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Quantifying End-Use Energy Intensity of the Urban Water Cycle

Afreen Siddiqi*
Research Scientist, Engineering Systems Division
Massachusetts Institute of Technology, Cambridge, MA, USA
e–mail: siddiqi@mit.edu

Olivier L. de Weck
Associate Professor of Aeronautics and Astronautics and Engineering Systems,
Massachusetts Institute of Technology, Cambridge, MA, USA
e–mail: deweck@mit.edu

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ABSTRACT

The water end-use segment (WES), consisting of activities that utilize water in homes and buildings, has been identified as a major component of energy use in the urban water supply system. In this paper, we present an analytical framework that can be used at the planning stages of new urban developments to assess future building-level water demands and associated energy requirements. The framework is applied to Masdar City, a new urban area in the United Arab Emirates, which has been targeted in its design to be a future zero-carbon and zero-waste city. Our results show that the energy intensity (in electric kWh) in WES for Masdar may range from 2.6 – 4 kWh/m^3. The dominant use of energy in this segment is attributed to water heating requirements, and the total energy use for obtaining hot water is estimated to range from approximately 20 – 50 Million kWh annually. It is found that the residential sector in the city can have the greatest impact in affecting energy requirements associated with water use. We estimate that for every unit reduction (in litres/person/day) of in-door residential water use, up to 225 kWh may be saved annually.

INTRODUCTION

Urban water supply systems, historically planned and designed on least-cost approaches (Haimes, 1977), are now increasingly evaluated on factors related to environmental sustainability (Lundie et al., 2004). In particular, energy consumption has been studied in operational (Cohen et al., 2004) and full lifecycle stages (Racoviceanu and Kamey, 2010; Sharma et al., 2009; Stokes and Horvath, 2009; Arpke and Hutzler, 2006) of the water infrastructure. In the US, it

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* Corresponding author

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has been reported that up to 80% of municipal water and wastewater costs are solely for electricity (Gay and Sinha, 2011). In Australia, it has been estimated that by 2030 there maybe a 200% – 400% increase in energy use (as compared to 2007 levels) by water utilities due to increased adoption of desalination and other energy intensive sources (Kenway et. al 2008). The growing attention to energy use in water systems has been motivated by rising cost of energy (EnergyPrices, 2012) as well as an increasing desire to reduce the energy footprint for long-term environmental sustainability (Lundie et al. 2004; Sharma et al., 2009). Motivated by this wider context, this work describes a quantitative framework that has been developed to investigate energy requirements for building-level water use in urban areas. The framework is applied to Masdar City, a new urban area planned in the United Arab Emirates (UAE) and one that represents an emerging trend of urban development designed upfront with high environmental sustainability goals (Alfaris et. al. 2010). We present an in-depth analysis of water-use related energy in buildings (as planned – and mostly yet to be built - for Masdar City), and include the energy assessment of the new decentralized configurations of water supply.

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In general, there are five key segments in the urban water system infrastructure: Provision (abstraction), Treatment (purification), Distribution, End-Use and Wastewater Disposal (after treatment). Each segment has some associated energy requirement. Energy is needed to abstract raw water from a source (such as a river, lake, sea or aquifer) and then to convey it (by pumping) to a site of treatment. In water treatment, energy is expended for purifying the raw water (through filtration, flocculation and disinfection, or desalination in case of seawater) to drinking water quality standards (Jimenez and Asano, 2008). The purified water is distributed through pumping and pressurization – that require energy - and transported to end-users (Filion, 2008). In water end-use (water consumption at the building, facility, or lot scale) in a city, energy is consumed for on-site pumping (*e.g.* in the case of high rise buildings), and water heating (Cheng, 2002). Water is usually heated in homes in gas-fired or electric heaters that supply hot water for use in faucets, showers, and appliances such as dishwashers and clothes washers (Plappally and Lienhard, 2012). In landscaping applications in homes and buildings, some additional pumps and electrical control equipment (such as motors and valves) may be used that add to the energy associated with water use. In Industrial facilities, various processes may use water for operations and have associated energy requirements typically in terms of pumping, pressurization, heating, cooling and treatment of the water. Once the water has been used in homes and buildings, the wastewater is typically collected by a sewerage system, treated and then discharged to a receiving water body – all of these steps use energy (Jimenez and Asano, 2008). With increasing

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scarcity of water in many cities around the world, there is a growing trend towards partially reclaiming wastewater for further use. This is done by treating greywater (*i.e.* water with no human wastes *e.g.* from laundry, dish washing, *etc.*), and reusing it in the city for non-potable applications (Gikas and Tchobanoglous, 2009). For a particular region, the energy intensity in the various segments can vary due to differences in topography, regional climate, water quality, extent of residential and industrial mix, distribution architecture, usage patterns, and wastewater treatment technologies.

A number of studies have attempted to quantify the energy intensity of urban water use (Cohen et al. 2004; deMonsabert and Liner, 1998; Kenway et al. 2008; Racoviceanu and Kamey, 2010). Of the different segments, the water end-use segment (abbreviated as WES in the remainder of this paper) in particular has been found to be the most energy intensive. This is typically considered to encompass the set of water-using activities at the end use level in homes, and commercial and industrial buildings, before it is discharged to wastewater collection and disposal segment. In past studies, it has been found that energy associated with final use of water in these activities adds up to be an appreciable fraction of total energy use in buildings. For instance, in Australia it has been found that residential hot water uses several times more energy than that is used to deliver urban water services, with the ratio ranging from 4.7 in Adelaide to 11.2 in Melbourne (Kenway et. al, 2008). In the UK, it has been reported that 89% emissions associated with the supply-use-treatment cycle of water in the domestic sector is during the ‘use’ phase within homes (Clarke, et. al. 2009). In a study focused on San Diego County in the US, it was found that the energy for urban water end-use was highest (at 3.16 kWh/m^3) as compared to other segments such distribution and treatment (Cohen et al, 2004). Findings such as these have spurred development of online tools that residents can use to estimate water-related energy in their homes (Wecalc, 2012).

While water-related energy use has been estimated in prior studies, it has typically been computed at an annual, aggregate city-level basis using fixed parameter assumptions (Kenway et al, 2011). In this work, we present a more detailed estimation of energy requirements for WES on finer temporal and spatial levels. Additionally, we expand the notion of WES to not only encompass energy use associated with water use alone, but also include the provisioning, treatment and reuse elements that are likely to be adopted at the building-level in many existing and future cities. Water system planners and designers have been re-visiting traditional urban centralized architecture of supply and disposal (Gikas and Tchobanoglous, 2009; Nolde, 2005; Sharma et al. 2010) and increasingly considering a shift towards new supply, use and disposal architectures. The new configurations are hybrid-systems where reticulated municipal supply is augmented

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with building-level water provisioning (*e.g*. through rainwater harvesting) and wastewater treatment (through on-site greywater treating and reuse) particularly in water scarce regions that have growing urban demands (Friedler and Hadari, 2006; Nolde, 2005; Sharma et al., 2009). While the shift towards these architectures is motivated by water availability and limits to expansion of centralized systems, the associated energy impacts of the new hybrid configurations are still under investigation (Racoviceanu and Kamey, 2010; Retamal et al. 2010). The framework we describe in this paper has been created for furthering this research and allows for estimating building-level energy use not just related to water utilization but also for on-site sourcing and on-site treatment.

In this paper, using Masdar City as a reference case, we focus on the question of energy intensity of water use in buildings. We consider the new hybrid-configurations of building-level water supply and reuse, and explore the impact on energy use through water conservation and usage patterns. This work while focused on Masdar, builds a quantitative understanding of water use energy in buildings, and at a more general level serves as an illustrative analysis that may be undertaken for other areas where new urban development schemes are being planned with emphasis on long term environmental sustainability.

Overall, we expect this work to be useful for planners seeking to create new developments sensitive towards water and energy use. However, we also note that water and energy use at the building-level is of direct concern to the occupants who pay utility bills. Water conservation can be effectively incentivized for the users through messaging campaigns that convey quantitative energy costs in buildings associated with water use. Thus, in addition to urban planners and developers, this work can also be of interest to environmental protection agencies or municipalities aiming to reduce water and energy demands within their jurisdictions.

MODELLING FRAMEWORK

The framework has been created in MATLAB^{TM} (Mathworks, 2012) for computing energy requirements related to water use in buildings. It is meant for upfront estimation of inside water use during early planning stages of an urban area, and produces estimates based on input data of buildings, water demand type, and local temperature and precipitation.

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The framework consists of several modules. Fig. 1 shows a schematic of the computational architecture with key modules, inputs and outputs. The smallest spatial-scale considered is the building or plot-level, and the time resolution (daily, weekly, monthly etc.) in the computation is set based on the purpose of the analysis. The computation is carried out for each building and for each time step and then aggregated appropriately for cluster level (collection or group of buildings) and city-level information. The details of the assumptions, inputs, and key equations used in some of the major modules are described in the following sub-sections.

Figure 1: Modelling framework with key computation modules (shown as boxes) and inputs and outputs (shown in brackets).

Inputs

The required inputs include time-series data of regional temperature and precipitation, building-level definition of the urban area, water source options for each building, and a ranking matrix between source types and use applications.

Each plot (building) is defined with a number of parameters, a sample of which is shown in Table 1. The data in the table is a partial sample of a database of buildings that serves as input for the analysis.

Table 1: Sample input database of building-level parameters used in analysis

The Plot Number is a unique identifier for the plot in the city; Plot Area is its total area; Floors is total number of stories in the building; Total Floor Area is the summed area of all floors in the building; Roof Area is the open area (available for solar panels, rain water collection etc) on the building’s roof; Usage Type is the utilization purpose (*e.g.* residential, commercial, industrial); Floor Area is the area allocated to a particular Usage Type; Number of Occupants is the estimated number of occupants for each usage type in the building.

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The level of detail, such as shown in Table 1, is available once a master plan has been drafted. The approach used in this study is thus useful at that stage of the planning process where sufficient details are available for making estimates of water and energy use at building-level scale.

Demand Module

This module computes water demand for each building based on its usage type (*e.g*. residential, commercial etc.), number of occupants (where applicable), or floor area. The default demand coefficients (litres/person/day or litres /m^2/day) for different applications are shown in Table A in the Appendix. For each usage type, three kinds of coefficients for low, average and high demand levels have been encoded that can be specified to generate a range of water demands. The water demand for a building is computed as shown in Eq. (1):

$$w_b = c^i p^b + c_c^j a_c^b + c_i^k a_i^b \tag{1}$$

where w_b is the water demand for building '*b*' in litres /day , p^b is the number of occupants expected in building *b*, a_c^b is the commercial/office area in building *b*, a_i^b is the industrial area in building *b*, c^i is the per person demand coefficient at level *i*, c_c^j is the commercial demand coefficient at level *j* and c_r^k is the industrial demand coefficient at level *k*. The values of coefficients are selected based on the specific kind of building. For instance, for a hotel building, the value of c^i ranges from 200 to 400 L/person/day, while for a residence building the value for c^i ranges from 100 to 250 L/person/day for low to high levels respectively (see Table A). The coefficients can be changed as needed for different geographical regions. Note, we do not specifically characterize uncertainty in the calculations, and deal with variations in a simple way by using ranges for the data that are provided in standard handbooks for estimating demand (Mays, 2000). Since the results are primarily intended for use in planning and high-level analysis, we consider this approach sufficient for such purpose.

