Toni Tukia

Determining and modeling the energy consumption of elevators

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Thesis supervisor:

Prof. Matti Lehtonen

Thesis advisor:

M.Sc. (Tech.) Claudio Donghi

Aalto University
School of Electrical Engineering

AALTO UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING

ABSTRACT OF THE MASTER'S THESIS

Author: Toni Tukia

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Supervisor: Prof. Matti Lehtonen

Advisor: M.Sc. (Tech.) Claudio Donghi

This thesis analyzes the performance of commonly used energy consumption estimation and classification standards, guidelines, and models against actual consumption data of elevators. The scope of this thesis is in the used and generated active energy, in kWh, excluding the division of energy consumption between different components of the elevator system. The literature review of this field revealed the lack of actual long-term measurement data. Thus, this thesis develops and tests suitable long-term energy consumption measuring systems that can be remotely monitored. In addition, this thesis identifies a typical daily energy usage and travel pattern for both weekdays and weekends for elevators used in a mid-rise office building located in Espoo, Finland. Supporting statistics on the elevator usage for analyzing the gathered consumption data, was attained from KONE Elink, an elevator usage statistics reporting system. The results indicate that the upcoming ISO/DIS 25745-2 standard will outperform the widely used VDI 4707-1 guideline and the KONE EnerCal tool when estimating the annual consumption of elevators. Nevertheless, both ISO/DIS 25745-2 and VDI 4707-1 yield to highly similar energy efficiency classifications, which are also an important aspect, especially for the prospective buyer and for the manufacturer of the elevator in marketing perspective. The consumption ratio, or percentage of total consumption, of elevators in the pilot building was identified to be under 2%, which complies with other Finnish research, but is less than the widely recognized E4 Project suggests. The results also confirm the large dependence of the electricity consumption of elevators on the amount of traffic, and especially on the number of travels, as the correlation coefficient was calculated to be 0.986. The developed metering systems proved to be viable, and the research can be continued in multiple locations with both elevators and escalators.

Keywords: Elevator, Energy usage, Consumption model, Measuring, Trafic profile, Loading profile, Photovoltaics, Energy storages

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Tämä diplomityö käsittelee laajasti käytettyjen hissien energiankulutusmallien ja -standardien paikkansapitävyyttä hyödyntämällä espoolaisen toimistotalon todellisia hissien kulutustietoja, jotka on kerätty työn aikana kehitetyillä etäluettavilla energiankulutusmittausjärjestelmillä, sillä työn kirjallisuuskatsaus paljasti, että pitkäaikaista kulutustietoa ei ole helposti saatavilla, ja että suurin osa aikaisemmista tutkimuksista perustuu lyhytaikaisiin mittauksiin. Tutkimusta varten saatiin taustatietoa rakennuksen hissien KONE Elink -käyttöraportointijärjestelmästä. Tulokset ennakoivat, että tuleva ISO/DIS 25745-2 standardi antaa tarkempia arvioita hissien vuosikulutuksesta kuin laajalti käytetty VDI 4707-1 ohjeistus tai KONE EnerCal -työkalu. Kuitenkin sekä ISO/DIS 25745-2 että VDI 4707-1 antavat lähes samat energiatehokkuusluokat, jotka ovat tärkeitä esimerkiksi asiakkaalle ja sitä kautta valmistajalle markkinoinnin näkökulmasta. Hissien suhteellisen kulutuksen todettiin mittauskohteessa olevan alle 2 %, mikä on vähemmän kuin arvostettu E4-projekti ilmoittaa, mutta vastaa muita suomalaisia tutkimuksia. Lisäksi tulokset vahvistavat hissien sähkönkulutuksen suuren riippuvuuden liikenteestä ja etenkin matkamäärästä, sillä korrelaatiokertoimeksi laskettiin 0.986. Kehitetyt mittausjärjestelmät todettiin toimintakelpoisiksi, ja tutkimuksia voidaan jatkaa muissakin kohteissa sekä hisseillä että liukuportailla.

Avainsanat: hissi, energiankulutus, kulutusmalli, mittaaminen, liikenneprofiili, kuormitusprofiili, aurinkokennot, energiavarastot

Preface

This thesis was inspired by the Energizing Urban Ecosystems (EUE) Program, and it was done at the Aalto University with collaboration and guidance from KONE Corporation.

