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Energy efficiency of elevated water supply tanks for high-rise buildings

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Abstract

High-rise housing, a trend in densely populated cities around the world, increases energy use for water supply and corresponding greenhouse gas emissions. This paper presents an energy efficiency evaluation measure for water supply system designs and a mathematical model for optimizing pumping energy through the arrangement of water tanks in a building. To demonstrate that the model is useful for establishing optimal design solutions that integrate energy consumption into urban water planning processes which cater to various building demands and usage patterns, measurement data of 22 high-rise residential buildings in Hong Kong are employed. The results show the energy efficiency of many existing high-rise water supply systems is about 0.25 and can be improved to 0.26-0.37 via water storage tank relocations. The corresponding annual electricity that can be saved is 160-410 TJ, a 0.1-0.3% of the total annual electricity consumption in Hong Kong.

Keywords

Building, water supply, energy efficiency, water consumption, storage tank location

List of symbols

A	Area (m^2)
C	Constant head pressure
E	Energy (MJ)
E_a, E_d	Annual energy (MJ $year^{-1}$), daily energy (MJ day^{-1})
g	Gravity ($=9.81 ms^{-2}$)
H	Pressure head of water column (m of H_2O)
h	Height (m)
i, j	Building floor counts, $i, j = 1, 2, \ldots n$
N	Number count
O	Occupant area ratio (ps m^{-2})
V	Volume (m^3)
v	Volumetric water demand over a specified period (m^3)
α	Energy efficiency
η_c	Overall transmission efficiency
η_e	Electric motor efficiency
η_m	Mechanical transmission efficiency
η_p	Pump efficiency
ϑ	Random number between 0 and 1

ρ	Water density (=1000 kgm^{-3})

Subscript

0	of reference
$1,2,\ldots n$	of demands $1,2,\ldots n$, from the bottom floor to the top floor
I, II	of cases I and II
a	of annually
B	of building storey
b	of water tank base
c	of water tank base to inlet
d	of daily
f	of friction in upfeed water pipe
ff	of floor to floor
L	of lower zone
l	of water lift
o	of outlet
out	of output
$pump$	of water pump
s	of occupant
U	of upper zone
%	of percentage

Superscript

$\sim$	of distribution

*	of relative
‘	of improvement

1. Introduction

High-rise housing development, a trend in densely populated cities around the world, increases water supply energy consumption. A study of pumping energy use in urban water supply systems showed that the average energy consumption in residential buildings equalled 45% of the total pumping energy needed to deliver water from the treatment plants to households [1].

In Hong Kong, a developed city on hilly terrain with limited usable land for buildings, very tall buildings are a trend in recent developments. Indeed, many newly constructed government-funded residential buildings are over 40 storeys or over 100 m and the current average residential building height in the city is estimated to be 25.8 storeys [2]. The total annual water consumption is about 1200 Mm^3 $year^{-1}$ (i.e. the per capita daily consumption is 408 $Lday^{-1}$), and it will grow to 1315 Mm^3 $year^{-1}$ by 2030 [3]. Correspondingly, water supply systems in buildings account for approximately 1.6% of the total city electricity use according to the expression below, where E_{pump} is the energy use for pumping a volumetric water demand v_{pump}, N_B (=25.8 storeys) is the average building height, constants 3.6 and 60 accounts for unit conversion, 1 indicates additional pump lift of 1 storey height over the building topmost floor, and 1.2 is a lumped value for pump and motor efficiencies, pipe friction and building storey height respectively[1].

$$E_{pump} = 3.6 \times \frac{1.2(N_B + 1)\ v_{pump}}{60} \qquad \ldots (1)$$

As the water pressure head at the government water mains in Hong Kong is insufficient to reach the topmost appliances in almost all high-rise buildings, gravity storage tanks on building rooftops (or on intermediate mechanical floors) are designed for distributing water through down feed pipes [4]. To minimize the problems of water leakage or damage in supply pipes and appliances caused by excessive water pressure on lower floors in low demand situations, proper working pressure limits (e.g. 100-450 kPa) can be maintained using pressure reducing valves (PRV). PRVs with adjustable settings and screwed joints are commonly installed to maximize application flexibility.

Although energy efficiency is a major concern for sustainable high-rise developments, there is no existing measure that systematically addresses the issue with respect to the optimal design and operation of high-rise water supply systems. Design solutions which integrate effective energy use into water planning process should be developed so as to save energy, reduce waste and protect our environment [5,6]. This paper proposes an energy efficiency evaluation measure for water supply system designs in buildings. Verification measurements in some high-rise residential buildings of Hong Kong are used to demonstrate the applicability of the evaluation model. Energy performance targets for some system designs, together with estimated energy savings potential are also derived.