Building Water Allocation Module

In this module, various water source options available to the building are allocated to each application (kitchen, showers, taps etc.). The default source is reticulated municipal supply for each building. Additionally, each building can be specified to use water from a rainwater tank, on-site recycled (grey) water tank, or recycled water from a

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cluster-level treatment and supply tank. The cluster definitions (if using cluster-level recycling) also need to be provided in which the buildings comprising a cluster are specified.

The water sources rankings for applications are used to appropriately allocate available water supplies to specific use (application) demands. For instance, a building may have the following scheme: water for cooking and human consumption is derived only from the municipal supply, rain water if available can be used for showers, faucets (taps), laundry and toilets (*i.e.* non-potable uses only), and grey water if available can be used only for toilets and laundry. Grey water may also be used for industrial usage and so on. Consider the sample case shown in Fig. 2 where demands for a residential building are shown. Suppose this building was specified as having no rainwater harvesting system, but connected to a cluster-based recycled water supply line (in addition to the default municipal supply). Using the source rankings (as described earlier), the demand volume for the kitchen, showers and taps are associated with the municipal supply, while the demand volume for toilets and laundry is associated with recycled water supply for the building.

Building Energy Consumption related to Water Use

In this module, we model three elements for computing energy consumption related to water use at the building-level: heating, pumping, and on-site recycling (Cheng, 2002; Friedler and Hadari, 2006). The energy consumption of water use associated with the operation of various appliances such as dishwashers, laundry machines *etc*. is factored indirectly in our computation through inclusion of their hot water use.

We assume that at the building-level, three types of water sources maybe available: reticulated supply from the city, rainwater harvested from the roof top, and recycled water produced from on-site treatment units that use wastewater generated within the building. This provision is made to enable the assessment of new hybrid architectures of urban water supply that are increasingly being adopted in many new developments around the globe (Sharma et al. 2009).

Fig. 2 shows a schematic representation of a building with on-site grey water recycling and a rainwater harvesting system. The municipal supply is shown with an additional pump to illustrate the on-site booster pumping that is needed for tall buildings.

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Figure 2: Water source options of municipal supply, on-site recycling and rainwater harvesting and usage of these water different sources (represented through coloured bars on each floor) in a multi-storey building.

Energy for Heating

Energy used for heating water depends on ambient temperature, hot water temperature, and the heater efficiency. In residential uses, hot water is used in kitchen dishwashers, faucets, showers and laundry machines. The energy used for heating water was computed as (Kenway et. al, 2008):

$$E_H = \frac{V_H \rho c \Delta T}{\eta_h} \tag{2}$$

where, V_H is the volume of water heated in the building, ρ is the density of water (1000 kg/m^3), c is the specific heat capacity of water (4185 J/kg-K) and ΔT is the temperature difference between ambient and heated water. The temperature to which water is heated in residential hot water heaters is typically 45^o C – 70^o C (Cohen et al. 2004; Kenway et al. 2008). The parameter η_h is the efficiency of the water heater. For gas heaters, the efficiency typically ranges from 50%-70% and for electric heaters from 75-95% (CECCEC, 2013). In our work we have used a baseline assumption of 70%.

The volume of heated water in a building, V_H, can be computed as:

$$V_H = \sum_{i=1}^{A} \alpha_{h_i} v_i \tag{3}$$

where, v_i is the total volume of water used in application *i*, α_{hi} is the fraction of hot water used in application *i*, and A is the total number of applications in which water is used in the building.

In residential use, we have modelled four applications that use hot water: kitchen, shower, faucets and laundry. In the default case, we use the following fractions based on reported data (Kenway et al. 2008; Racoviceanu and Kamey, 2010): kitchen ($\alpha_{hi} = 0.6$), shower ($\alpha_{hi} = 0.5$), faucets ($\alpha_{hi} = 0.5$) and laundry ($\alpha_{hi} = 0.5$). More detailed analysis can be done by varying these fractions to see the impact on water heating energy requirements. Also note, that the

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assumption here is that all buildings have their own water heaters (and there is no provision of hot water from a centralized source to different buildings).

Energy for On-site Pumping

The reticulated water supply, provided by a utility, is typically at a pressure that is sufficient for providing water up to a certain number of stories in a building. Tall buildings require additional pumping to boost the water supply to the upper floors. This additional pumping is done on-site. There are also additional pumping requirements if supplementary water sources such as rain-water harvesting systems (with storage tanks located on ground-level) or on-site water recycling units are installed in the building (Retamal and Turner, 2010).

The total energy required for pumping water in the building, E_P, is computed in the model as:

$$E_p = e_p\left[\underbrace{\left(V_M \cdot \max\left(F+1-f_M, 0\right)\right)}_{\text{building height}} + \underbrace{V_{RW} F}_{\text{rainwater}} + \underbrace{V_{WW} F}_{\text{recycled wastewater}}\right] \tag{4}$$

where (Cheng, 2002):

$$e_p = \frac{\gamma\, h_F \left(1+\alpha_l\right)}{\eta_p}. \tag{5}$$

F is the number of floors in the building; f_M is the number of floors to which the municipal supplied water can reach without on-site pumping in the building and is typically equal to four. The parameter γ is the specific weight of water, *i.e.* weight of one unit volume of water. For 1 m^3 of water (with a mass of 1000 kg), it is: $\gamma = mg = 9800$ N (g is acceleration due to gravity) (Cheng, 2002).

The variable e_p is the energy (in J) needed to pump one cubic meter of water over one floor of the building with floor height h_F , frictional pipe losses α_l and pumping efficiency η_P (Cheng, 2002). This pumping energy factor is then multiplied with the volume of municipal water supplied V_M, volume of rainwater harvested and supplied V_{RW}, and volume of on-site recycled wastewater V_{WW} along with the number of floors, *F*, over which the water is pumped.

Energy for On-site Recycling

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The energy used for recycling grey water in a building, E_r, depends on the technology used in the recycling units such as membrane bioreactor systems, rotating biological contractor systems etc. (Nolde, 2005) and total volume of water that is treated for re-use. In the framework module, it is computed as:

$$E_r = e_r \sum_{i=1}^{A_g} v_i \qquad (6)$$

where e_r is the energy intensity of the building recycling unit (in J/m^3), v_i is the volume discharged from application i that produces grey water, and A_g is the number of all grey water producing applications (that typically include kitchen, showers, faucets, and laundry).

The total energy consumed for using water in a building is then given by:

$$E_T = E_H + E_P + E_r \qquad (7)$$

Model Outputs

Fig. 3 shows sample results for plot A-01 (described in Table 1) in which it is assumed that rainwater harvesting and on-site grey water recycling is available. A notional time-series (weekly time-step) data of precipitation and temperature were provided as inputs. The weekly water requirement for this plot (as computed by the demand module) is estimated to be approximately 225 m^3 (based on its usage type and a constant occupancy level). The fluctuations in the municipal supply arise due to rainwater utilization (when available) as shown in the top right chart that then reduces the demand for municipal water (as shown in the top left chart). The time horizon used in this example is of 52 weeks (one-year).

Figure 3: Sample results of water and associated energy use in mixed-use (commercial and industrial) building with rainwater harvesting and on-site grey water recycling systems. Top left plot shows estimated water demand for building. Top right plot shows rainwater used in building (based on precipitation data). Bottom left plot shows

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volume of recycled water used. Bottom right shows estimated energy (in electric kWh) associated with water heating (red line), water pumping (blue line) and water recycling (grey line) within the building.

CASE STUDY: MASDAR CITY

Masdar City is a planned urban development located 17 km South-East of Abu Dhabi in the United Arab Emirates (UAE). The city master plan has been designed by the British architectural firm Foster + Partners and is targeted to be a sustainable, zero-carbon, zero waste community (Foster and Partners, 2007). Given the strong upfront focus on environmental sustainability in its planning, we considered Masdar City to be an interesting case to study in detail.

Masdar has a planned area of 6 km^2, and will house 50,000 people, 1,500 businesses, and a technical university. It is expected that more than 60,000 additional workers will commute daily from neighbouring areas. The project was estimated (in 2007) to cost US$22 billion and is targeted for completion by about 2020 (Locke, 2009). The design of the city includes a mix of residential, commercial/institutional and industrial zones, and some of the individual buildings have been designated for mixed (residential and commercial) use. The city has a grid-based plan and consists of two squares. The larger square houses most of the buildings, facilities, and the university. For this case study we have focused only on the larger square. In the study, we used plot-level information from a database provided in the Master plan (Foster and Partners, 2007).

Demand Model Benchmarking

Using the water system description provided in the planning documents (Foster and Partners, 2007), we evaluated the demand model built in our framework. We used the same coefficients for the usage types that had been specified in the plan. For instance, for residential indoor demand, we used 180 litres/person/day as has been assumed in the master plan. Fig. 4 shows a comparison of the computed daily water demand by major building types (shown along the x-axis) as obtained from our model along with data provided in the baseline Masdar water system plan (Foster and Partners, 2007).

Figure 4: Comparison of water demand estimates (for types of buildings shown along x-axis) computed with framework against data in Masdar master plan. SEZ is abbreviation for Special Economic Zone.

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Overall, the computed data (in black bars in Fig. 4) matches reasonably well with the provided data (in grey bars in Fig. 4). In some building types however there are some larger discrepancies, *e.g*. for the University and for the commercial offices. The total computed indoor demand from our model was 13,537 m^3/day while the estimate provided in the city plan document is 11,500 m^3/day. This discrepancy is due to not all the coefficients for all types of buildings being given in the master plan (in which case we used data shown in Table A for calculating water demand).

The demand model not only computes total water requirements, but also breaks down the required water by application type. The breakdown is done for residential and commercial categories for which average data are well known (Cheng, 2002; Mays, 2000) and is provided in Table B in the Appendix. For the industrial case and for certain building types (*e.g*. Hospital), however, only an aggregate demand was computed.

Water Demand Scenarios

In order to investigate the energy consumption in the WES in Masdar, we first created a number of water demand scenarios. There are different building types defined in the Masdar master plan (Foster and Partners, 2007). We aggregated these types into three broad categories: residential, commercial and industrial as shown in Table 2.