I am very grateful to KONE for letting me participate in this interesting project from the very early stage. Especially, I would like to thank my advisor Mr. Claudio Donghi for commenting this thesis and for organizing important phone conferences with KONE people. I would also like to acknowledge the following KONE people: Dr. Marja-Liisa Siikonen, Mr. Harri Hakala, Mr. Janne Sorsa, Mr. Henri Hakonen, Mr. Ossi Salosaari, and Mr. Hannu Nousu, who have contributed to the contents of this thesis and provided crucial information for the thesis. I would also like to send special thanks to Mr. Mika Hautamäki for providing his expertise in installations and practical issues at the measurement sites.

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I appreciate the huge help and support from my family and friends prior to and during this thesis.

Otaniemi, 2.5.2014

Toni K. V. Tukia

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Symbols and abbreviations

Symbols

$\%S$	average travel distance in percentage of the full lifting height
$E_{\mathrm{A_{limit}}}$	limiting daily energy consumption value for energy efficiency class A
$E_{\mathrm{travel,spec}}$	specific travel demand
H	full lifting height
j	jerk, change in acceleration
k	load factor
n_{d}	number of trips per day
P_{id}	power demand in idle mode
p_{index}	solar power index
$P_{\mathrm{m,h}}$	average hourly power in a certain month
Q	nominal load
R_{id}	ratio of idle time of total standby time
t_{ssh}	sunshine hour ratio

Abbreviations

CT	current transformer
DC	direct current
DDNS	Dynamic Domain Name System
E4	Energy-Efficient Elevators and Escalators
EUE	Energizing Urban Ecosystems
EV	electric vehicle
LED	light emitting diode
PE	protective earth
PEN	combined protective earth and zero conductor
PMSM	permanent magnet synchronous motor
PV	photovoltaic
SML	Smart Message Language
SSH	Secure Shell cryptographic network protocol
TCP/IP	Transmission Control Protocol / Internet Protocol
UPS	uninterruptible power supply
VDI	Association of German Engineers
VPN	Virtual Private Network

1 Introduction

The EU [1] and other international organizations [2] are pursuing greenhouse gas emission reductions to battle climate change. To achieve these reductions, the EU aims to increase energy efficiency by 20% by the end of this decade. The energy efficiency of buildings should be of main concern, as they currently contribute to approximately one-third of the total final energy consumption [3]. With rising energy prices, improving the energy efficiency of buildings also provides a monetary incentive for the owners of buildings [4]. The energy consumption of elevators can account for 3 to 8% of the total electricity consumption of a building, though these figures can widely vary depending on the use and type of building [5]. Moreover, because of this variation, the building owner remains uncertain about the proportion of total energy used by the elevator system [6, Sec. 5.1.2].

Elevators are categorized into seven classes in terms of their energy consumption. These classification schemes have been developed and proposed by different organizations [7], [8]. However, even though the energy efficiency class is determined according to the schemes, it is still difficult to estimate the annual energy consumption of the elevator system, as the utilization rate and the amount of people using the appliances are uncertain prior to installation [9]. Moreover, much debate has focused on whether the energy classification should be based solely on the design of the device, as with other household appliances, or whether the classification should also depend on the end-use [10].

Most studies examining the energy consumption of elevators have estimated the annual consumption rates of elevators based on simple calculation models. These models typically utilize consumption measurements from reference running cycles which are derived from known standards or guidelines. The final energy consumption, or energy class, is thus achieved by defining and estimating certain key factors. Therefore, the final outcome of these models, especially the projected annual energy usage, always has some degree of inaccuracy, justifying the need for comparing the models against actual long-term measurement data.

1.1 Target of study

In order to determine the accuracy of these models, the aim of this thesis was to compare the measured energy consumption of elevators with the models currently in use. Additionally, the thesis develops and validates a measuring system designed especially for this type of data gathering, as a major driver for this thesis was to establish the basis for a long-term measurement project inside the Energizing Urban Ecosystems (EUE) Program.

In addition, the thesis inspects the plausibility of using solar energy to fulfill the energy need of elevator systems during peak demand to reduce the costs of electricity usage. To understand the need of power and energy, this thesis analyzes the electricity consumption data of the building against the energy demand pattern of the elevator system and energy production curve of a photovoltaic system.