2. Energy efficiency of building water supply systems

Water supply by an elevated reservoir over a town is used and this arrangement has been commonly adopted in buildings by locating a roof tank. However, both systems are not identical in terms of energy efficiency. Figure 1 illustrates these two water supply system designs: (a) an elevated water tank that feeds demands with little height differences (e.g. an elevated water tower over a town); (b) a roof tank that feeds distributed demands with large height differences (e.g. a roof tank on top of a building). For a high-rise building, the system design is characterised by the water lift demand height ratio h_l^* given by Equation (2), where $(h_n - h_1)$ is the height difference between the demands at the top and bottom for demand height $i = 1,2,...n$ and h_l is the water lift height.

$$h_l^* = \frac{h_n - h_1}{h_l} \qquad \text{… (2)}$$

The water lift height h_l is the sum of the height measured from the tank base to the tank inlet h_c - approximated by the tank volume V_c, the height difference between the demand n and the tank base h_b, and the height difference between the water surface (i.e. of the reservoir in design (a) or of the break tank in design (b)) and the top demand location h_n,

$$h_l = h_c + h_b + h_n ; h_c \sim V_c^{1/3} \qquad \text{... (3)}$$

The water lift demand height ratios for system designs (a) and (b) are $h_l^* = 0$ and $h_l^* > 0$ respectively. For a high-rise building, the ratio $h_l^* \sim 1$ is dominated by the demand heights $h_l \sim h_n$ and $h_b + h_c << h_n$.

The desired minimum water pressure head H_o, say 5m (H_2O) in some design practices, is assumed at the demand point and the friction head required in the upfeed water pipe H_f is taken as a portion of the pipe length (i.e. 10% of h_l) [7],

$$H_o = 5; H_f = 0.1 h_l \qquad \text{… (4)}$$

Consider the case of uniformly distributed demands along the building height (i.e. $v_1 = v_2 = ... = v_i = v_n = v$), the demand heights h_i, where $i = 1,2,...n$, for the two designs (a) and (b) are expressed by,

$$\begin{cases} h_l^* = 0 : h_1 = h_2 = \ldots = h_n \\ h_l^* > 0 : h_2 - h_1 = h_3 - h_2 = \ldots = h_n - h_{n-1} = C_{ff} \end{cases} \quad \ldots (5)$$

E_{out}, (MJ) the potential energy for the water demands at height h_i (i.e. 'output energy' of a design) is given below, where ρ (=1000 kgm^{-3}) is the water density and g (=9.81ms^{-2}) is the gravity,

$$\forall h_l^* : E_{out} = \rho g \sum_i v_i h_i ;\ i = 1,2,\ldots n \quad \ldots (6)$$

It can be rewritten for both designs,

$$\begin{cases} h_l^* = 0 : \quad E_{out} = \rho g n v h_n \\ h_l^* > 0 : \quad E_{out} = \rho g n v \left(\dfrac{h_1 + h_n}{2} \right) \end{cases} \quad \ldots (7)$$

The 'input energy' of both designs is the pumping energy of lifting water up to the tank E_{pump} (MJ) as defined below, where η_c is the design overall transmission efficiency,

$$\forall h_l^* : E_{pump} = \frac{\rho g n v h_l}{\eta_c} = \frac{\rho g n v \left(H_o + H_f + h_n + h_b + h_c \right)}{\eta_c} \quad \ldots (8)$$

Energy efficiency, which is the 'output energy' divided by the 'input energy', is a measure of pumping energy performance. It can be determined for the water supply systems using the heights, pipe friction and allowable pressure head,

$$\alpha = \frac{E_{out}}{E_{pump}} ; \begin{cases} h_l^* = 0 : \quad \alpha = \dfrac{h_n \eta_c}{5 + 1.1\left(h_n + h_b + h_c \right)} \\ h_l^* > 0 : \quad \alpha = \dfrac{\left(\dfrac{h_1 + h_n}{2} \right) \eta_c}{5 + 1.1\left(h_n + h_b + h_c \right)} \end{cases} \quad \ldots (9)$$

Table 1 exhibits some example design parameters for building water supply systems. A top demand height $h_n \geq 10$ m, i.e. a height of 3 storeys, was chosen for illustration. The design overall transmission efficiency η_c (34-62%) accounted for 50-80% of the pump efficiency η_p, about 90%-100% of the mechanical transmission efficiency η_m accounting the power transmission between the motor and pump, and 70-90% of the electricity motor efficiency η_e [8]. For simplicity, constant efficiencies are assumed: $\eta_p = 0.65$, $\eta_m = 0.9$, $\eta_e = 0.9$, and $\eta_c = 0.5625$,

$$\eta_c = \eta_p \eta_m \eta_e \qquad \dots (10)$$

According to Figure 2, the values of energy efficiency α for water supply system designs of h_l^* between 0 and 1 using the design numbers in Table 1 are approaching 0.5 and 0.25 for $h_l^* = 0$ and $h_l^* > 0$ respectively with an increased height h_n.

