EMPIRICAL PREDICTION OF OFFICE BUILDING LIFT ENERGY CONSUMPTION

Dr Paul Bannister, Chris Bloomfield, and Haibo Chen
Exergy Australia Pty Ltd, Canberra, Australia
Paul@xgl.com.au

ABSTRACT
Simulation packages have not traditionally considered lift energy as a variable for explicit modelling. However, with the increasing emphasis in the use of simulation to predict post-construction energy use, there is an increasing need to develop improved methods for predicting lift energy in a manner that is likely to inform technology choice and post-construction monitoring.

In this paper, the results of a significant survey of lift consumption in office buildings in Australia are presented. Empirical correlations have been developed that link energy use to basic technology and building size variables, permitting a degree of customisation of the benchmarks to individual buildings.

The importance of lift energy in total energy use is confirmed by the finding that in the 57 buildings surveyed, 8.4% of the total base building (i.e. all consumption other than tenant light and power) energy bill was attributable to lifts.

The results also indicate significant potential for energy efficiency in lift consumption, particularly through selection of lift technology.

INTRODUCTION
Most simulation packages provide well defined methodologies for the prediction of lighting and air-conditioning energy. However, actual building consumption includes a number of significant energy end-uses outside these services, of which lifts constitute a significant item. While the theoretical prediction of lift energy is possible, the use of empirically derived correlations can provide a simpler approach that is well grounded in reality and does not require a detailed understanding of lift technology.

This paper reports the results of an empirical study into lift energy use in office buildings in Australia, one of the outcomes for which was the development of empirical correlations that represent the energy use of lifts as a function of basic building size variables and lift technologies.

The work reported in this paper constitutes part of a wider investigation into lift energy consumption in lift energy use in offices and hotels, which was funded by the Australian Government Department of Climate Change and Energy Efficiency.

PROJECT STRUCTURE
The project consisted of a series of key steps:

- Examination of the range of technologies available to existing and new office buildings.
- Identification of the building and technological parameters that impact lift energy consumption and assess the significance of their influence.
- Gathering of sample data on the population of lifts in Australian office buildings.
- Development of empirical correlations between building and technological factors and total lift energy consumption in formats suitable for use with individual buildings and overall building population assessment.

This paper covers the data gathering and collation and the development of empirical correlations. Further details of the larger project may be obtained by application to the Department of Climate Change and Energy Efficiency via the authors.

DATA COLLECTION
Industry Data Collection
There is little data available internationally on lift energy consumption. Recent studies by Nipkow and Schalcher (2006) and the E4 Consortium (2010) have provided some insights into the patterns of lift energy use, highlighting in particular the remarkably large amount of energy associated with stand-by operation. However, neither of these references provides data in a format that enables forward benchmarking of lifts for new projects. As a result, the project focussed on data collection as a fundamental component of the overall methodology. Data was collected with the assistance of a Technical Advisory Group (TAG). This group consisted of key stakeholders in the lift services sector, including lift manufacturers, commercial property owners/managers and lift services consultants.

As part of the data collection exercise, a questionnaire was distributed asking a variety of...
technical and operational questions, with data requested falling into one of three major categories

- Building characteristics – such as Net Lettable Area (NLA), occupancy hours, building height, fire stairs accessibility and building quality (PCA grade). This information was provided by the building facility managers.
- Lift characteristics – such as hoist mechanism, drive type, rise height, floors serviced and other technology related information. This information was provided by the lift contractors, which was usually the equipment manufacturers or vendors.
- Metered building and lift energy consumption – This was a mix of third party utility metered data, on site sub metered data and temporary logging.

Sample Data
Of the data received, a total of 57 office building responses with sub metered lifts were used in the development of the office building lift energy consumption benchmark. The 57 responses cover over 1,400,000 m² of total NLA (net lettable area, being the space leased to tenants), which is approximately 6.1% of the total Australian office market (PCA 2010).

For buildings within the data sample, the measured lift energy use represented between 1.3% and 17% of the base building energy consumption and averaged 8.4% over the entire sample. The base building energy consumption is the energy of all building services except tenancy lighting and tenancy plug loads. This indicates that lifts are a significant contributor to total building consumption and are thus worthy of more detailed consideration than perhaps has been the case to date.