1.2 Scope of study

The specific aim of this study was to examine the energy usage of elevators used in a mid-rise office building located in Espoo region, Finland. This thesis focuses on the consumed and generated energy in kilowatt-hours, kWh, and generally excludes other measurable quantities of electrical systems.

This thesis does not examine the detailed construction of elevators, nor is the segregation of energy consumption between the different components in the electrical or mechanical system of elevators measured or widely inspected in this thesis. The scope of this thesis is in traction elevators, mostly excluding hydraulic elevators.

1.3 Structure of the thesis

The remainder of this thesis is structured as follows. Chapter 2 introduces the typical methods currently used in energy consumption modeling and analyzes the results of the previous measurement campaigns that have been implemented in various countries to provide sufficient background information. Chapter 3 describes the measuring equipment, their characteristics, and related devices. The chapter also provides information on the measurement site, traffic pattern of the elevators, the electricity consumption of the building, and introduces a photovoltaic power generation model. Chapter 4 presents the readings gathered by the measuring system and the estimates given by the models introduced in Chapter 2, and Chapter 5 analyzes these results and factors affecting them. Chapters 6 and 7 conclude the findings and success of this thesis and provide ideas for further studies.

2 Background

This chapter focuses on describing the models, and the theories behind them, concerning the energy consumption of elevators. The main focus of the first section is to introduce three energy consumption estimation schemes that are used in this thesis. First, Section 2.1.2 presents the energy efficiency classification scheme used today by most elevator manufacturers, while Section 2.1.3 is dedicated to the second scheme, which is an upcoming standard that has a more profound method to estimate the energy usage. The third method of estimation is an energy calculation tool called EnerCal, and the basic concept of its calculation model is discussed in Section 2.1.4. The second part of this chapter introduces and briefly analyzes some measurement results from previous campaigns.

The European elevator manufacturers have typically based their energy classifications on a scheme developed by VDI [7], the Association of German Engineers (Verein Deutscher Ingenieure). Another standard, ISO 25745-1: 2012 [11], describes a methodology for measuring the energy consumption in running mode and in standby for both elevators and escalators. However, this standard lacks the energy classifications, which will be introduced later in part two [8] for elevators and part three for escalators and moving walks [12]. At the time of writing this thesis, these parts of the standard were still under development. Nevertheless, some descriptions of the calculation methods are already available, for example, in [10], [13] and [14].

It is clear that the factors affecting the energy consumption for indoor transports include the building type, traffic pattern, total run time, number of start-ups, and the design of the mechanical and control systems. However, the contribution of these factors is uncertain, since some of the factors can be changed or improved, such as the technology and control method, and some, such as the amount of traffic, cannot usually be controlled.

2.1 Energy consumption models of elevators

Elevators have many approaches regarding their energy consumption models. These models use the amount of estimations, simulations, and measurement data in different proportions. The amount of executed measurement campaigns is still low, but the interest in large measurement projects will increase in the future, due to the lack of knowledge in this area.

Elevators are generally divided into two different types: hydraulic elevators and traction elevators. The basic structure of these can be seen in Figure 1 on the next page. This thesis focuses mostly on the traction elevators, due to the nature of elevators that will be included in the measurement campaign discussed in Chapter 1. The most significant difference between the two elevator types is that the traction elevators have a counterweight, commonly with a weight of the car and half of the nominal load combined. The use of a counterweight produces interesting properties to the electricity consumption of the elevator. In theory, with a small load, typical of any passenger elevator, the elevator traveling up will not require any excess energy to produce the vertical shift, and the same situation occurs with a load heavier than the counterweight that is going down. In these cases, the elevator can be seen to generate electricity, and this energy is typically turned into heat in a brake resistor, if the supply to the grid is not made plausible with a regenerative unit [15, Sec. 8.5]. Traditionally, traction elevators use ropes for hoisting, but belted systems are increasing their popularity as well [16].