$$\begin{cases} h_l^* = 0: & \alpha = \dfrac{\eta_c h_n}{5 + 1.1(h_n + 13)} = \dfrac{\eta_c h_n}{19.3 + 1.1 h_n} \\ h_l^* > 0: & \alpha = \dfrac{\eta_c \left(\dfrac{h_n + 1}{2}\right)}{5 + 1.1(h_n + 13)} = \dfrac{\eta_c (h_n + 1)}{38.6 + 2.2 h_n} \end{cases} \qquad \dots (11)$$

$$h_n \to \infty : \begin{cases} h_l^* = 0 : \alpha \sim \dfrac{\eta_c}{1.1} \sim 0.5 \\ h_l^* > 0 : \alpha \sim \dfrac{\eta_c}{2.2} \sim 0.25 \end{cases} \qquad \dots (12)$$

It is noted that for a residential building height of up to 300 m in Hong Kong, the energy efficiency values are 0.44 and 0.24 for designs (a) and (b). The design parameters h_b, h_c, h_n, H_o have significant contributions to the energy efficiency.

3. Water demand model

A water demand model is required to calculate the water consumption at height from Equation (6). The average daily water consumption on a floor $v_{i,d}$ is determined by Equation (13), where $N_{s,i}$ is the number of occupants on floor i, $v_{s,d}$ is the average daily per-capita water consumption, $O_{s,i}$ is the occupant area ratio on floor i and A_i is the total apartment area on floor i [9],

$$v_{i,d} = N_{s,i} v_{s,d} \, ; \; N_{s,i} = O_{s,i} A_i \qquad \ldots (13)$$

A number of studies approximated the regional profiles of occupant area ratio O_s and average daily per-capita water consumption $v_{s,d}$ in buildings by parametric distribution functions as shown in Table 1 [10,11]. Parameters $v_{s,d}$ and $O_{s,i}$ in Equation (13) can be determined via Monte Carlo simulations at percentile $v_{s,d}, O_{s,i} = \vartheta \in [0,1]$ through the distribution functions $\tilde{v}_{s,d}$ and $\tilde{O}_s$, where ϑ is a random number taken from a pseudo random number set generated by the prime modulus multiplicative linear congruential generator [12]. The pseudo set has been applied in a number of engineering applications with reasonable predictions made [5,13].

$$\int_{-\infty}^{v_{s,d}} \tilde{v}_{s,d} \, dv_{s,d} = \vartheta \in [0,1] \, ; \; \int_{-\infty}^{O_{s,i}} \tilde{O}_s \, dO_s = \vartheta \in [0,1] \, ; \; v_{s,d} \in \tilde{v}_{s,d} \, ; \; O_{s,i} \in \tilde{O}_s \qquad \ldots (14)$$

The total (daily) water consumption is used to calculate the pumping energy input to a building water supply system,

$$n v_d = \sum_{i=1}^{n} v_{i,d} \, ; \; E_{pump} = \frac{\rho g h_l \sum_{i=1}^{n} v_{i,d}}{\eta_c} \qquad \ldots (15)$$

4. Survey

A survey of 22 government-funded residential buildings in Hong Kong (Table 2) was used to examine the validity and applicability of the proposed water demand model and the energy efficiency measure. It was noted that the apartments were rented to lower-income families.

In each of the sampled buildings, water secured from the city mains was stored in a break tank and transferred through a pair of transfer pumps to the rooftop gravity tanks for distribution to every floor of the building. There are two separated water supply networks in Hong Kong – one for fresh water supply and the other for seawater flushing; only one old building was using freshwater for water closet flushing and had no separate flushing water tank.

The buildings varied from 15 to 40 storeys, with an average height of 29 storeys. Number of apartments, apartment floor area, roof tank volumes and demand heights of all buildings are summarized in Table 2. Demand distributions in some buildings were vertically uneven as indicated through the number and size of apartments. The heights of bottom demand (h_1) were below 5 m, except for Building 2 (27.6 m) and Building 18 (15.7 m). The data of height difference between the tank base and the top demand (i.e. h_b) were 10 m or less, except for Buildings 3 (12 m), 4 (11.5 m) and 18 (14.5 m). Heights between any two (vertically) consecutive demands were about 2.7 m.

5. Results

In the surveyed buildings, electricity energy use was metered continuously for 24 hours for all water supply pumps to determine the total daily pumping energy (input energy to the system) consumption as presented in Table 2. It was noted that a single-day energy consumption monitoring period might fall between two roof tank filling cycles i.e., cases of the roof tank empty or in full and the corresponding energy to fill-up the roof tank can be taken as the error of energy estimates. In this study, the probable errors of measurement were taken at a half of this error and indicated as error bars in Figure 3.

Figure 3 shows the predicted daily pumping energy consumption against the measured one for the surveyed buildings. The predictions, which were based on typical pump efficiency details displayed in Table 1, reasonably agreed with the measurement results. The predicted average daily water consumption of a floor $v_{i,d}$ at height h_i was used to determine the output energy E_{out} (Equation (6)) for the buildings and thus the energy efficiency of existing roof tank design as shown in Table 2.

