were then divided into hourly values using a diurnal profile of traffic intensity developed by Sailor Sailor and Lu, 2004 based on data for many states and cities, and the U.S. national profile developed by Hallenbeck et al., 1997. To spatially allocate this vehicle travel onto the roadway network we made the assumption that all traffic was either on freeways or on major & minor arterials. Based on data from the state of Texas Department of Transportation it was further assumed that 75% of all traffic was on major roadways with the remainder evenly distributed on minor roadways. While this approach represents a useful first step it could be significantly improved through incorporation of detailed traffic modeling that would further differentiate the broad categories of major and minor roadways into numerous discrete roadway links.

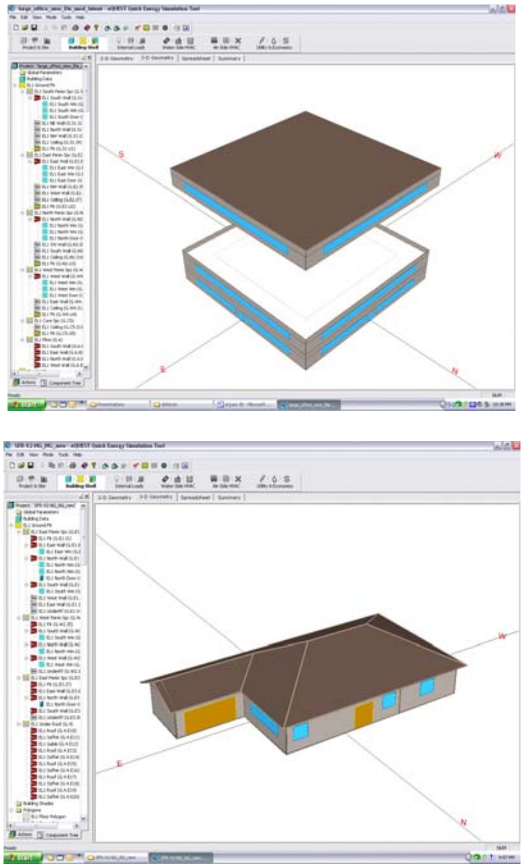

**Figure 4**. Prototype building geometries used for determining building energy consumption and anthropogenic sensible and latent heating.

To convert transportation sector travel distance data into heat and moisture emissions it is necessary to make some assumptions about the vehicle fleet and typical fuel characteristics. It is estimated that the fleet fuel economy in Houston is 8.5 km/l (~20mpg). With a typical fuel heating value of 45 $x10^6$ J/kg and typical fuel density of 0.75 kg/l it is then estimated that 3975 J of heat are liberated for each meter of vehicle travel.

Vehicle exhaust contains a significant amount of water vapor. This is a direct result of the combination of hydrogen atoms in the fuel ($C_xH_y$) with oxygen in the air. While composition of fuel varies, data from the Oak Ridge National Laboratory and the National Renewable Energy Laboratory indicate that 1 liter of gasoline or diesel fuel yields about 0.9 to 1.0 kg of water vapor. Again, assuming a fleet fuel economy of 8.5 km/l it can be estimated that 0.12 g of water vapor is liberated for each meter of vehicle travel.

## 4. GEOSPATIAL MAPPING

Geospatial mapping of energy consumption is limited by the availability and detail of geospatial data. GIS databases often include information that is crucial for energy use mapping as well as supplemental data that can help inform building prototype simulation modeling. Building floor space and building type are necessary for geospatial mapping of building energy use. Roadway type and location are necessary for apportioning energy use in the transportation sector. Depending on the region, much of the information necessary for geospatial mapping and building prototype simulation is contained in parcel-scale GIS databases. Fortunately, collection of parcel information is federally mandated. Tax assessors, usually at the city or county level, are responsible for reporting on site assessment of individual parcels. Although all parcel information is collected, the degree to which this information is available in GIS format varies by city, county and state. In 2003 the Federal Geographic Data Committee surveyed state, county and city governments Stage and Meyer, 2006 to assess the number of parcels in the United States and the degree to which parcel data have been converted to a GIS. With 34 states reporting relevant information it was estimated that data for 61% of parcels in these states were available in digital format. Thirteen states had more than 70% of their parcel data in GIS format. Larger cities typically had higher rates of converted parcels. To further investigate the availability of GIS-based data useful for bottom-up energy consumption analysis, we examined the ten largest cities in the U.S. In all cases, city parcel GIS data were either publicly available or available for purchase from the county or city. Building type or land use classification of parcels was available for all cities. In most cases geospatial building floor space, as well as additional information applicable to building simulations, were also available. For cities lacking building floor space information in their parcel GIS data, this information could be obtained through the local county or state tax assessor office and then linked to a geospatial database through parcel IDs. As a result, the methods employed in the present study can be readily adapted for use in modeling many other large U.S. cities.