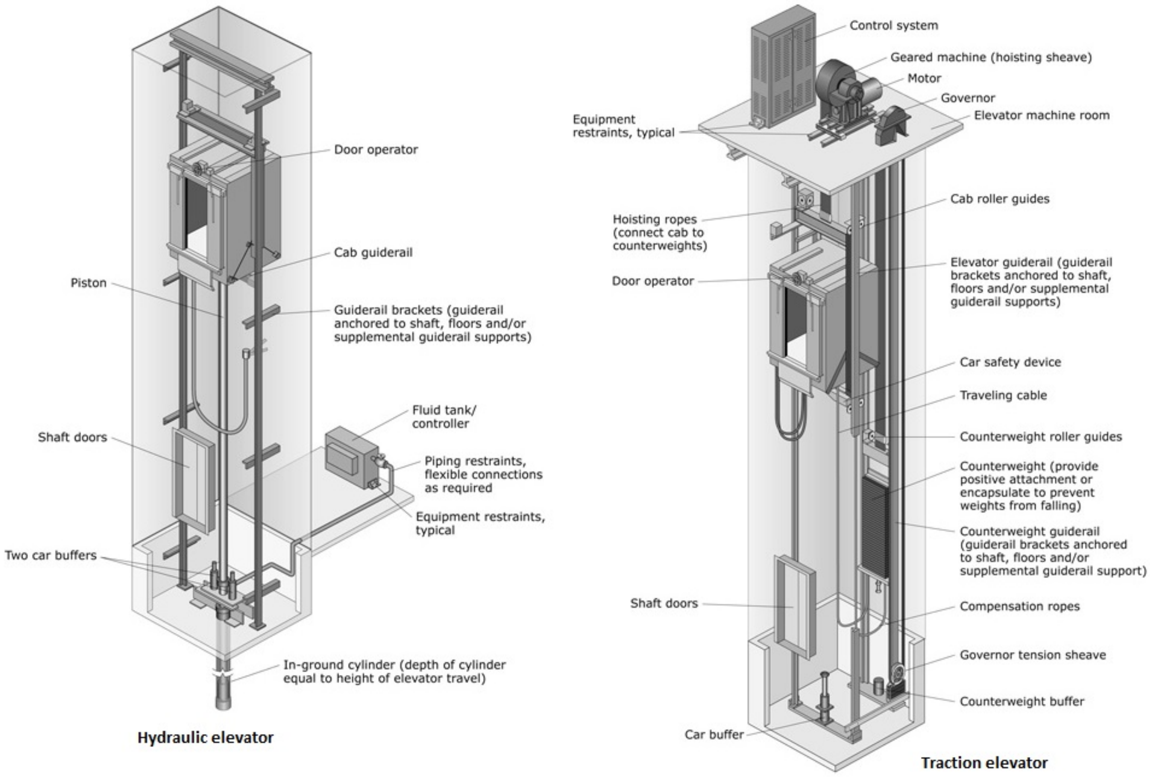

Figure 1: Diagram adapted from [17] showing basic construction of hydraulic and traction elevators.

The following sections introduce the most common models used to estimate the energy consumption of elevators. Most of the other studies published in this field are based on pure mathematical calculations or simulations [18]. The aims of these studies vary between energy consumption minimization, as in [19], and energy efficiency, as in [20], where the aim is to achieve energy savings without degraded performance. The studies may also assume a certain type of elevator system or traffic distribution in their simulations [21]. Some simulations can be used to emulate the daily operation of an elevator with specific parameters, such as the number of floors, the floor height, and the population inside the building. These simulations can indicate the contribution of the different factors of building usage to the energy consumption of elevators [10], [22]. The simulations are mostly run on traffic-simulation software, e.g., Elevate [23].

2.1.1 ISO 25745-1 standard

This section provides some basic information on the ISO 25745-1 standard [11] that provides a consistent method to measure the actual energy consumption of an installed elevator, escalator or moving walk. This method forms the basis of the current guidelines and upcoming standards classifying the devices by their energy efficiency. Furthermore, this standard provides guidance for examining the changes in energy consumption over the lifetime of the measured system.

This standard guides to measure both main and ancillary power. The former mainly consists of actual components related to mechanical movement, while the latter includes lighting and ventilation. Figure 2.1.1 presents the measuring locations for the main and ancillary power. It is also possible to measure only the main