Figure 4 plots the energy efficiency against the top demand height, with cases $h_l^* = 0$ and $h_l^* > 0$ shown for comparison. As expected in roof tank designs, energy efficiency values obtained for the surveyed buildings were close to the lower side of $h_l^* \sim 1$. A few cases were found below $h_l^* \sim 1$ for two reasons: (1) demands were unevenly distributed and dominated by more occupants on lower floors (Buildings 4 and 8), (2) there was an excessive height difference between the tank base and the tank inlet (h_b; Buildings 3 and 18). Buildings 2 and 17, in which the bottom demand locations (h_1) were higher, gave higher energy efficiency (~0.28).

6. Application and energy implications

The energy efficiency of a high-rise building can be optimized by the proper arrangement of water storage tank(s). Two example designs are illustrated below:

(I) One supply tank for each demand height

An individual tank is reserved for every floor ($h_l^* = 0$) in a building. Based on the data in Table 1, the energy efficiency α_I is given by the average energy efficiency of all individual floors,

$$\alpha_I \sim \frac{1}{h_n - h_1}\int_{h_1}^{h_n} \frac{h_n}{34.3 + 1.96h_n} dh_n = \frac{1}{h_n - h_1}\left[\frac{h_n}{1.96} - 8.93\ln(34.3 + 1.96h_n)\right]_{h_1}^{h_n}; \; h_1 \geq 0 \qquad \ldots (16)$$

or expressed in discrete function, assuming floor-to-floor height, C_{ff} , is constant.

$$\alpha_I \sim \frac{1}{n}\sum_{i=1}^{n} \frac{h_i}{34.3 + 1.96h_i} \; ; \; h_1 \geq 0 \qquad \ldots (17)$$

The calculated values of α_I for the 22 surveyed buildings using this arrangement are shown in Table 2 and Figure 4. The arrangement offers energy efficiency improvements ranging from 11 to 55%. The energy efficiency improvement α' (in percentage $\alpha'_{\%}$) is expressed by,

$$\alpha' = \alpha_I - \alpha_{h_l^* > 0}; \; \alpha'_{\%} = \left(\frac{\alpha_I}{\alpha_{h_l^* > 0}} - 1\right) \times 100\% \qquad \ldots (18)$$

It is noted that using more riser pipes in this arrangement causes energy loss and energy may not be saved for top demand height $h_n <$ 20 m. However, the improvement becomes significant for greater h_n, e.g. $\alpha'_{\%} = 46\%$ and 73% for $h_n =$ 100 m and 200 m respectively.

(II) One roof tank and one intermediate tank

Demands v at height h in an n-storey building are subdivided on the j-th floor and zoned vertically into the upper (U) and lower (L) zones, where C_{ff} is the floor-to-floor height,

$$v = \{v_1, v_2, ...v_j\}_L \quad , \{v_{j+1}, v_{j+2}, ...v_n\}_U \; ; \; h = \{h_1, h_2, ...h_j\}_L \quad , \{h_{j+1}, h_{j+2}, ...h_n\}_U \qquad \ldots (19)$$

$$h_j = h_1 + (j-1)C_{ff} \; ; \; h_{j+1} = h_j + C_{ff} \; ; \; h_n = h_1 + (n-1)C_{ff} \qquad \ldots (20)$$

Correspondingly, the energy output E_{out} is,

$$\begin{cases} E_{out,L} = \rho g \sum_{i=1}^{j} v_i h_i = \rho g j v \left(h_1 + \dfrac{(j-1)C_{ff}}{2} \right) \\ E_{out,U} = \rho g \sum_{i=j+1}^{n} v_i h_i = \rho g (n-j) v \left(h_1 + \dfrac{(n+j-1)C_{ff}}{2} \right) \end{cases} \qquad \ldots (21)$$

The water tank size is assumed proportional to the demands and the height of tank inlet h_c is given by,

$$\begin{cases} h_{c,L} = \sqrt[3]{V_c \; j/n} \\ h_{c,U} = \sqrt[3]{(1 - j/n)V_c} \end{cases} \qquad \ldots (22)$$

The energy input E_{pump} is,

$$\begin{cases} E_{pump,L} = \dfrac{\rho g j v \left(H_o + H_{f,L} + h_1 + (j-1)C_{ff} + h_{c,L} + h_b \right)}{\eta_c} \\ E_{pump,U} = \dfrac{\rho g (n-j) v \left(H_o + H_{f,U} + h_1 + (n-1)C_{ff} + h_{c,U} + h_b \right)}{\eta_c} \end{cases} \qquad \ldots (23)$$