Table 2. Masdar Building Types Aggregation into three general categories

[1] SEZ –Special Economic Zone,

[2] ADFEC – Abu Dhabi Future Energy Company

Demand levels were varied between low, average and high for the three aggregated building types (residential, office/commercial, and industrial). For three levels and three types, 3^3 = 27 combinations were possible, and all the 27 possibilities were generated for analysis (see Fig. 5). Table A in the appendix provides details of the demand coefficients used for the different levels.

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Figure 5: Indoor water demand scenarios (shown in blue bars) for Masdar. The letters in the x-axis labels, L, A, and H, indicate demand levels of Low, Average and High for residential, commercial, and industrial sector respectively.

The total daily demand that corresponds closest to the 11500 m^3/day estimate for Masdar in the baseline master plan is associated with the AHA scenario here. The AHA scenario yields a daily water requirement of 11,200 m^3 and corresponds to the average residential, high office/commercial, and average industrial demand case.

RESULTS: ENERGY COSUMPTION FOR WATER USE

For the 27 different water demand scenarios, we estimated the associated energy requirement in the WES. The water supply/source architecture was based on the baseline plan for the city in each scenario. In the baseline plan, it is assumed that buildings receive municipal water (obtained through desalination), and can also use cluster-level recycled grey water. There is no rainwater harvesting system due to extremely low precipitation in the area (WRAB, 2009). At the building level, the energy associated with water use in Masdar as modeled in our framework, is thus only due to water heating in residential and commercial use and booster pumping if the building is higher than four floors.

Furtheremore, in this study, no assumptions of water heating (or cooling) have been made for the industrial sector due to lack of details and data regarding the specific water applications/processes in that sector in Masdar. Masdar is intended to be focused on clean/renewable energy technologies such as photovoltaics and wind power, and therefore we do not expect high water usage as in some industries (such as paper mills, petrochemical plants *etc*.) As a result, it can be expected that the residential sector will constitute a larger share of the energy use due to its water heating applications (that have been factored in this study).

Figure 6: Estimated annual energy requirement for water heating and pumping across all buildings in Masdar for different water demand scenarios.

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Fig. 6 shows the estimated energy required annually for heating water (in thermal kWh) and for pumping municipal water and recycled grey water (in kWh electric) from cluster-level treatment units. It is assumed that the hot water is heated from given ambient temperature (as defined by mean monthly temperature data shown in Table C in the appendix) to a temperature of 50°C. The diurnal patterns and insulation effects have been neglected here.

It can be seen that the pumping energy is two orders of magnitude less than the heating energy. This is because of the high heat capacity of water and also due to the urban form of Masdar in which only low rise buildings, mostly having four or less floors. The maximum number of floors in any building in the city is eight (Foster and Partners, 2007).

We combine the energy for heating and pumping requirements to compute the total WES energy intensity, $\varepsilon_{\text{end-use}}$ using Equation 8 as follows:

$$\varepsilon_{End-Use} = \frac{E_H + \eta_C E_p}{V_{buildings}} \tag{8}$$

The electric pumping energy, E_p, is multiplied with a factor η_C to convert it from electrical to thermal (or primary) energy based on the efficiency of energy conversion in power plants. This conversion factor is typically equal to three, *i.e.* it takes three units of thermal energy to produce one unit of electrical energy (Cohen et al. 2004; Plappally and Lienhard, 2012). $V_{\text{buildings}}$ is the total indoor water demand (which is assumed to be fully met) across all buildings. Fig. 5 shows the computed energy intensity of the WES for the different water demand scenarios in the red line plot. The values vary between ~ 7.8 kWh/m^3 to 12 kWh/m^3. In electrical equivalent (using a factor of 3), this translates to 2.6 – 4 kWh/m^3.

The oscillating pattern can be explained as follows: Consider the first three scenarios: LLL, LLA and LLH. The intensity progressively decreases across the three cases because the total volume of water ($V_{\text{buildings}}$ in Eq. 8) goes up (see Fig. 5). Since no water heating component is modeled for the industrial case, E_H does not increase proportionately with $V_{\text{buildings}}$, as a result $\varepsilon_{\text{end-use}}$ decreases. It can be noted that the three lowest points in the plot all correspond to cases in which the residential sector has low demand (LLH, LAH and LHH), and the three highest points in the plot are for HLL, ALL, and HAL – all cases in which the residential sector has high or average demand. This indicates the dominance of the residential sector in driving the WES energy intensity for Masdar.

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Monthly Variation of WES Energy

In general, monthly variation of the WES can occur due to change in water demand (driven by seasonal effects), availability and use of rainwater and changes in hot water usage levels. For the case of Masdar, the precipitation is negligible (WRAB, 2009), so rainwater harvesting is not considered as a feasible option here. In the study, we assumed the water demand to be constant (which is a reasonable first order assumption for indoor water use). The energy for heating water, however, does vary due to temporal changes in ambient temperature (see Eq. 1). As mentioned previously, we do no account for pipe insulation, and do not include diurnal temperature changes. For a first order estimate, only mean monthly data (shown in Table C) are used. The results from these simplified assumptions can be used for relativistic comparisons across the monthly time-scale and are shown in Fig. 7.

Figure 7: Monthly Energy Requirement for Water Use in Buildings in Masdar

It can be seen that there are appreciable differences in WES energy on a month to month to basis. The line-plots in the figure correspond to different water demand scenarios. It can be seen that the amplitude of the plot across the months (for any particular demand scenario) ranges in magnitudue from ~ 1 GWh to ~ 2.5 GWh. Conservation of water at different times of the year thus has significantly different energy impacts.

Energy savings through hot water use have been subject of discussion in the context of countries with colder climates (Kenway et al. 2008; Racoviceanu and Kamey, 2010), it can be seen that even in hotter regions, such as the UAE, there can be appreciable energy savings with improved building hot water mangement. An interesting possibility for locations with warmer climates is to heat the water using solar-thermal rooftop systems. Such systems are being increasingly adopted (EmiratesNews, 2012) and even mandated (JordanTimes, 2012). However, analysis such as the one presented here can be used for quantifying and evaluating the costs and benefits for installing such systems.

Impact of Water Heating on WES Energy Requirements

Since the water heating energy dominates the WES energy requirement (as shown in Fig. 6), the impact of hot water is investigated in detail. For that purpose, a range of hot water fractions for each of the four applications (kitchen,

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shower, faucets and laundry), α_{hi}, modelled in the framework were used. For each case, the fraction varied from 10% to 70%, and a total of 81 combinations with different levels of hot water use in the four modelled applications were used to obtain a range of associated energy use for hot water.

Figure 8: Monthly variation in water heating energy for varying hot water use levels. The baseline water demand scenario AHA was used.

Fig. 8 shows the variation in heating energy required for water on a monthly basis for different hot water use levels. There are 81 data points for each month, and the results are computed with the assumption of 50°C temperature for hot water. The lowest data points (along the y-axis) correspond to smallest hot water fractions. Note that the impact of reducing the hot water fraction can be significant in the colder winter months of (December though February).

Building-Level Variation in WES Energy

In addition to temporal variation of WES we also explored the spatial variation. In that regard, the computed annual WES energy requirements for each individual building along with its computed water demand was evaluated. Fig. 9 shows the results. Each point in the plot represents computed data for a particular building. The variation in water demand (and primary energy for water use) spans a few order of magnitudes across the buildings (due to the variation in lot sizes, occupancy levels, water use application types etc.) The lines of constant WES energy intensity are drawn to show how the buildings compare on the basis of per unit water use. From Fig. 9 it can be seen that the variation is from 2 kWh/m^3 to 14 kWh/m^3. This type of up front analysis, based on baseline development plans, can be useful in identifying initial targets for improving efficiency and focusing conservation efforts once the buildings have been constructed and operationalized.

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Figure 9: Energy intensity of water use in individual buildings computed using building parameters in planning document for Masdar. Identifying high energy intensity buildings upfront can aid in focusing efficiency plans.

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Energy Consumption Across All Water Segments

For comparative purposes, we also evaluated other major segments of the water system of Masdar City. The energy requirements in the water production, distribution, recycling and sewerage treatment segments were modeled in an aggregate basis using water volume estimates and enegy intensity data from the basline system design as reported in (Locke, 2009) for consistency, and using other published sources as needed.

Using the building demands (for each scenario), the required volume of water for distribution, and desalination was determined. A leakage factor (of 20% as provided in the baseline plan) in the distribution system was also assumed. The grey water volume that is reused along with black water (*i.e.* water from toilets containing human wastes) volume that would be treated for disposal was also determined. In the production segment, desalination through a Reverse Osmosis (RO) system was assumed (as discussed in the master plan) in which the lower range of the electrical energy consumption is 4 kWh/m^3. The distribution system energy intensity is obtained from empirical data of an urban area with flat topography (which is also the case for Masdar) (Kenway et al., 2008). The energy intensity of greywater recycling is based on data provided in (Friedler and Hadari, 2006), and of waste water treatment in (Gleick, 1994). Fig. 10 shows the results (all electrical energy has been converted into primary thermal equivalent).

Figure 10: Energy Required Annually in the Water Segments in Masdar City

It can be seen that the total water-related energy from production to disposal for Masdar City can range from 35 GWh to 93 GWh for various water demand scenarios. For the case in which the water demand matched with the baseline demand in the master plan (AHA scenario), the total annual energy requirement is 76.3 GWh. Compared with the lowest demand scenario, the energy difference is 41.5 GWh or ~14 GWh$_e$. Fig. 10 also shows that the buildings use (end-use) segment has the highest annual energy requirement fraction. This illustrates the potential for energy savings through reduced water use in buildings (particularly in the residential sector).

For a broader perspective of energy intensity in urban water systems, the computed data for Masdar (using our framework) and published data for other cities around the globe is shown in Table 3.

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Table 3. Energy Intensity of Urban Water Segments in Different Cities

a: For Masdar, the End-Use intensity corresponds to the AHA demand scenario

b: based on reported data in (Cohen et al. 2004), table 9

c: based on reported data in (Kenway et al. 2008), Fig 4

d: based on reported data in (Cheng, 2002), pp 264

For the case of Masdar, the End-Use intensity corresponds to the AHA demand scenario (converted into kWh_e from Fig. 5) and is based on our computed results. The intensities for the other segments for Masdar (Supply & Treatment, Distribution and Wastewater Treatment) are based on information in the master plan and other published literature described earlier. For the other cities, the data corresponds to information provided by regional utilities.

Table 3 shows that the energy intensity associated with supply and treatment (production) of water for Masdar (at 4 kWh/m^3) is high. Thus it is imperative for Masdar City that this energy for use by the water system be generated by renewable sources such as wind, solar or geothermal power if it is to live up to its environmental sustainability goals. Also, it should be noted that we have focused on quantifying the energy intensity (and not emissions since that is beyond the scope of this paper). At the most fundamental level, for long-term sustainability it is important to seek a lower energy footprint (no matter whether it comes from fossil fuel or solar power).