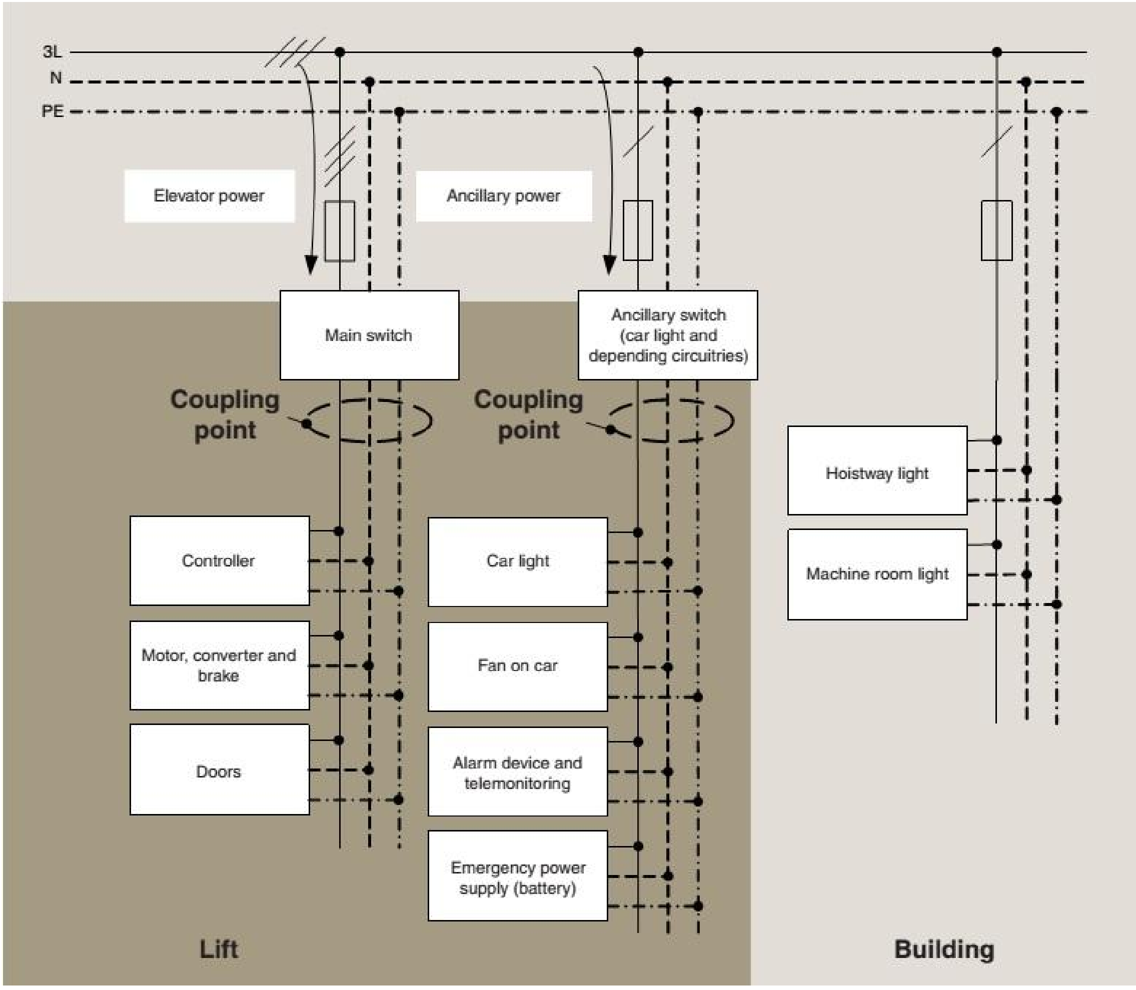

Figure 2: Schematic diagram for energy demand of elevators [11].

coupling point in elevator systems where the ancillary equipment is behind the same main switch [11]. This is the situation in many modern elevators, making the measurement procedure more straightforward.

Both the ancillary and the main power are measured when the elevator is running and stationary. Stationary time consists of idle and standby states. Idle condition refers to the situation when the elevator is left stationary after the run and before the standby mode is entered. The standard defines standby as condition when the elevator is stationary and has a reduced consumption level compared to plain idling. Generally, the standby condition can be seen to start after five minutes of idling. [11]

This standard demands that the measuring equipment must be compatible with the technology of the measured system, including regenerative drives, which are within the scope of this thesis. In addition, the accuracy of the measured value must be at least $\pm$ 10%, i.e., the general accuracy of the measuring device should be of good quality. This is basically achieved with the demand that the meters used shall comply with IEC 62053 [24] or IEC 61000-4-30 [25]. [11]

When considering typical modern elevators with the ancillary equipment behind the main switch, the measurements are basically separated into two parts: running energy and stationary energy. The ISO 25745-1 defines the running energy measurement procedure as follows:

1. connect the energy meter to all phases at the main coupling point;
2. measure and record the supply voltages;
3. set the energy meter to measure energy;
4. set the elevator to cycle between terminal landings, automatically, or manually;
5. run the empty car to the bottom landing;
6. start the measurement;
7. start the terminal landings cycle (with door functioning);
8. stop the measurement after a minimum of 10 cycles;
9. record the energy value and the number of cycles executed;
10. divide the total energy with the number of cycles to produce an average value, and record it.