The energy efficiency α is,

$$\begin{cases} \alpha_L = \dfrac{h_1 + \dfrac{(j-1)C_{ff}}{2}}{\dfrac{\left(H_o + H_{f,L} + h_1 + (j-1)C_{ff} + h_{c,L} + h_b \right)}{\eta_c}} = \dfrac{\eta_c \left(2h_1 + (j-1)C_{ff} \right)}{2\left(H_o + 1.1\left(h_1 + (j-1)C_{ff} + \sqrt[3]{V_c \; j/n} + h_b \right) \right)} \\ \alpha_U = \dfrac{h_1 + \dfrac{(n+j-1)C_{ff}}{2}}{\dfrac{\left(H_o + H_{f,U} + h_1 + (n-1)C_{ff} + h_{c,U} + h_b \right)}{\eta_c}} = \dfrac{\eta_c \left(2h_1 + (n+j-1)C_{ff} \right)}{2\left(H_o + 1.1\left(h_1 + (n-1)C_{ff} + \sqrt[3]{(1-j/n)V_c} + h_b \right) \right)} \end{cases}$$

$$\ldots (24)$$

The overall energy demand efficiency is determined by,

$$\alpha_{II} = \alpha_L \, j/n + \alpha_U (1 - j/n) \quad \ldots (25)$$

This arrangement offers energy efficiency improvements $\alpha'_{\%}$ of 1% to 24% as exhibited in Table 2. Figure 5 graphs the energy efficiency ranges of this arrangement for a building when h_1 = 4.2 m, V_c = 40 m^3, and n = 20 (0.21-0.26), 40 (0.23-0.28), 60 (0.25-0.29) and 80 (0.25-0.3). As there are additional pipe frictions in the separated piping networks, no significant energy savings can be achieved when the intermediate tank is close to the roof or the lowest floor. The optimal height for zoning is about the middle height of the building, i.e. $j \sim n/2$. Figure 6, in which a building height of 25.8 storeys (current average residential building height in Hong Kong) is highlighted, shows the annual energy output $(E_{a,out})$ for the water demands against building height, and the corresponding annual energy input $(E_{a,pump})$ for the roof tank systems with energy efficiency values α in between 0.25 and 0.45. It can be seen that energy consumption is proportional to building height. For the height of 25.8 storeys, $E_{a,out}$ is 456 TJ and corresponds to an energy input of 1822 TJ (1.2% of Hong Kong's total electricity consumption (149366 TJ)) at $\alpha = 0.25$ (of only roof tank arrangement). Figure 7 depicts the potential energy savings through efficiency improvements α'. It demonstrates that the potential annual energy can be saved for Hong Kong is 410 TJ $(\alpha' = 0.06)$ if design arrangement (I) is adopted or 160 TJ $(\alpha' = 0.02)$ if design arrangement (II) is taken up.

7. Conclusion

Energy efficiency in buildings is a sustainable development strategy in Hong Kong. It is necessary to develop a method to systematically address energy efficiency with respect to the optimal design of high-rise water supply systems. This paper presented an energy efficiency evaluation measure for water supply system designs and developed a mathematical model for optimizing pumping energy through the arrangement of water tanks in a building. The model was demonstrated to be useful for establishing optimal design solutions that integrate energy consumption into urban water planning processes which cater to various building demands and usage patterns. The results showed that the energy efficiency of many existing high-rise water supply systems was about 0.25 and could be improved to 0.26-0.37 via water storage tank relocations. The corresponding annual electricity could be saved was 160-410 TJ, a 0.1-0.3% of the total annual electricity consumption in Hong Kong.

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Figure 1. Gravity tank systems

Figure 2. Energy efficiency for water supply systems in high-rise buildings

Figure 3. Daily pumping energy consumption of 22 residential buildings in Hong Kong

Figure 4. Energy efficiency α_I of water supply systems

Figure 5. Energy efficiency α_{II} of a water supply system with roof and intermediate gravity tanks

Figure 6. Annual energy consumption for building water supply system

Figure 7. Potential energy savings through efficiency improvements

Table 1. Selected number of design parameters for building water supply systems.

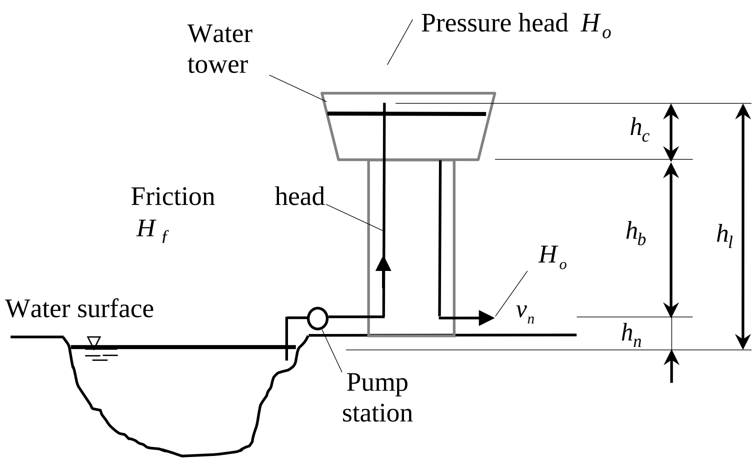
Pump efficiency η_p		0.65
Mechanical transmission efficiency η_m		0.90
Electric motor efficiency η_e		0.90
Total water storage tank volume V_c (m^3)		27
Height between tank base and the last demand location h_b (m)		10
Height of the bottom demand location h_1 (m)		1
Height of the top demand location h_n (m)		≥10
Height of the tank inlet measured from tank base h_c (m)		3
Friction head loss in pipes H_f (m)		$0.1h_l$
Minimum water pressure head allowed at the outlet H_o (m)		5
Occupant area ratio O_s (ps m^{-2}) [10]	(public residential)	0.085 (0.03)
	(private residential)	0.096 (0.04)
Yearly per-capita water consumption (m^3 ps^{-1} $year^{-1}$) [9,11]	(freshwater)	70 (13)
	(seawater)	22 (10)