The data presented in this report was obtained from electricity meters installed on lift motor room electricity distribution boards. These boards typically include coverage for the lift drives, controls, lift car services, lighting and air-conditioning to lift cars and the lift motor room. The reported energy consumption variously does or does not include energy associated with heat rejection from the lift motor room air-conditioning unit, depending upon the circumstances of the individual building. Analysis of the sample data did not reveal any significant impacts relating to the inclusion of lift motor room servicing.

Sample Data Distributions
The demographic distribution of survey responses are tabulated below:

<table>
<thead>
<tr>
<th>STATE</th>
<th>No. of Buildings</th>
<th>No. of Lifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACT</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>NSW</td>
<td>31</td>
<td>317</td>
</tr>
<tr>
<td>VIC</td>
<td>7</td>
<td>129</td>
</tr>
<tr>
<td>QLD</td>
<td>4</td>
<td>53</td>
</tr>
<tr>
<td>WA</td>
<td>10</td>
<td>77</td>
</tr>
</tbody>
</table>

Drive technologies
Lift drive technology is believed to have a significant impact on energy consumption, through existing commercial information and feedback from the technical advisory group. The study collected data on the following drive types:

- DC Motor Generator Set (also known as Ward Leonard DC drive)
- DC Static Silicon Controlled Rectifier (SCR)
- AC Direct
- Variable Voltage AC (VVAC)
- Variable Voltage Variable Frequency AC (VVVFAC)
- Variable Voltage Variable Frequency Permanent Magnet (VVVFAC PM)
- Quattro DC Unity
- Hydraulic

Given the age of the Australian office building stock, the majority of lift installations in the sample employed DC Static SCR drives; meanwhile, only a small portion of buildings surveyed were serviced by newer VVVFAC drives. The distribution of lift numbers by drive technology is graphically presented in Figure 1.
Based on the distribution of lift technology, a number of drive types were combined to reduce the total number of categories to a manageable quantity. In particular, there were little or no data on:

- Regenerative DC motor-generator sets
- Regenerative VVAC drives
- Permanent magnet synchronous VVVFAC drives
- Quattro DC Unity drives.

Hence these categories have been merged or omitted from analysis.

### Lift Control System

From the sample distribution of relay vs. microprocessor, it is apparent that industry has seen a wholesale shift towards microprocessor controllers. This was confirmed during TAG discussions and Figure 4 reflects the industry trend.

![Figure 4 Sample distribution of relay vs. microprocessor](image)

### Lift Car Mass

Lift cars are a largely passive element of the lift system. However, there is some evidence that the mass of the lift car may affect overall energy consumption and indeed lift car mass is covered under the Hong Kong Energy Code (EMSD 2000).

There are three categories of car mass referred to informally by the industry:

- Light finish – light alloys, laminates etc
- Medium finish – timber and stainless steels
- Heavy finish – stone/tiles and glass

There is an apparent trend towards styling with glass and stone (heavy finishes). Only a small number (13%) of lifts use a light finish but there is sufficient representation for all three finishes.

![Figure 5 Sample distribution of lift car finish](image)

### PRELIMINARY ANALYSIS

#### Methodology

The objective of the analysis was to characterise lift energy consumption in the office building sector and produce a benchmark model based on the gathered data that will allow direct comparisons between lift energy use of different office buildings or lift systems (e.g. for potential lift upgrades). The methodology applied was as follows:

- Identification of variables that may affect lift energy consumption.
- Investigation of the scale of impact each variable is likely to have on lift energy consumption.
- Elimination of variables that are unlikely to affect lift energy consumption significantly.
- Establishment of the relationship between significant variables and lift energy consumption.
- Use of multiple linear regression to evaluate the relationships established and formulate a benchmark model.

#### Key Lift Energy Consumption Drivers in Office Buildings

The variables that were identified by the TAG which could potentially affect lift energy consumption in office buildings are:

- Occupied NLA
- Building Height (floors)
- Lift Floors
- Building Quality – PCA Grade
- Drive Technology (including regenerative braking)
- Control System
- Lift Motor Room Servicing
• Other lift characteristics (e.g. rated load, car finish etc)

While most of these are commonly understood metrics, we have defined Lift Floors as the total number of floors serviced by lifts (i.e. a 5-floor high building with two 5-floor high lifts has 10 Lift Floors). The metric provides a good representation of a building’s total lift displacement.

The impact of each variable on energy consumption was investigated empirically based on the data gathered. The most significant factors identified were:

• Occupied NLA
• Lift Floors
• Height (squared)
• Lift Drive Technology

Empirically, these four variables had the strongest observable impact on lift energy consumption.