Effect of Per Capita Water Demand Reduction

The daily per capita indoor residential demand of 180 litres assumed in the baseline plan for the city (Foster and Partners, 2007) can be considered to be generous if data from other water scarce regions is considered. For instance, in Brisbane, Australia it is 120 L/person/day, whereas 100 and even 60 litres per capita daily demand is reported in literature for some water scarce urban areas (Friedler and Hadari, 2006). It therefore seems reasonable to assume that it maybe possible to achieve lower indoor water use (than what has been planned) for Masdar. The energy impact of reduced per capita water demand in the residential sector was examined, and the results are shown in Fig. 11. The demand was considered from 60 L/person/day to 180 L/person/day, and low levels were assumed for commercial and industrial sectors.

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Figure 11: Energy savings possible (in Masdar City across all buildings) with reduction in daily per capita use. Low level of industrial and commercial water use is assumed here. The slope of the trend is 0.225 GWh/litre, *i.e*. a one litre reduction of per person per day in water use would result in ~ 225 kWh reduction in annual energy consumption in the city.

Compared with the 180 L/person/day demand scenario, the total energy difference with the 120 L/person/day case is ~13 GWh. The results also show that for every unit reduction in residential water use (*i.e*. 1 L/person/day), there can be annual energy savings of 225 kWh. A reduction in end-use water will impact energy used at building-level and therefore energy bill savings for the customers (particularly if water heating is based on electric or gas-fired heaters).

As noted earlier, this analysis, based on draft plans provides estimates to planners. The results can be used to potentially set new baselines (such as shifting to 120 L/person/day from 180 L/person/day) by providing a quantitative basis of the benefits. This can also inform trading and sizing of other inter-dependent design elements such as roof-top photovoltaic systems that are to provide on-site power generation in buildings in Masdar. More importantly, it potentially provides a basis for messaging to future occupants about the impact of their water use on energy consumption and helping to alter consumption patterns. Understanding who enjoys the savings is important for effective messaging and directing appropriate efforts to relevant stakeholders (Sharma et al. 2009). In the interest of lowering energy use and improving environmental sustainability, planners and city water managers can use these types of results to encourage water conservation.

CONCLUSIONS AND FUTURE WORK

A shift from traditional least-cost designs for urban water systems to new solutions that can perform well over their life cycle for multiple objectives (motivated by environmental sustainability) is occurring (Lundie et al., 2004). This work furthers the research on the topic of energy requirements for water end-use in an urban context and is connected to the broader research effort of integrated planning and design of urban infrastructure (Alfaris et al., 2010; de Weck et al. 2011; Siddiqi and Anadon, 2011). The analysis presented here serves as an illustrative example of how water and energy use can be considered in an integrated fashion to inform planning decisions as well as guide policies for water management in future cities.

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For the case study focused on Masdar City – a planned urban area in a region of the Middle East that is under going rapid urbanization – results show that the end-use segment can be expected to be comparable in its energy intensity with the more well known energy intense water production segment (based on desalination). Results summarized in Table 3 and in Fig. 12 collectively showcase the importance of the end-use segment in water-related energy and the impact of residential water use on energy requirements.

At a more general level, the analytical approach described here can serve as an illustrative example for similar evaluation for other areas. Some key insights that can be drawn from this work are that the energy intensity in the WES can be significant as compared to the other segments of the urban water system. When compared with on-site booster pumping and greywater recycling, water heating energy dominates the energy requirements in the WES. While this has been known to be true for cities in colder regions (Clarke, et. al. 2009; Kenway et. al. 2008), we find that even in the warm regions such as the UAE the heating energy for water use can be comparatively large. The importance for solar water heating is thus highlighted here.

We note that the results of this work are based on computations (using building plans data and water demand ranges). A key next step in our future work would be to use actual measurements of water and energy use in buildings for comparison against the predictive results. Some recent work has begun to characterize energy use in buildings (Martani et. al. 2012) using estimated occupancy data of buildings and actual water and energy consumption.

In this study, we accounted for pumping requirements for recycled grey water supplied from cluster-level recycling systems, however in analysis for other planned areas where building-level greywater cycling may be employed, one should include the possibility of energy recovery from the waste water streams.

In this paper, we focused on energy requirements alone and did not include cost considerations. In future work, we plan to incorporate cost assessments so that the trade-offs between centralized municipal supply versus the new hybrid configurations of on-site recycling (and rain water harvesting where applicable), solar water heating versus the more common electric or gas-fired heaters etc. can be analyzed. Ultimately, both cost as well as environmental

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performance data are needed for informing urban planning and design choices.

In the future, we also aim to expand the scope of analysis to investigate issues such as the impact of climate change (manifested through changed precipitation and rainwater availability, ambient temperature change etc.), adoption of new building-level technologies, and expected behavioural shifts in future usage (*e.g*. reduction in per capita use, extent of hot water use etc.). The goal for such analytical effort would be to obtain insights relevant for planners who are re-visiting traditional architectures and are seeking to develop new areas that adhere to higher standards of resource conservation, and strive towards long-term environmental sustainability.

NOMENCLATURE

a_c^b: area in building *b* to be used for commercial/office space [m^2]

a_i^b: area in building *b* to be used for industrial space [m^2]

c: specific heat capacity of water, 4185 [J/kg-K]

c^i: coefficient of per capita water demand for residential use at level *i* [litres/person/day]

c_c^j: coefficient of water demand for commercial space at level *j* [litres /m^2/day]

c_i^k: coefficient of water demand for industrial space at level *k* [litres /m^2/day]

E_H: energy for water heating in a building [J]

E_P: energy for water pumping in a building [J]

e_r: energy intensity of wastewater recycling [J/m^3]

E_r: energy for wastewater recycling in a building [J]

F: number of floors in a building

h_f : height of a building floor [m]

p^b : number of occupants expected for building b

V_H: volume of heated water [m^3]

w_b : in-door water demand for building ‘b’[litres/day]

α_{hi}: fraction of hot water use for application *i* [%]

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α_l: water pipe losses in a building

γ : specific weight of water [N]

$\varepsilon_{end\text{-}use}$: water end-use energy intensity [kWh/m^3]

η_h: water heater efficiency [%]

η_p : building pumping efficiency [%]

ρ: density of water, 1000 [kg/m^3]

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APPENDIX

Table A. Indoor Water Demand Coefficients*

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*Based on data provided in Table 3.2 and 3.3 in (Mays, 2000).

[1] SEZ –Special Economic Zone,

[2] ADFEC – Abu Dhabi Future Energy Company

Table B. Water Fractions by Application*

*Based on data provided in Section 5.2.3 in (Fosters and Partners, 2007).

Table C: Abu Dhabi Mean Monthly Temperature*

*Source: (UAEClimate, 2012).

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Quantifying End-Use Energy Intensity of the Urban Water Cycle

Figure Captions List

Figure 1: Modelling framework with key computation modules (shown as boxes) and inputs and outputs (shown in brackets).

Figure 2: Water source options of municipal supply, on-site recycling, and rainwater harvesting and usage of these water different sources (represented through coloured bars on each floor) in a multi-storey building.

Figure 3: Sample results of water and associated energy use in mixed-use (commercial and industrial) building with rainwater harvesting and on-site grey water recycling systems. Top left plot shows estimated water demand for building. Top right plot shows rainwater used in building (based on precipitation data). Bottom left plot shows volume of recycled water used. Bottom right shows estimated energy (in electric kWh) associated with water heating (red line), water pumping (blue line) and water recycling (grey line) within the building.

Figure 4: Comparison of water demand estimates (for types of buildings shown along x-axis) computed with framework against data in Masdar master plan. SEZ is abbreviation for Special Economic Zone.

Figure 5: Indoor water demand scenarios (shown in blue bars) for Masdar. The letters in the x-axis labels, L, A, and H, indicate demand levels of Low, Average and High for residential, commercial, and industrial sector respectively.

Figure 6: Estimated annual energy requirement for water heating and pumping across all buildings in Masdar for different water demand scenarios.

Figure 7: Monthly Energy Requirement for Water Use in Buildings in Masdar

Figure 8: Monthly variation in water heating energy for varying hot water use levels. The baseline water demand scenario AHA was used.

Figure 9: Energy intensity of water use in individual buildings computed using building parameters in planning document for Masdar. Identifying high energy intensity buildings upfront can aid in focusing efficiency plans.

Figure 10: Energy Required Annually in the Water Segments in Masdar City

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Figure 11: Energy savings possible (in Masdar City across all buildings) with reduction in daily per capita use. Low level of industrial and commercial water use is assumed here. The slope of the trend is 0.225 GWh/litre, i.e. a one litre reduction of per person per day in water use would result in ~ 225 kWh reduction in annual energy consumption in the city.

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Figure 1

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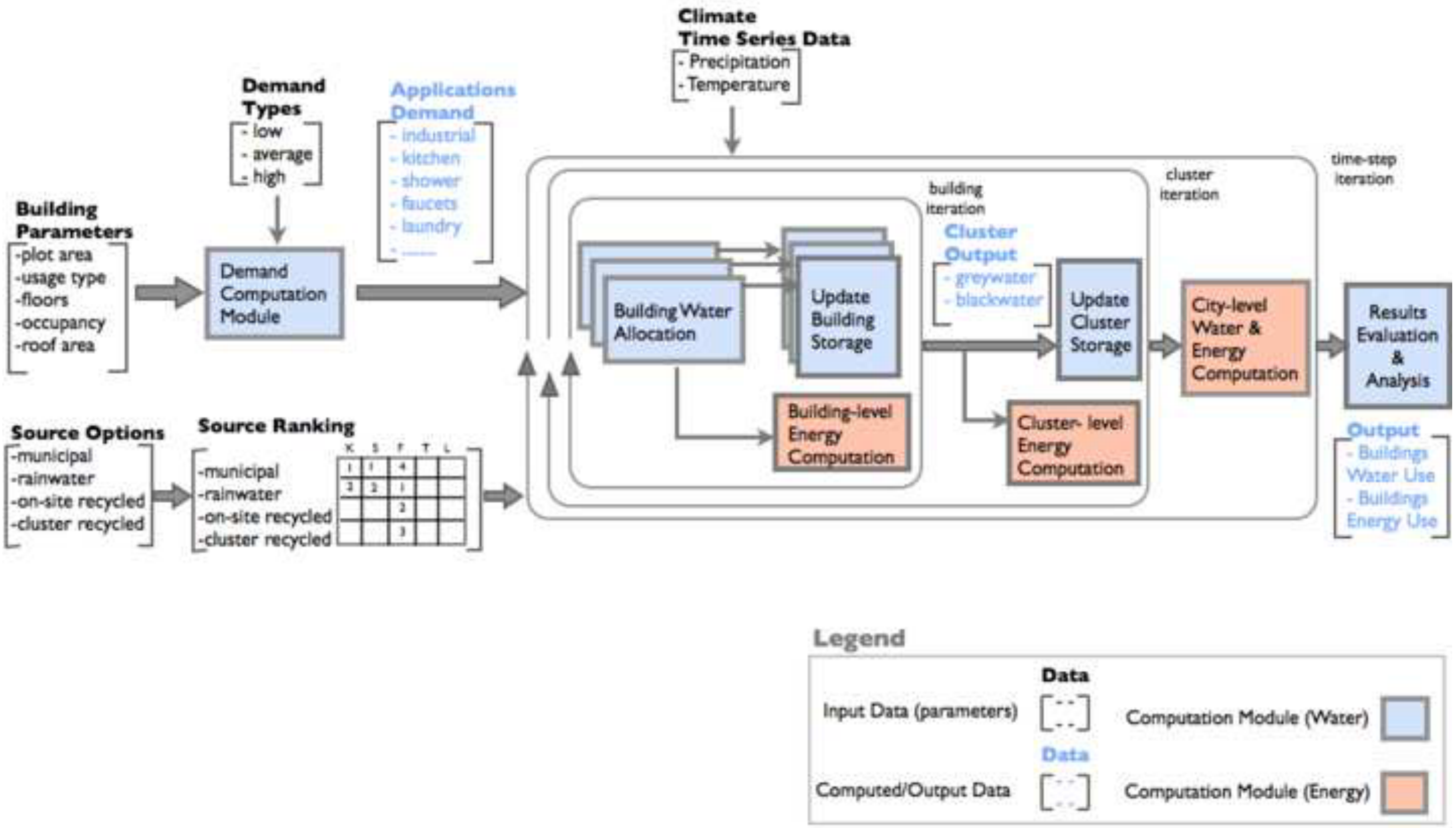