Standard deviation shown in brackets

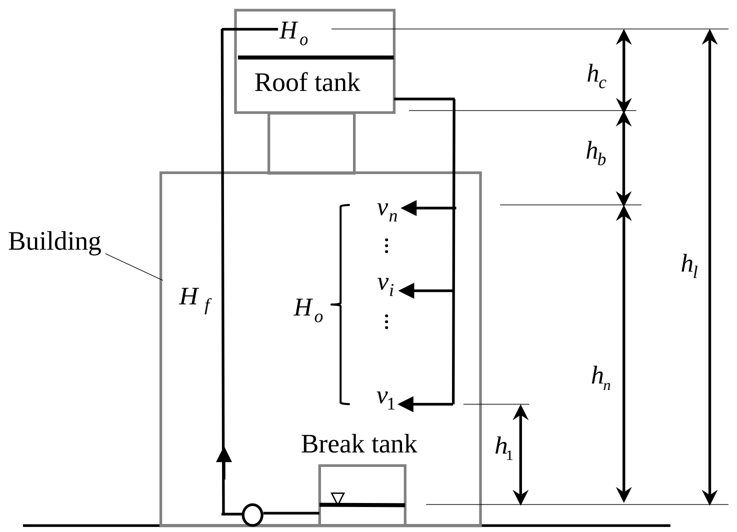
Table 2. Survey of 22 residential buildings in Hong Kong

No.	Storeys N_s	Apartments per storey	Apartment floor area (m^2)	Height h_1 (m)	Height h_n (m)	Height h_b (m)	Height h_l (m)	Tank volume V_c (m^3) Fresh water	Tank volume V_c (m^3) Flushing water	Measured daily pumping energy $E_{d,pump}$ (MJ)	Energy efficiency α Roof tank only	Energy efficiency α (I) One tank per floor	Energy efficiency α (II) One interme-diate tank
1	38	18	17-42	4.6	104.5	9.8	118	49	27	1043	0.24	0.35	0.28
2	38	18	17-49	27.6	126.6	9.0	139	50	27	1309	0.28	0.36	0.32
3	40	20	17-42	4.6	109.9	12.0	126	53	27	918	0.24	0.35	0.28
4	40	18-25	16-49	4.6	109.9	11.5	125	58	27	1068	0.23	0.35	0.28
5	40	20	17-42	4.6	109.9	9.5	123	55	27	934	0.24	0.35	0.28
6	36	18	32-49	4.5	99.0	6.5	109	55	27	1422	0.24	0.34	0.27
7	26	17	17-49	4.2	71.7	5.4	80	26	17	516	0.24	0.31	0.26
8	26	15-25	16-49	4.2	71.7	5.4	80	36	12	667	0.23	0.31	0.26
9	40	20	17-42	4.6	109.9	9.0	123	54	27	986	0.24	0.35	0.28

10	17	33	21	3.0	44.7	2.6	50	18	0	230	0.24	0.27	0.24
11	20	33	21	3.2	52.4	2.6	58	36	53	564	0.24	0.28	0.24
12	18	33	21	3.6	47.8	2.9	55	56	27	261	0.24	0.27	0.24
13	18	61	21	4.2	48.4	2.9	56	80	38	498	0.24	0.27	0.24
14	27	30	33-44	4.6	72.2	2.9	78	20	13	637	0.25	0.31	0.26
15	25	15	34-63	3.6	66.0	7.8	76	16	17	345	0.23	0.30	0.26
16	27	15	33-44	3.6	71.2	5.5	80	23	13	369	0.24	0.31	0.26
17	23	34	39-51	15.7	72.9	5.9	82	26	26	629	0.28	0.31	0.30
18	40	10	33-56	4.0	111.3	14.5	129	29	14	379	0.23	0.35	0.28
19	46	10	33-56	4.5	128.3	10.3	142	29	15	500	0.24	0.37	0.28
20	19	16	34-54	3.6	51.7	5.2	60	16	11	318	0.23	0.27	0.25
21	23	22	33-53	3.6	62.3	6.3	72	33.5	16.3	424	0.23	0.30	0.25
22	35	36	27	3.8	92.2	7.7	104	79	47	1264	0.24	0.33	0.27