The Hypothetical Model

Occupied NLA and Lift Floors are directly related to building size; for this reason, they are good first-order indicators for the scale of lift services provided by the base building and likely its energy consumption.

Figures 6 and 7 presents their respective relationships with annual lift energy consumption.

Both pieces of information should be readily available when simulating buildings. The remainder of this section will deal with how these two metrics are related to lift energy consumption.

Algebraically, energy consumption of lift operations can be expressed as:

\[ \text{Energy} = \text{Total work of lift system} + \text{Total standby losses} \]  

[Eqn 1]

Where the total work of the lift system can be approximated by the total distances travelled by all lifts (i.e. work = displacement*force). Here, a critical assumption is made based on the findings of the E4 project that working lift energy consumption on each trip is dominated by the flat peak consumption during lift motion (up trip) and not of the short acceleration/deceleration windows (E4 2010). The challenge is then to find a method to estimate the whole lift system workload using the following relationship.

\[ \text{Total work of the lift system} = \sum (\text{no. of trips by lift} \times \text{distance travelled per trip by lift}) \]  

[Eqn 2]

An important assumption can be made here that the average number of trips per lift remains roughly constant throughout the office building sector. This assumption is based on the premise that lifts are designed to service a fixed level of NLA per lift car as demonstrated in the following figure.

\[ \text{Energy} = \sum (\text{no. of trips by lift} \times \text{distance travelled per trip by lift}) \times \text{Lift Drive Technology} \]

[Eqn 2]

Figure 8 Total NLA vs. No. of Lifts

The sample data can be used to reliably estimate that on average there is 1 lift car servicing every 2,500m² of NLA. Furthermore, the data showed strong correlation between number of occupants and NLA (R²=0.85), indicating that NLA is a good predictor for the expected number of building occupants. The useful conclusion here is that in office buildings, by design, the average number of building occupants serviced (and the average number of trips made by each lift) over the course of a year remains comparable.

Equation 2 is therefore equivalent to:
Total work of the lift system
\[ = a \times \sum (\text{distance travelled per trip per lift}) \]
Where \(a\) is a constant (e.g. average number of trips per year)

To simplify matters further, the sum of distances travelled per trip per lift can be represented by the total Lift Floors of the building (defined earlier), i.e.

Total work of the lift system
\[ = a \times \text{Lift Floors} \quad [\text{Eqn 3}] \]

The total standby losses are largely dependent on the number of lift motors. Since NLA is directly proportional to the number of lifts:

Total standby losses \(= b \times \text{no. of lifts} \)
Total standby losses \(= b \times \text{NLA} \quad [\text{Eqn 4}] \)
Where \(b\) is a constant

By combining equations 3 and 4, the total energy consumption of a lift system is given by:

\[ \text{Energy} = a \times \text{Lift Floors} + b \times \text{NLA} \]

In order to account for lift efficiencies, we will incorporate a generic function \(f(\ldots)\) which may be used to adjust for any observable efficiency impacts by second order factors such as lift drive technology, fire stairs accessibility and lift motor room air conditioning etc.

The final theoretical model for the energy consumption of lifts is therefore:

\[ \text{Energy} = (a \times \text{Lift Floors} + b \times \text{NLA}) \times f(\ldots) \quad [\text{Eqn 5}] \]

Subsequent regression analysis will be used to confirm the significance of this theoretical relationship.

EMPIRICAL ANALYSIS

First Order Impacts
Equation 5 in the previous section describes a theoretical linear relationship between lift energy consumption, Lift Floors and occupied NLA with some other additional second order impacts yet undetermined.

Ignoring for now the uncertain second order impact \(f(\ldots)\), the theoretical model resembles a multiple linear regression of the form \(y = \beta_0 + \beta_1 x_1 + \beta_2 x_2\); therefore, a statistical package can be used to evaluate the \(\beta\) coefficients and assess their empirical significance. With annual lift energy consumption as the dependent variable, the following table presents the regression outcomes:

<table>
<thead>
<tr>
<th>Regression Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>R Square 0.803</td>
</tr>
<tr>
<td>Model Significance 9.05E-20</td>
</tr>
<tr>
<td>Observations 57</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept 30900</td>
<td>0.250</td>
</tr>
<tr>
<td>Lift Floors 598</td>
<td>0.000321</td>
</tr>
<tr>
<td>Occupied NLA 4.06</td>
<td>0.0372</td>
</tr>
</tbody>
</table>