As for the stationary energy usage, the standard defines this measurement procedure to be the following:

1. connect the energy meter to all phases at the main coupling point;
2. measure and record the supply voltages;
3. run the car through a reference cycle;
4. record the idle energy for a period of 1 min starting immediately after finishing the reference cycle;

5. maintain the empty car at the bottom landing for 5 min after the doors have closed and record the standby energy for a period of 1 min;

6. calculate the idle power in watts by dividing the recorded energy value by the measurement time and record the value;

7. calculate the standby power respectively.

This standard also suggests that additional measurements with various travel distances and loads could be executed, provided that these values are reported. The actual measuring device connections are introduced later in this thesis in Chapter 3.

2.1.2 VDI 4707-1 guideline

This chapter takes a more detailed view to the model which is currently typically used in classification, the VDI 4707-1 guideline [7], [26, Sec. 5.2.9]. The method is based on measurements described in the ISO 25745-1 [11]. The contents of the VDI 4707-1 are shortly demonstrated below.

This guideline states that the energy demand can be separated into two parts: standby demand and travel demand. When calculating energy efficiency classes with the VDI, the standby demand refers to the average standby power value that is measured after the elevator has been inactive for five minutes, as instructed in the ISO standard. Thus, the VDI guideline excludes the idle energy consumption and basically considers all inactivity as five-minute standby demand. As for travel demand, the guideline considers it as the total demand during specific trip cycles with specific loads. For this purpose, the guideline provides a load spectrum and another method to utilize the ISO reference running cycle measurements in the travel demand calculation process. The only clear difference in the guidance of the reference cycle is that the VDI allows the trip to start also from the top landing. However, from the energy perspective, this should not affect the total energy consumption, and this possibility is also mentioned in the ISO 25745 part two. Another difference is in the clearer instruction of the door functioning, as the VDI 4707-1 clearly states that the door has to be open at the beginning of the running cycle, and when the elevator has traveled to the other terminal landing, the doors will immeadiately open and close. The cycle ends when the elevator returns to the starting landing and reopens the door.

Elevators are assigned to different energy efficiency classes depending on their calculated standby and travel demand values. The classification process is conducted as follows. First, the measured standby power is compared to Table 1 to get a so called energy demand class for standby. For example, a standby demand of 30 W corresponds to demand class A. Another table needed for the classification process is Table 2. It depicts the categorization of elevators by their usage according to the guideline. This information is needed in the final calculation of the energy efficiency class.

The calculation procedure gets more challenging in the next step. The needed values of the elevator are:

Table 1: Energy demand classes for standby according to [7].

Power in W	≤ 50	≤ 100	≤ 200	≤ 400	≤ 800	≤ 1600	> 1600
Class	**A**	**B**	**C**	**D**	**E**	**F**	**G**

Table 2: Usage categories for elevators [7].

Usage category	**1**	**2**	**3**	**4**	**5**
Usage intensity/ frequency	very low very seldom	low seldom	medium occasionally	high frequently	very high very frequently
Average travel time in hours per day*)	0,2 (≤ 0,3)	0,5 (> 0,3–1)	1,5 (> 1–2)	3 (> 2–4,5)	6 (> 4,5)
Average standby time in hours per day	23,8	23,5	22,5	21	18
Typical types of buildings and use	• residential building with up to 6 dwellings • small office or adminis-trative build-ing with few operation	• residential building with up to 20 dwel-lings • small office or administrative building with 2 to 5 floors • small hotels • goods lift with few operation	• residential building with up to 50 dwel-lings • small office or administrative building with up to 10 floors • medium-sized hotels • goods lift with medium op-eration	• residential building with more than 50 dwellings • tall office or administrative building with more than 10 floors • large hotel • small to medium-sized hospitals • goods lift in production process with a single shift	• office or administrative building over 100 m in height • large hospital • goods lift in production process with several shifts

*) Can be determined from the average number of trips and the average trip duration.