(a) $h_l^* = 0$



(b) $h_l^* > 0$

Figure 1. Gravity tank systems

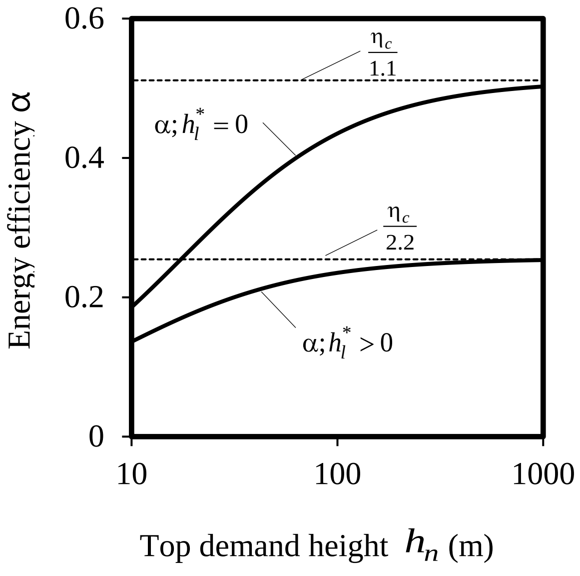


Figure 2. Energy efficiency for water supply systems in high-rise buildings

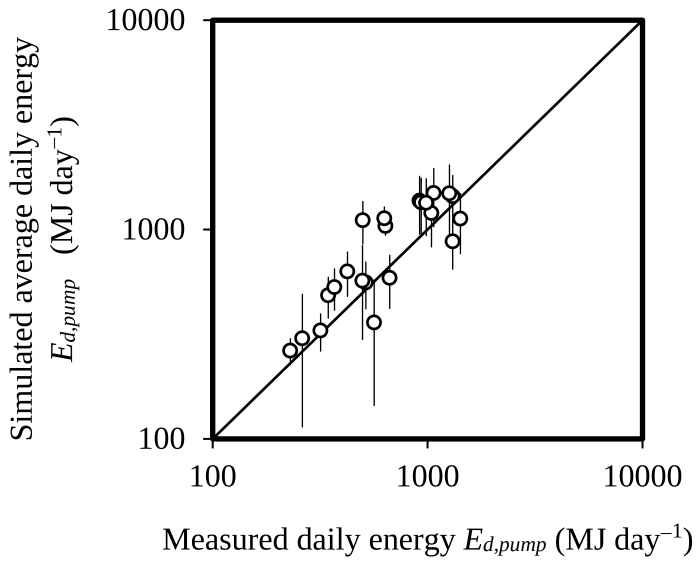


Figure 3. Daily pumping energy consumption of 22 residential buildings in Hong Kong