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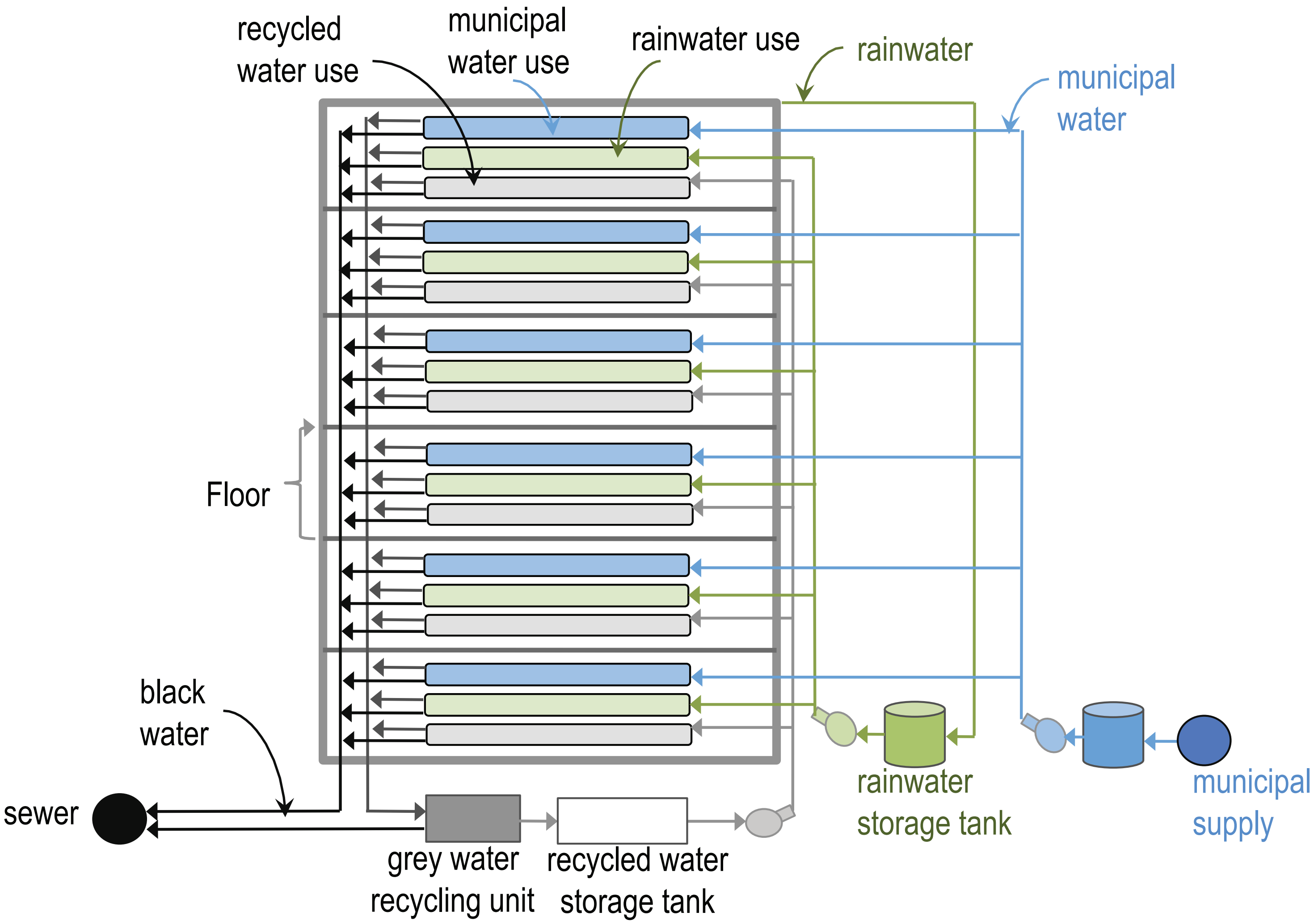

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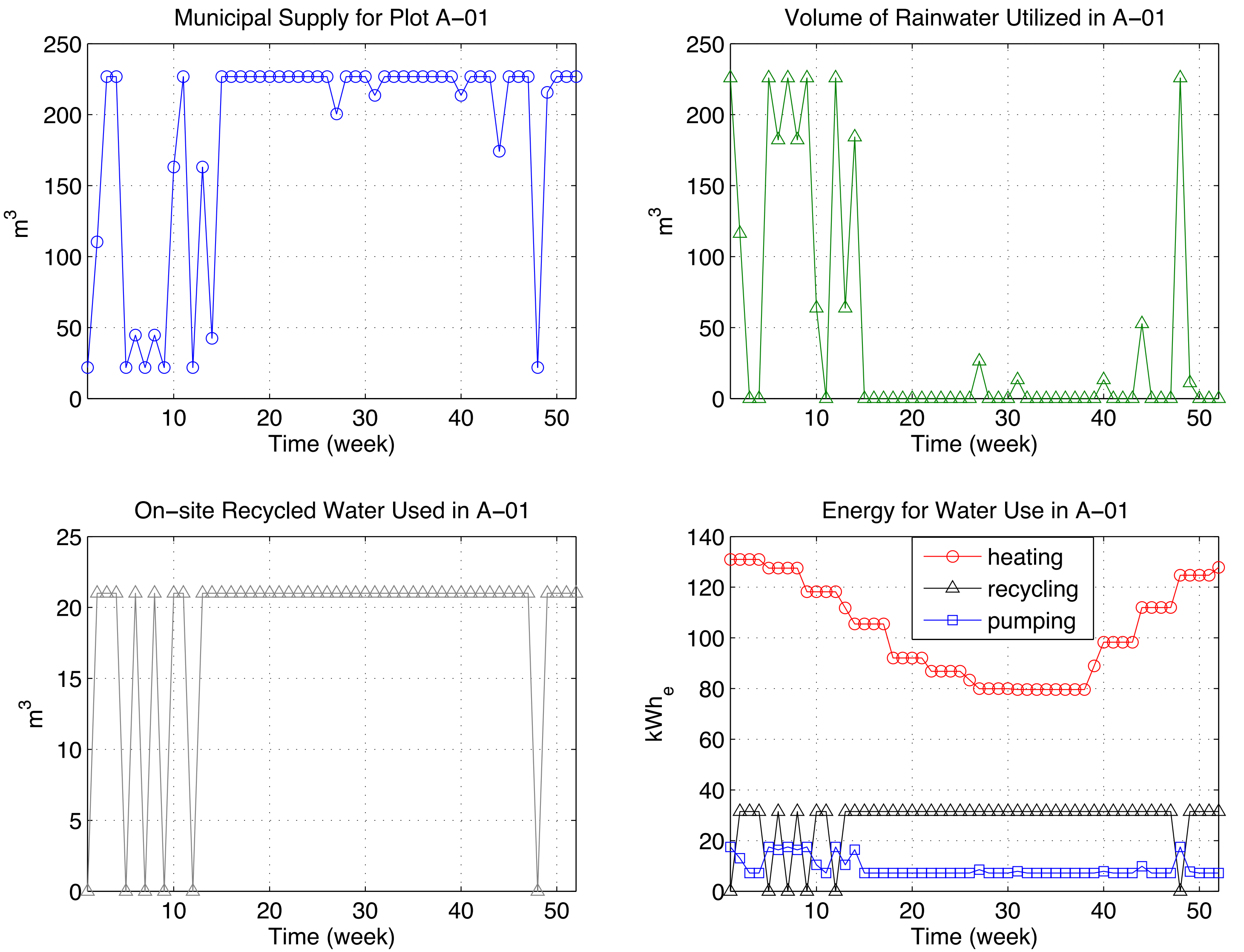