## 5. RESULTS

Spatially-resolved energy consumption maps for the building and transportation sectors are shown in Figs. 5 and 6, respectively. These figures are for a snapshot at 5pm on a typical August day.

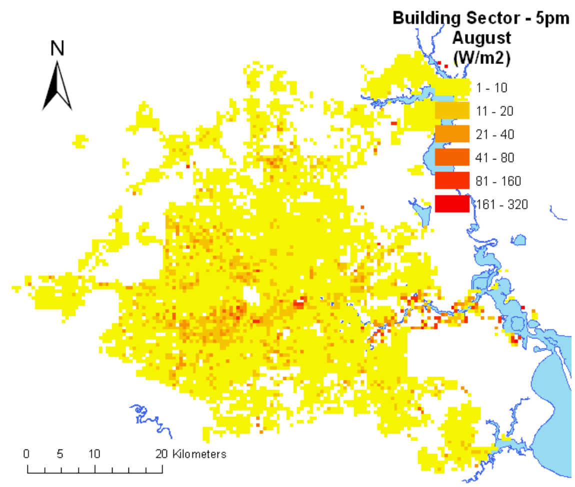


**Figure 5**. Building sector energy use for late afternoon in August.

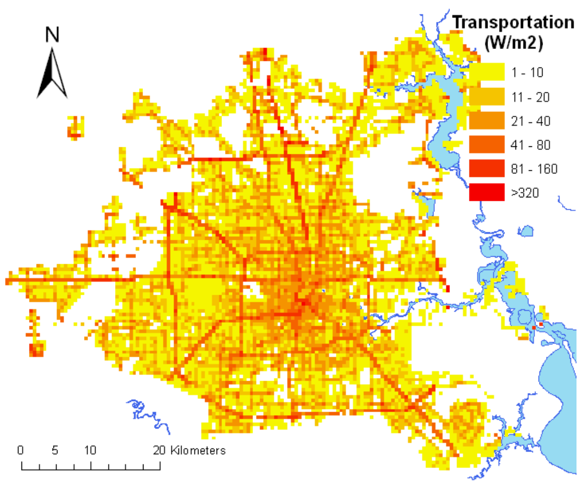


**Figure 6**. Transportation sector energy use for late afternoon in August.

The energy consumption figures presented above are just a first step in generating data useful for urban atmospheric modeling applications. Ultimately, the atmospheric model requires gridded input of anthropogenic sensible heat emissions ($W/m^2$) and anthropogenic moisture emissions ($g/m^2$). As noted earlier, energy use in the building sector is related to, but different from anthropogenic sensible heating. Specifically, in smaller buildings where the building heat rejection is accomplished by air flow over coils the entire building thermal load (energy consumption plus environmental load) will be rejected as sensible heating. The modeling that we have done to date (for Houston) suggests that heat rejection from such buildings (all of which is sensible) is 50 to 100% greater than the building energy consumption in summer and slightly less than the building energy consumption in winter. The total heat rejection rates are similar in buildings with evaporatively-cooled systems (e.g., cooling towers). In such buildings, however, this heat is partitioned into sensible and latent components. In summer, evaporatively-cooled systems reject 50 to 80% of their heat in the form of latent heating. In the winter this decreases to less than 50%. The actual monthly variation in energy consumption, total heat rejection, and latent heating from 5 prototypical buildings with evaporative cooling towers is illustrated in Fig. 7.

## 6. DISCUSSION AND CONCLUSIONS

The Houston case study reveals that the bottom-up method can accurately capture total building energy consumption. Key information sources (i.e. GIS and building energy surveys) are available for most large U.S. cities and therefore the method is widely applicable.

While an increasing number of studies are pointing out the need to include waste heat in atmospheric model simulations of cities, the difficulty in obtaining suitable energy consumption profile data has hampered modeling efforts. The small number of urban climate modeling studies that have included anthropogenic waste heat have generally assumed that energy consumption is equivalent to anthropogenic sensible waste heat emissions. The present study has shown that this is not a good assumption, and has illustrated the need for bottom-up estimates of anthropogenic sensible and latent heat emissions.