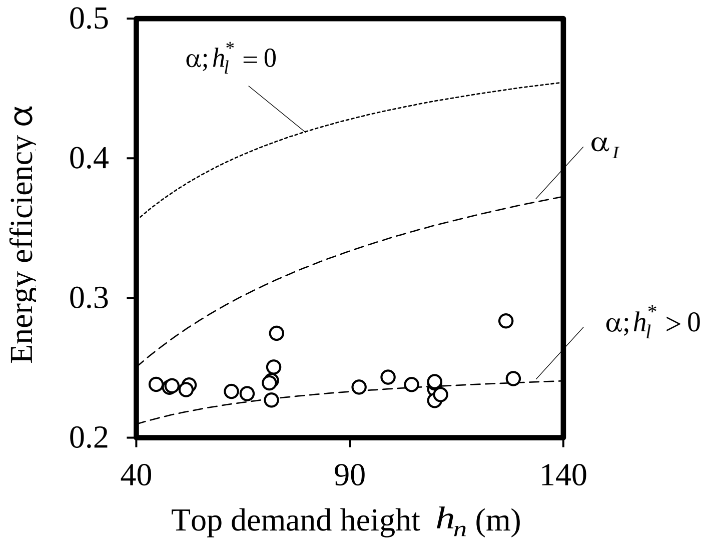


Figure 4. Energy efficiency α_I of water supply systems

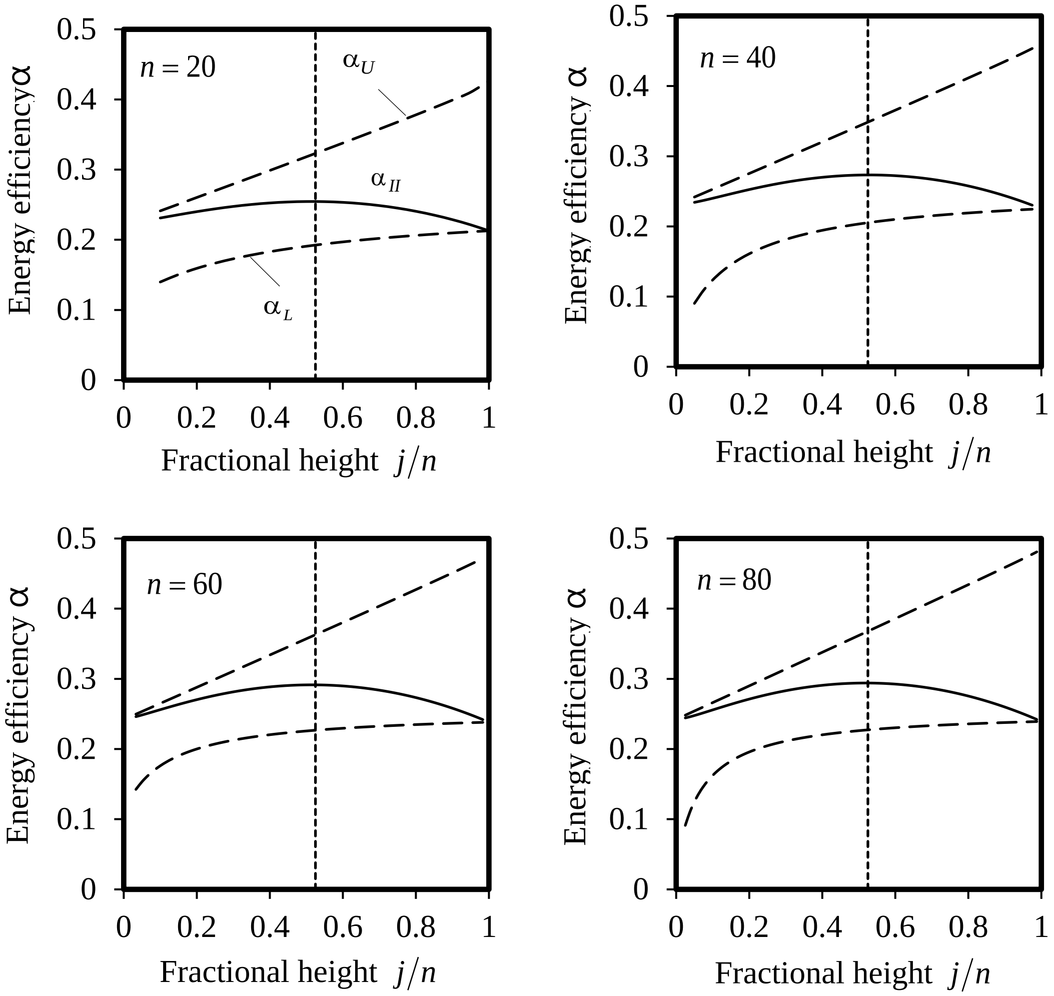


Figure 5. Energy efficiency α_{II} of a water supply system with roof and intermediate gravity tanks

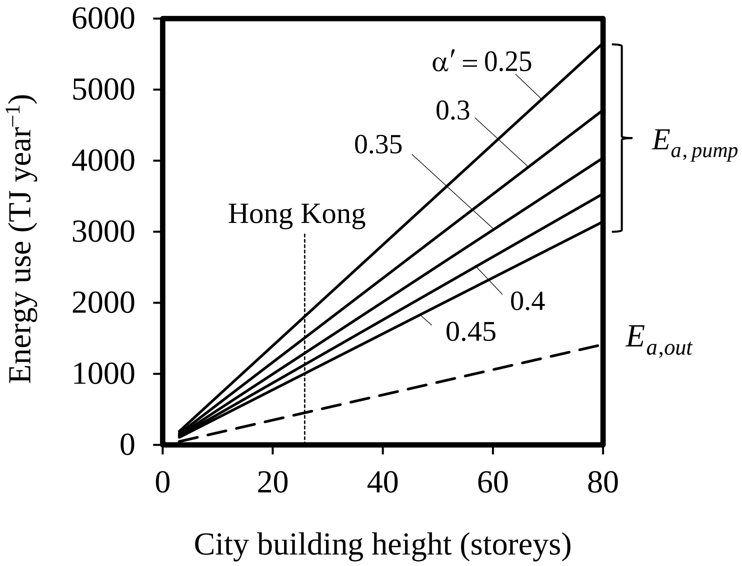


Figure 6. Annual energy consumption for building water supply systems

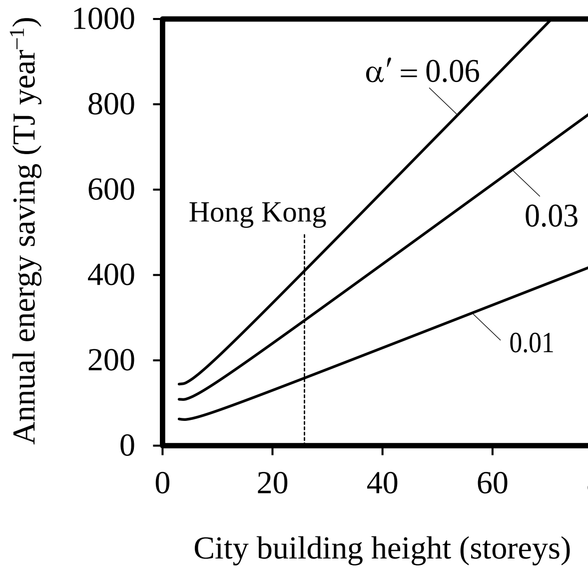


Figure 7. Potential energy savings through efficiency improvements