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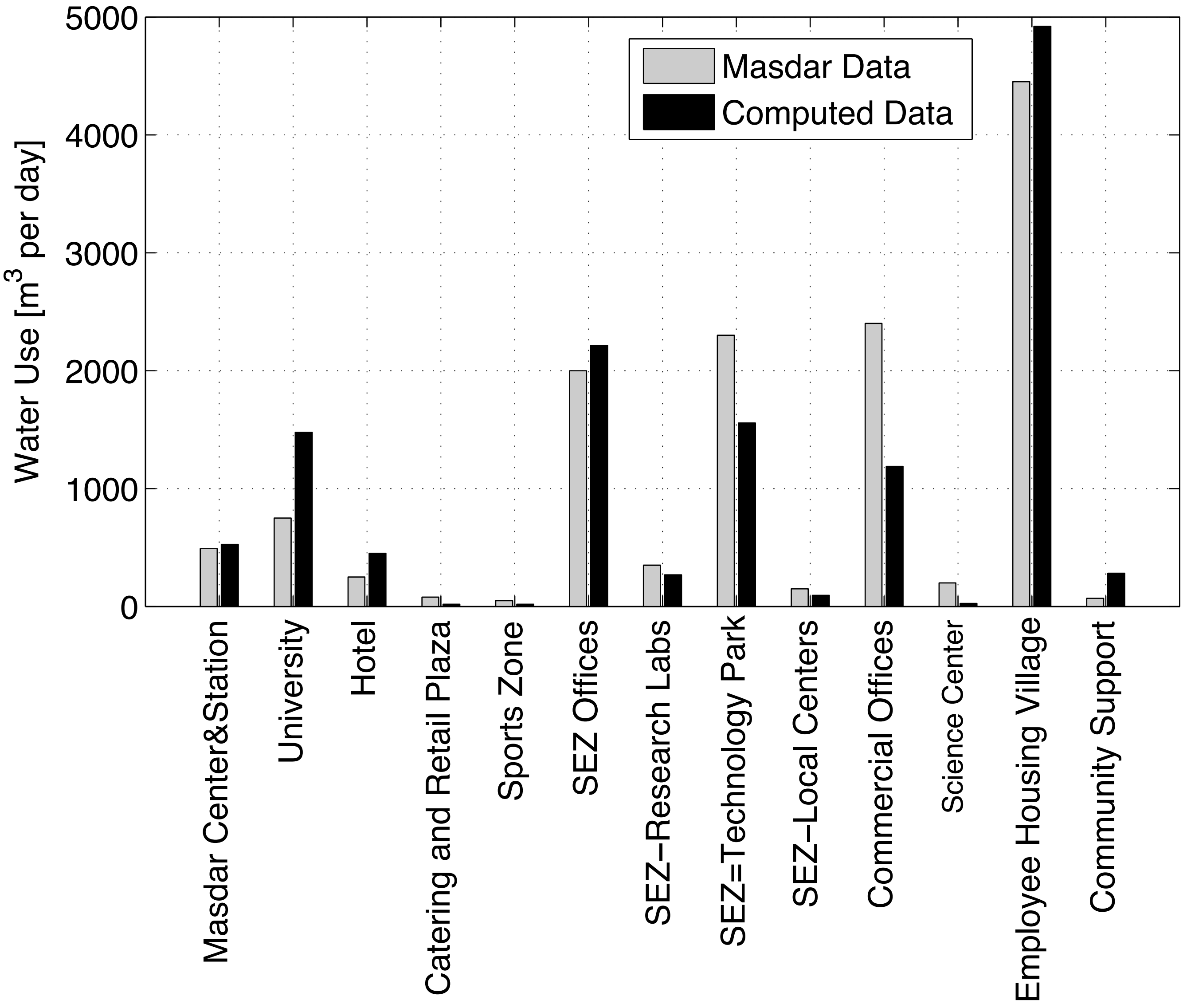

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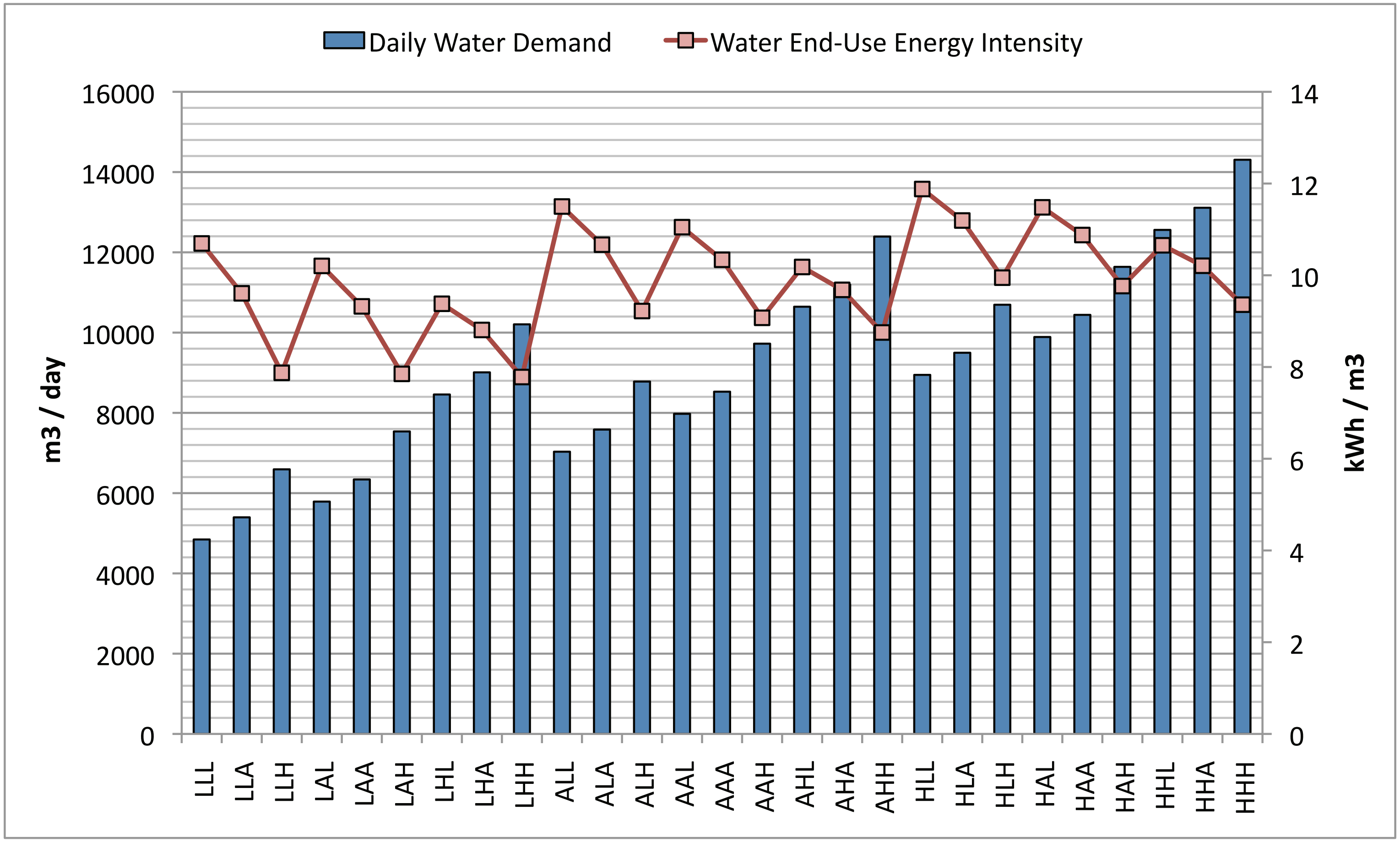

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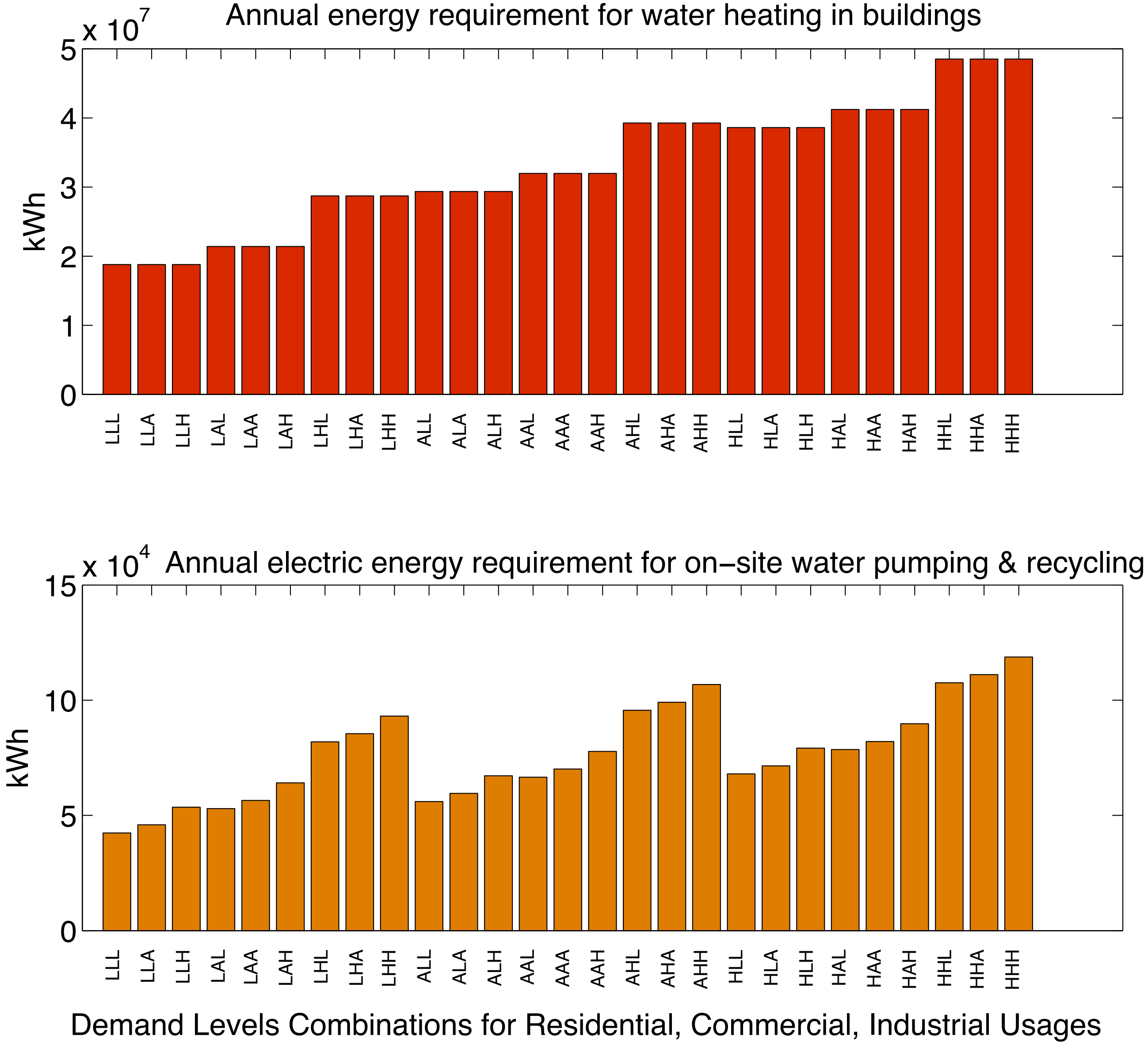