Based on the regression statistics, Lift Floors and Occupied NLA combined is able to explain approximately 80% of the variability in lift energy consumption. The model significance is quite strong while the significance levels for Lift Floors and occupied NLA as explanatory variables are acceptable. The significance of the intercept is questionable and when discarded has the following impact on the coefficient values:

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept 0</td>
<td>#N/A</td>
</tr>
<tr>
<td>Occupied NLA 5.47</td>
<td>0.000455</td>
</tr>
<tr>
<td>Lift Floors 528</td>
<td>0.00055</td>
</tr>
</tbody>
</table>

The revised regression provides a benchmark to predict annual lift energy consumption for a given building as long as the occupied NLA and Lift Floors are known. Equation 6 below presents the model numerically:

Annual Lift Energy (kWh) = 528 \times \text{Lift Floors} + 5.47 \times \text{occupied NLA (m}^2\text{)} \quad [\text{Eqn 6}]

Figure 9 compares the model predicted lift energy consumption with the actual metered energy consumption.
The outcomes of Figure 10 mostly conform to expectations with the exception of VVAC and AC Direct drives, which reflected better efficiencies than anticipated (similar performance to DC Static SCR was expected). In Figure 10, Residual = Actual – Predicted, so positive residuals indicate that the site is using more energy than predicted (under-predicted) and a negative residual indicate that the site is using less energy than predicted (over-predicted). DC motor generator sets are the worst for energy efficiency with the highest % residuals while VVVFAC drives recorded the best energy efficiencies with the lowest % residuals.

Figure 10 also confirms that regenerative braking contributes to a noticeable drop in lift energy consumption but the benefit is not conclusive for all drive technologies; notably, DC Static SCR was the only drive technology with a large data set of both regenerative and non-regenerative drives.

To quantify the observed consumption differences by drive technology, a multiple linear regression modelling approach can be used. In this way, the following relationship has been evaluated:

\[
\%\text{residual} = \beta_{\text{DC Gen}} \times \%\text{DC Gen} + \beta_{\text{DC SCR non-regen}} \times \%\text{DC SCR non-regen} + \cdots + \text{Const} \quad [\text{Eqn 7}]
\]

Where

\[
f(\ldots) = 1 + \%\text{residual}
\]

\[
\% [\text{drive } X] = \frac{\sum \text{floors serviced by lifts with drive type } X}{\sum \text{floors serviced by all lifts}}
\]

[Eqn 8]

This form ensures the sum of all drive proportions across a building will add up to 1. For example, if a building consists of two 20-floor high DC SCR lifts each servicing 10 floors (and 10 express floors) and two 10-floor high VVAC lifts servicing 10 floors (no express floors), the proportions would be evaluated in the following way:

Total Lift Floors = 20 (floors) x 2 (DC SCR) + 10 (floors) x 2 (VVAC)

Total Lift Floors = 60 floors

% DC SCR driven = 40/60 = 67%

% VVAC driven = 20/60 = 33%

The proportion of servicing by drive technology is evaluated for each of the drive technologies identified. After carrying out multiple regression analysis as per the relationship described in Equation 7, the observable impact of drive technology on lift energy consumption is summarised in table 4:

<table>
<thead>
<tr>
<th>Drive technology coefficients</th>
<th>Coefficients</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.0960</td>
<td>0.202</td>
</tr>
<tr>
<td>DC Gen-set (all)</td>
<td>0.588</td>
<td>0.0103</td>
</tr>
</tbody>
</table>

The estimate provided by the above equation is of course a first order prediction of the energy consumption that can be further improved by examining some potential second order impacts.

**Second Order Impacts**

After accounting for 80% of the variability in lift energy consumption, residual analysis revealed that the following factors may have a second order impact on lift energy consumption:

- Lift drive technology
- Fire stairs accessibility
- Lift control system
- Car finish weight

**Lift Drive Technology**

A box whisker plot has been produced to show the distribution of % residual lift energy by drive type.