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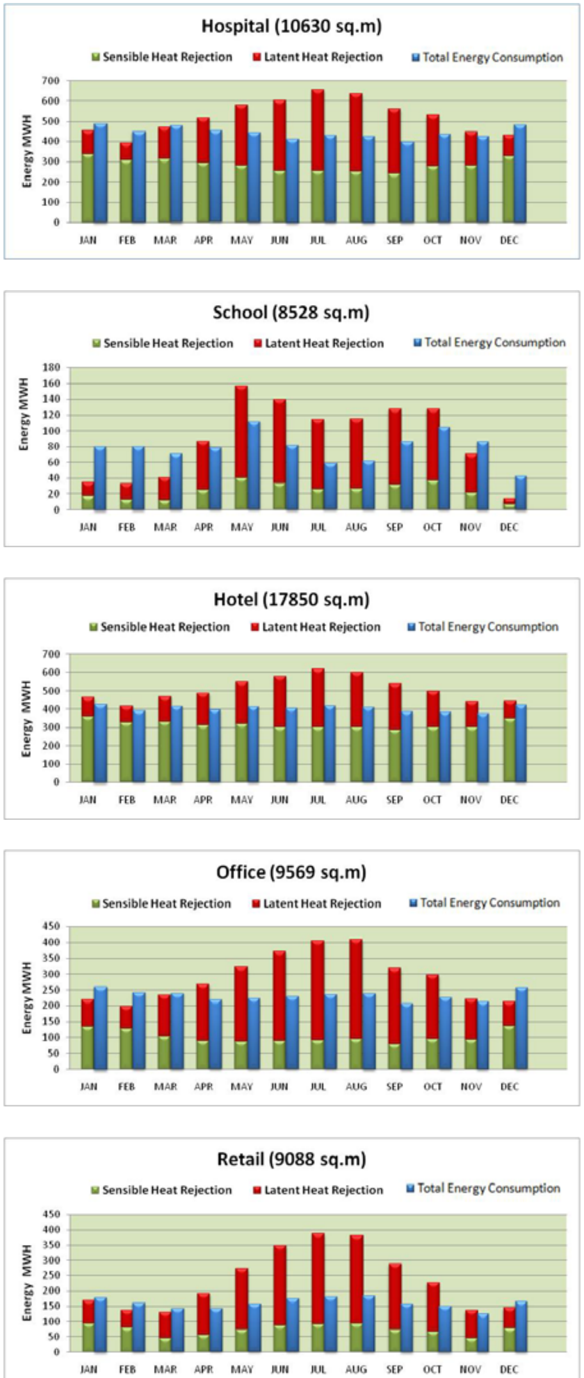


**Figure 7**. Monthly variation of building energy consumption, total building heat rejection, and latent heat emissions from various types of large prototypical buildings with cooling towers.

## REFERENCES

Abushakra, B., J. S. Haberl, and D. E. Claridge, 2004: Overview of existing literature on diversity factors and schedules for energy and cooling load calculations. *ASHRAE Transactions, Jan 25 2004*, Anaheim, CA, United States, Amer. Soc. Heating, Ref. Air-Conditoning Eng. Inc., Atlanta, GA 30329, United States, 164-176.

Abushakra, B., A. Sreshthaputra, J. S. Haberl, and D. E. Claridge, 2001: Compilation of diversity factorsand schedules for energy and cooling load calculations1093-RP.

DOE, 2006: 2006 buildings energy data book, 124 pp.

EIA, 1999: 1999 Commercial Building Energy Consumption Survey.

——, 2001: 2001 Residential Energy Consumption Survey.

Hallenbeck, M., M. Rice, B. Smith, C. Cornell-Martinez, and J. Wilkinson, 1997: Vehicle Volume Distribution by Classification, 54 pp.

Huang, J. and E. M. Franconi, 1999: Commercial heating and cooling loads component analysisLBL-37208.

Huang, Y. J. and J. Brodrick, 2000: A bottom-up engineering estimate of the aggregate heating and cooling loads of the entire US building stock. *Proceedings ACEEE Summer Study on Energy Efficiency in Buildings*, **10,** 10-135.

Huang, Y. J., H. Akbari, L. Rainer, and R. Ritschard, 1991: 481 Prototypical Commercial Buildings for 20 Urban Market Areas. Technical Documentation LBL-29798, 208 pp.

Ichinose, T., K. Shimodozono, and K. Hanaki, 1999: Impact of anthropogenic heat on urban climate in Tokyo. *Atmospheric Environment*, **33,** 3897-3909.

NREL, 2005: Building America Research Benchmark DefinitionNREL/TP-550-37529.

Reiter, P. D., 1986: Early results from commercial ELCAP buildings: Schedules as a primary determinate of load shaoes in the commercial sector. *ASHRAE Transactions 1986. Technical Papers Presented at the 1986 Annual Meeting*, Portland, OR, USA, ASHRAE, Atlanta, GA, USA, 297-309.

Sailor, D. J. and H. Fan, 2004: The importance of including anthropogenic heating in mesoscale modeling of the urban heat island. *84th annual meeting of the AMS, Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone*, Seattle.

Sailor, D. J. and L. Lu, 2004: A top-down methodology for developing diurnal and seasonal anthropogenic heating profiles for urban areas. *Atmospheric Environment*, **38,** 2737-2748.

Stage, D. and N. Meyer, 2006: An Assessment of Parcel Data in the US - 2005 Survey Results, 15 pp.

Torrance, K. E. and J. S. W. Shum, 1975: Time-varying energy consumption as a factor in urban climate. *Atmospheric Environment*, **10,** 329-337.

USDoT, 2003: Urbanized Areas - 2000 Selected Characteristicswww.fhwa.dot.gov.