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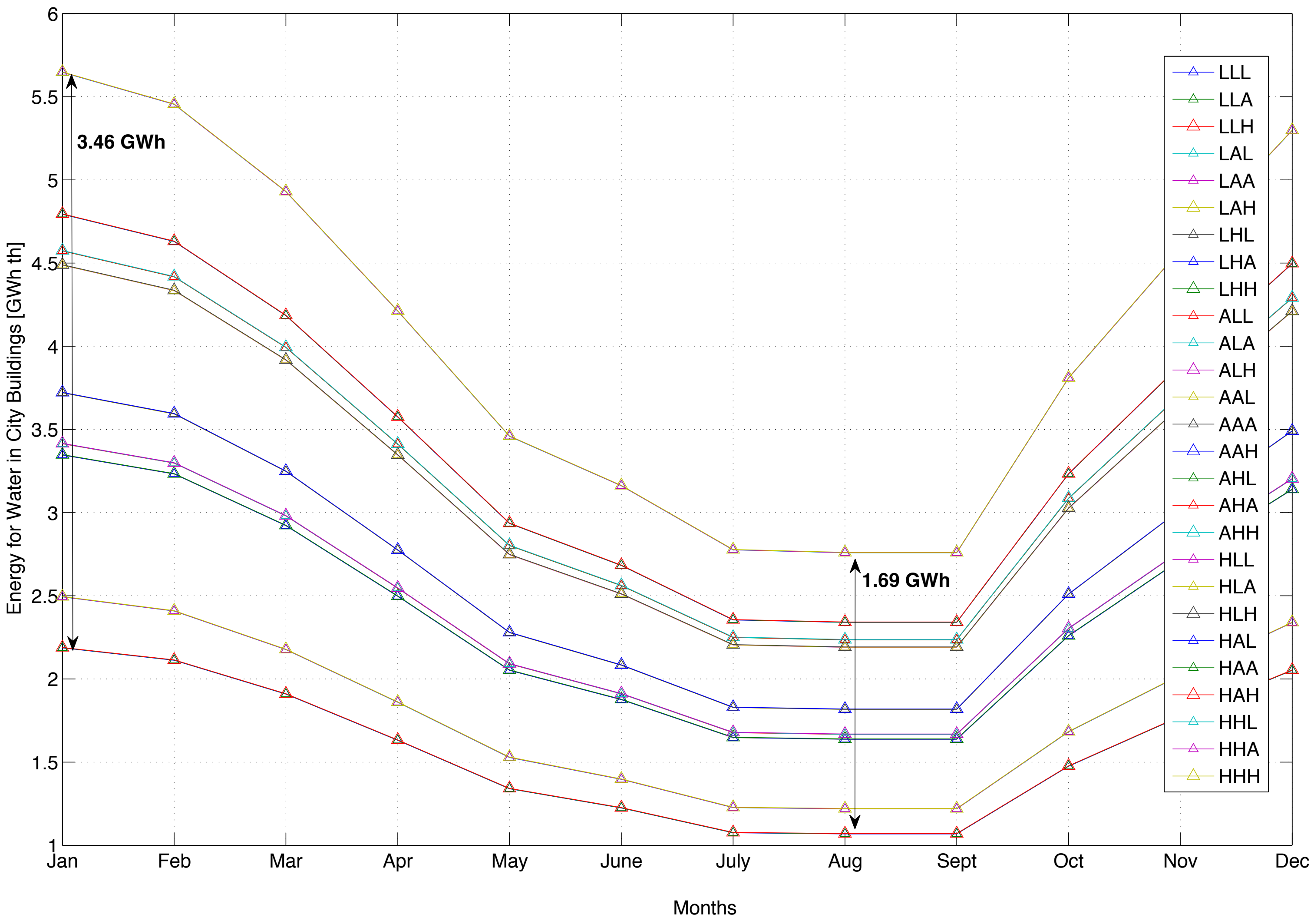

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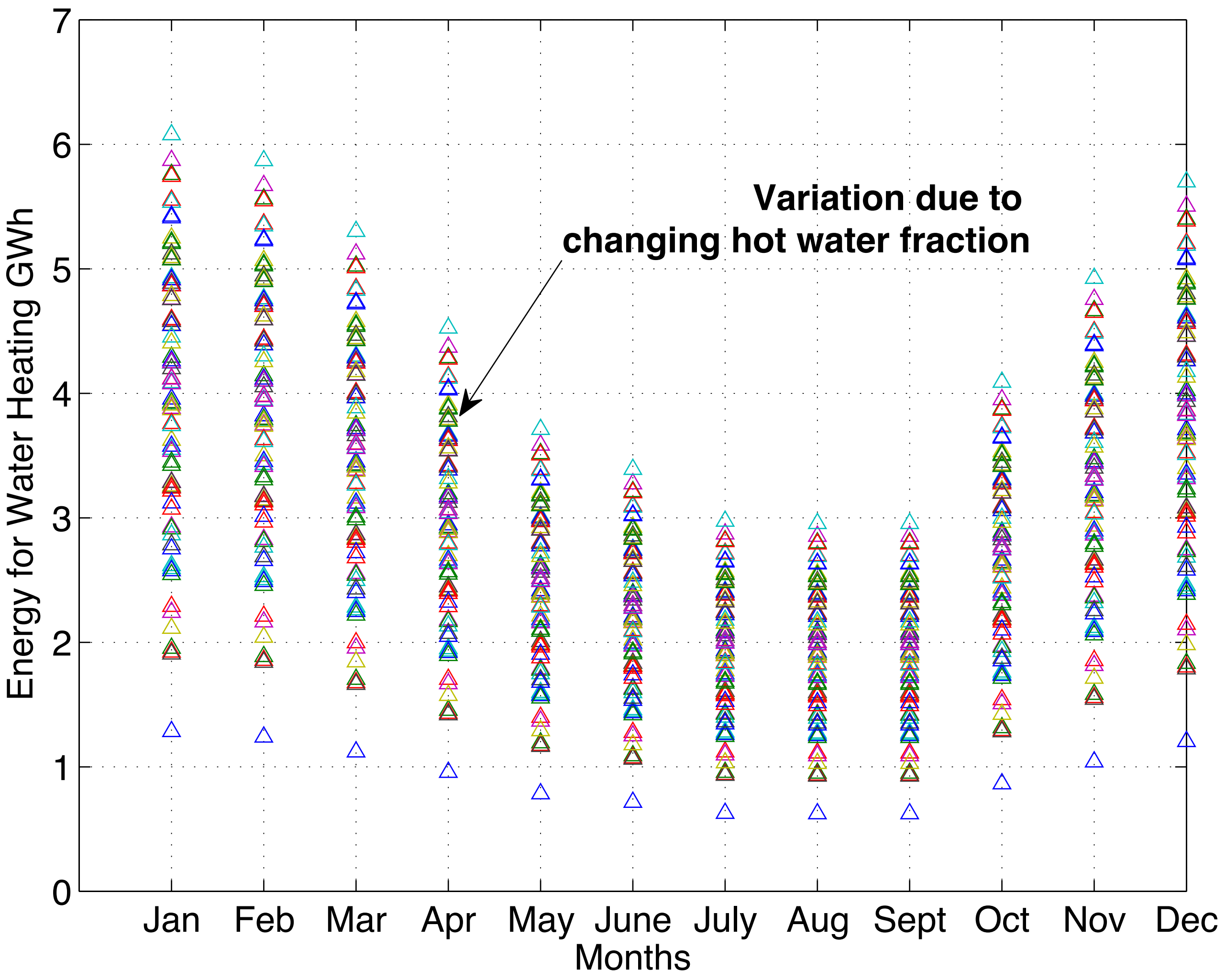

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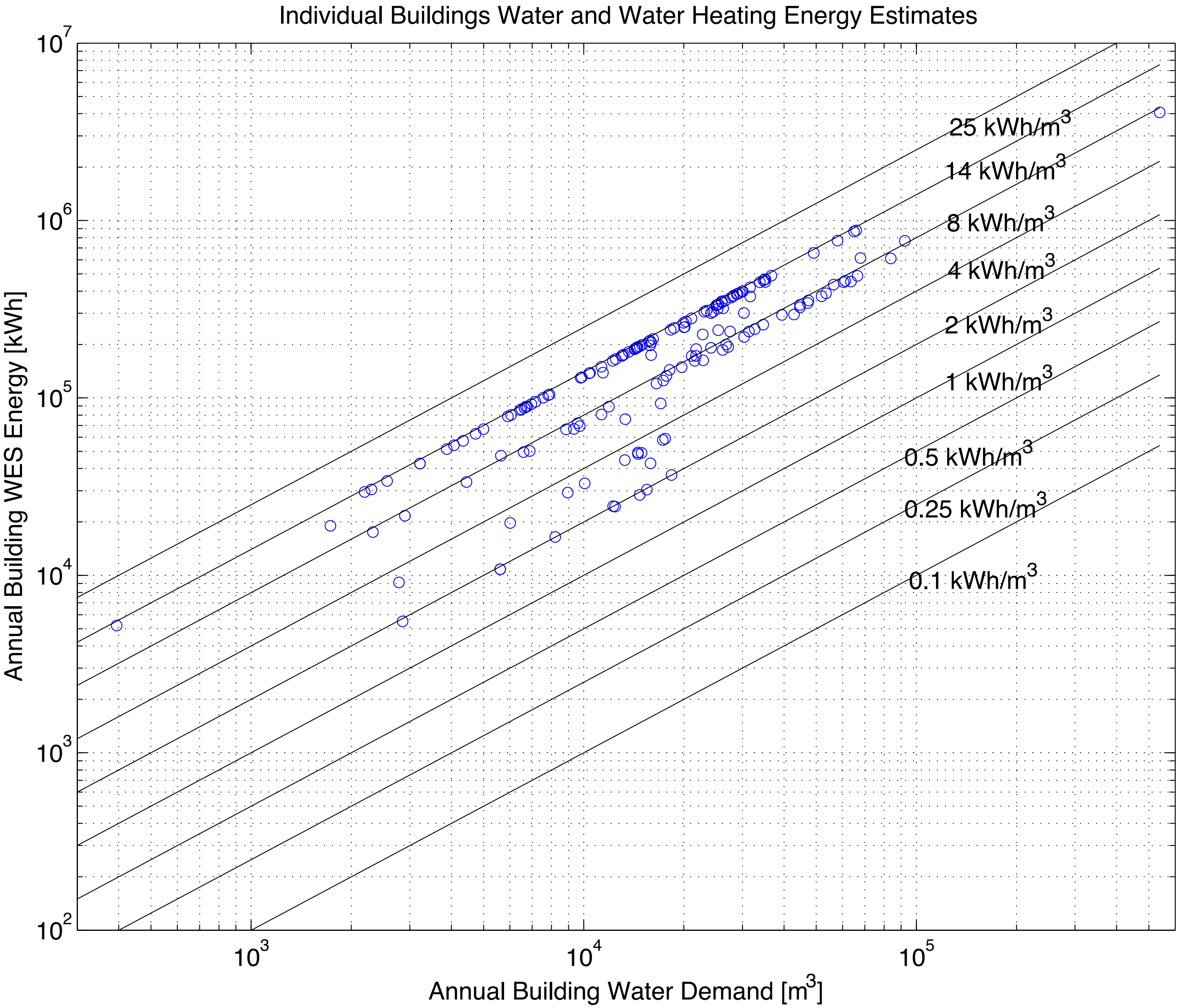