Figure 10 Residuals distributed by drive technology

The box-whisker plot is ideal for presenting differences between populations and groups the sample population into 7 categories by drive type. Within each category, the boxes represent the 25th to 75th percentiles of lifts by % residuals while the ends of the whiskers extend to the maximum and minimum intensities within that population. The two halves of the boxes meet at the median consumption level observed.
With acceptable significance levels (at least ~80% confidence), the second order correction based on drive technology is therefore,

\[
f(\ldots) = (1 - 0.096 + 0.588 \times \%\text{DC Gen} \\
+ 0.326 \times \%\text{DC SCR}_{\text{non-regen}} \\
- 0.260 \times \%\text{VVVFAC}_{\text{non-regen}} \\
- 0.367 \times \%\text{VVVFAC}_{\text{regen}})
\]

[Eqn 9]

Access to Fire Stairs

The impact of tenant accessible fire stairs on lift energy consumption was uncertain in the preliminary analysis. To see if there are any second order effects, the box and whisker plot (Figure 11) presents the distribution of % residual by access to fire stairs (residuals are prior to drive technology correction).

If the impact is significant, the % residuals for buildings without tenant access to fire stairs would be noticeably higher than building with easy access. As such, Figure 11 suggests that prior to correcting for lift drive technology, there is a noticeable difference in median performance between buildings with and without tenant access to fire stairs. A t-test for equivalence of sample means was unable to establish a statistically significant difference between the average performance of buildings with and without tenant access to fire stairs.

Although the empirical evidence is inconclusive, the direction and magnitude of the impact after correcting for lift drive technology conforms to industry expectations (buildings with tenant access to fire stairs is on average 6% more efficient). This suggests that providing tenants with access to fire stairs may provide some reasonable lift energy savings.

Lift Control System

There is a substantial amount of commercial and anecdotal evidence noting the improved energy efficiency of microprocessor lift controls over the traditional relay lift controls. The following box and whisker plot presents the distribution of % residuals by lift control system type.

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Although the empirical evidence is inconclusive, the direction and magnitude of the impact after correcting for lift drive technology conforms to industry expectations (buildings with tenant access to fire stairs is on average 6% more efficient). This suggests that providing tenants with access to fire stairs may provide some reasonable lift energy savings.
The distribution of % residual suggests that there is little difference between lifts with heavy and medium cars; however, a significant 30% difference in median performance is observed for lifts with light cars. The impact is so prominent that a t-test for sample means can provide strong statistical support for the claim (with at least 85% confidence). This outcome suggests that lift systems using light lift cars will be significantly more efficient than heavier car options.

After correcting for lift drive technology impacts, the mean % residual for lifts with light cars is approximately -18%. The benchmark model can therefore be corrected by:

\[ f(...\) = (1 + \text{drive correction} - 0.18*\text{Light Car}_{1,0}) \]

**FULL BENCHMARK MODEL**

The full benchmark model with second order correction for drive technology is presented below,

Annual Lift Energy Consumption (kWh)

\[ = (528 * \text{Lift Floors} + 5.47 * \text{occupied NLA(m²)}) \]

\[ * (1 - 0.0960 + 0.588 * \text{DC Gen}) \]

\[ + 0.326 * \% \text{DC SCR}_{\text{non-regen}} \]

\[ - 0.260 * \% \text{VVVFAC}_{\text{non-regen}} \]

\[ - 0.367 * \% \text{VVVFAC}_{\text{regen}} \]

\[ - 0.18 * \text{Light Car}_{0,1} \]  \[\text{[Eqn 10]}\]

This is a relatively simple equation which can be used to forward predict energy consumption for lifts in simulation models. Note that the energy coverage of this benchmark includes lift motor room air-conditioning, as described earlier in the paper. Figure 14 below compares the full benchmark model predicted lift energy consumption against metered lift energy consumption.

![Figure 9 Full Benchmark Model Predicted vs. Actual Lift Energy Consumption](image)

**SUMMARY OF MODEL LIMITATIONS AND ASSUMPTIONS**

Although the model provides high statistical correlation to measured lift energy consumption, several important caveats should be observed:

- The model is limited to office building lift services.
- The sample data is limited to buildings over 3000m² in NLA (mostly over 5000m² NLA). Extrapolation of the model to smaller buildings should be performed with care.
- Although 80% of the variance is explained by the consumption drivers, there remains 20% of unexplained fluctuations in lift energy use.
- While the benchmark model is a good predictor of lift energy use, it is empirical and thus limited in its specific validity for an individual building.

**CONCLUSION**

In this paper, empirical lift energy consumption has been correlated against key input variables in order to develop a predictive benchmark equation which can be used in simulation models to assist in the prediction of total building energy.

**ACKNOWLEDGEMENT**

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