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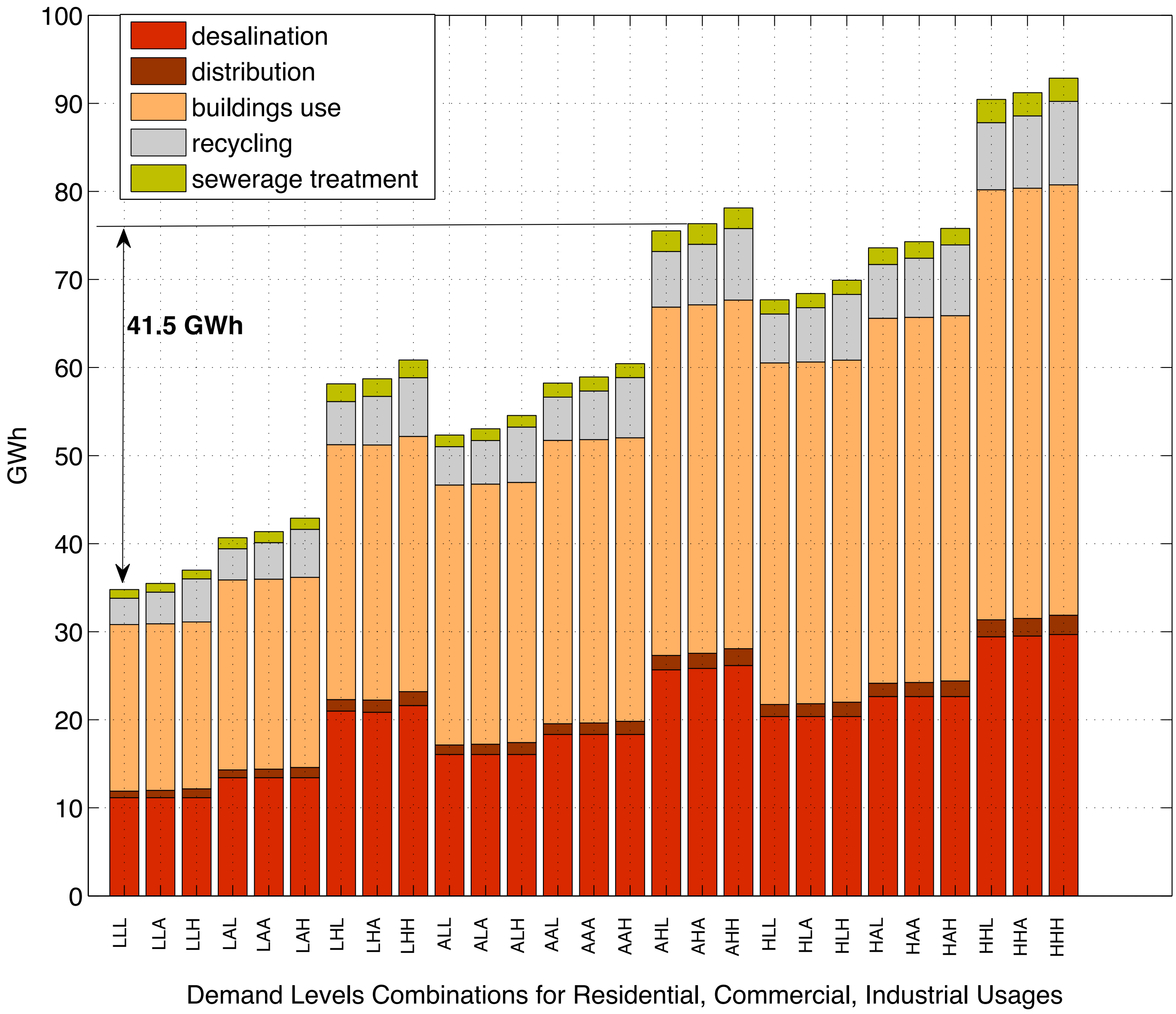

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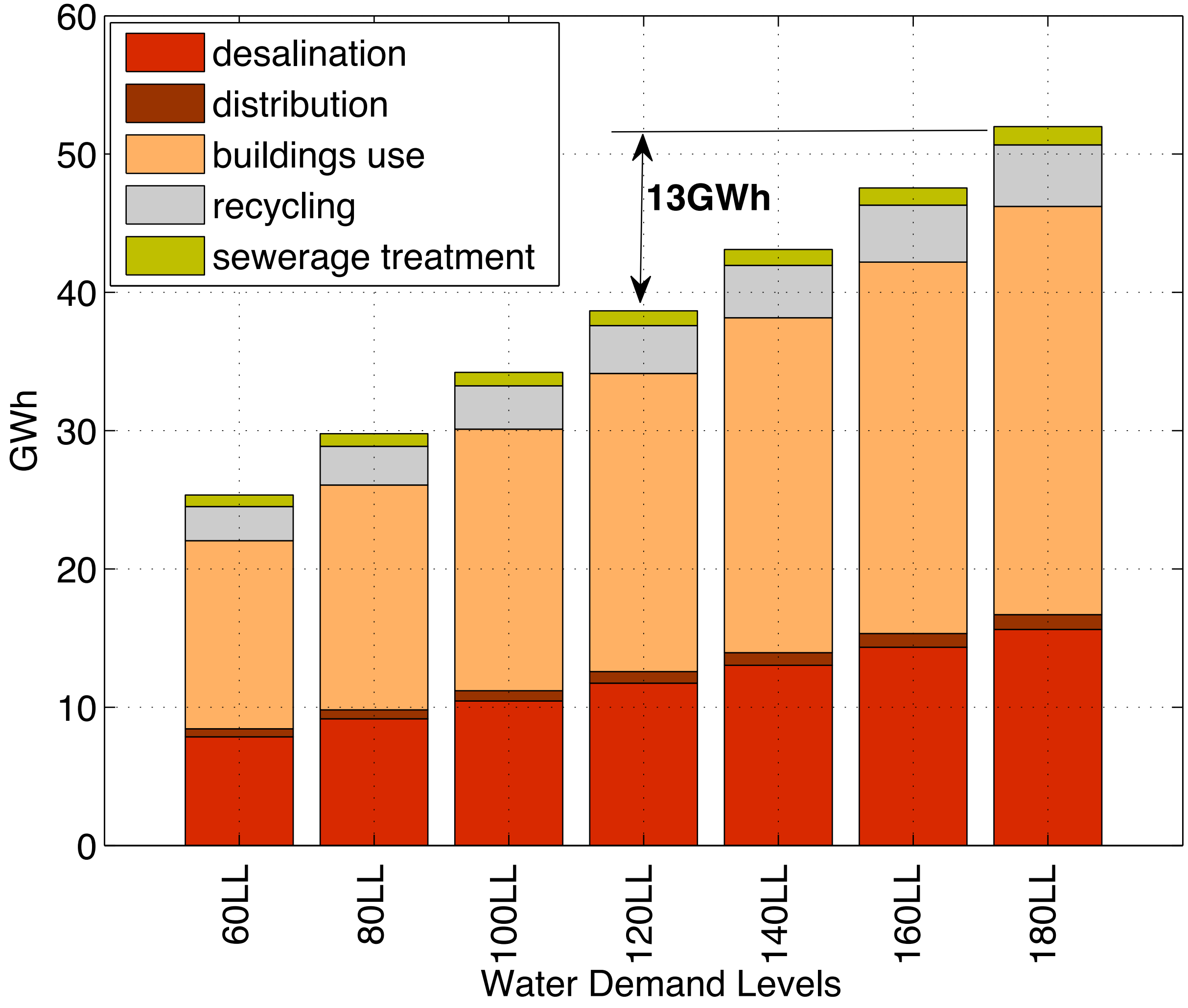

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Table 1: Sample input database of building-level parameters used in analysis

Plot No.	Plot area [m^2]	Floors	Total Floor Area [m^2]	Roof Area [m^2]	Usage Type	Floor Area [m^2]	Number of Occupants
A-01	19,766	5	44,474	14,627	Offices	4,447	222
					Industrial	17,789	198
					Car park	22,237	
A-02	31,844	6	143,298	31,844	Residential	50,154	1,003
					Car park	93,144	
:	:	:	:	:	:	:	:

Table 2. Masdar Building Types Aggregation into three general categories

Aggregate Category	Masdar Building Type
Residential	Residential
Office/Commercial	SEZ[1]-Offices, ADFEC[2] Headquarters, Commercial, Retail, Retail Plaza, SEZ-Local Center, Railway Station, Catering, University, Hotel
Industrial	SEZ-Technology Park, SEZ-Research Labs

[1] SEZ –Special Economic Zone,
[2] ADFEC – Abu Dhabi Future Energy Company

Table 3. Energy Intensity of Urban Water Segments in Different Cities

Segment Intensity [kWh$_e$ /m^3]	Masdar[a]	San Diego[b]	Sydney[c]	Melbourne[c]	Taipei[d]
Supply & Treatment	4	1.70	0.03	0.01	0.21
Distribution	0.14	0.27	0.92	0.11	0.17
Urban Indoor End-Use	3.26	3.16			
Wastewater Treatment	0.41	0.46	0.5	1.14	0.41

a: For Masdar, the End-Use intensity corresponds to the AHA demand scenario
b: based on reported data in (Cohen et al. 2004), table 9
c: based on reported data in (Kenway et al. 2008), Fig 4
d: based on reported data in (Cheng, 2002), pp 264

Table A. Indoor Water Demand Coefficients*

Building Use Type	Units	Low	Avg.	High
Residential	L/person/day	100	180	250
Retail, Retail Plaza, SEZ-Local Centre, Railway Station, SEZ[1]-Offices, ADFEC[2] Headquarters, Commercial	L/m^2/day	1	1.9	4.8
Catering	L/person/day	10	15	20
Hotel, Service Apartments	L/person/day	200	300	400
University	L/person/day	60	70	80
SEZ-Technology Park, SEZ-Research Labs	L/m^2/day	0.2	1.5	4.4

*Based on data provided in Table 3.2 and 3.3 in (Mays, 2000).
[1] SEZ –Special Economic Zone,
[2] ADFEC – Abu Dhabi Future Energy Company

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Table B. Water Fractions by Application*

Indoor Applications	Residential	Commercial	Industrial
Kitchen	0.15	0.09	
Showers	0.2		
Faucets	0.1	0.28	
Toilets	0.34	0.63	
Laundry	0.21		
Industrial Processes			1

*Based on data provided in Section 5.2.3 in (Fosters and Partners, 2007).

Table C: Abu Dhabi Mean Monthly Temperature*

Month	Temperature (C)	Month	Temperature (C)
January	17.9	July	34.3
February	19	August	34.4
March	22	September	34.4
April	26.1	October	28.4
May	30.4	November	24
June	32.1	December	19.9

*Source: (UAEClimate, 2012).

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