- Nominal load Q, in kg
- specific travel demand $E_{\text{travel,spec}}$, in mWh/(kgm)
- time of standby t_{standby}, in hours per day
- time of usage t_{travel}, in hours per day
- nominal speed v_{nom}

The equation for the limiting values for specific energy efficiency classes of the elevator, in mWh/(kgm), can be expressed as found in [7]:

$$E_{\text{elev,spec,max}} = E_{\text{travel,spec,max}} + \frac{P_{\text{standby,max}} \cdot t_{\text{standby}} \times 1000}{Q \cdot v_{\text{nom}} \cdot t_{\text{travel}}} \tag{1}$$

where the $E_{\text{travel,spec,max}}$ is the maximum value of a specific travel energy demand class presented in Table 3 below. For instance, if the calculated value of $E_{\text{travel,spec}}$ is 0.6 mWh/(kgm), the energy demand class for travel is B for the elevator.

Table 3: Energy demand classes for travel according to [7].

Specific energy consumption in mWh/(kgm)	≤ 0.56	≤ 0.84	≤ 1.26	≤ 1.89	≤ 2.80	≤ 4.20	> 4.20
Class	**A**	**B**	**C**	**D**	**E**	**F**	**G**

If the elevator has, for example, the following characteristics:

- Type of building: large hotel
- Nominal load: 1000 kg
- Nominal speed: 2.0 m/s
- Average travel time: 3 h
- Average standby time: 21 h
- Full lifting height: 35 m

then, looking at Table 2, it can be stated that the usage category is 4. The limiting value according to (1) for class A can be calculated as:

$$\begin{aligned} E_{\text{elev,spec,max}} &= 0.56 \text{ mWh/(kg} \cdot \text{m)} + \frac{50 \text{ W} \cdot 21 \text{ h} \cdot 1000 \text{ mWh/Wh}}{1000 \text{ kg} \cdot 2.0 \text{ m/s} \cdot 3 \text{ h} \cdot 3600 \text{ s/h}} \\ &= 0.61 \text{ mWh/(kg} \cdot \text{m)} \end{aligned}$$

and for class B it is respectively

$$\begin{aligned} E_{\text{elev,spec,max}} &= 0.84 \text{ mWh/(kg} \cdot \text{m)} + \frac{100 \text{ W} \cdot 21 \text{ h} \cdot 1000 \text{ mWh/Wh}}{1000 \text{ kg} \cdot 2.0 \text{ m/s} \cdot 3 \text{ h} \cdot 3600 \text{ s/h}} \\ &= 0.94 \text{ mWh/(kg} \cdot \text{m)} \end{aligned}$$

The rest of the class limiting values for a certain usage category are calculated in the same fashion, i.e., the corresponding maximum values of the same class are taken from Tables 1 and 3 and inserted to the equation.

The energy efficiency class is determined by calculating the total specific energy demand of the elevator and comparing it to limiting values. In this example, the P_{standby} was given as 30 W. Further, if the reference cycle energy demand for travel is measured at 60 Wh with respect to the ISO standard, the specific energy demand of the elevator when traveling is calculated from

$$E_{\text{travel,spec}} = \frac{k \cdot E_{\text{referencetrip}}}{Q \cdot 2 \cdot H} \tag{2}$$

where the full lifting height, H, is doubled, because the reference trip includes the full cycle up and down. The factor k represents a load factor typically used in calculations to compensate the effect of not loading the elevator car during the measurements. This example presumes a load factor of 0.7, a value determined by the guideline to typical traction elevators with a counterbalance weight with a mass of car plus 40 to 50 percent of the nominal load. The guideline also introduces a method of adding up measured reference cycle demands with a certain load-dependable ratio, instead of operating with this load factor. However, this method is far more complex to execute and report. Nevertheless, this method is practical to use in various simulations and energy calculations tools one of which is introduced in Section 2.1.4.

With the values given, the specific energy demand of travel will be:

$$\begin{aligned} E_{\text{travel,spec}} &= \frac{0.7 \cdot 60 \text{ Wh}}{1000 \text{ kg} \cdot 2 \cdot 35 \text{ m}} \\ &= 0.6 \text{ mWh}/(\text{kg} \cdot \text{m}) \end{aligned}$$

The total specific energy demand can be calculated similarly to (1):

$$\begin{aligned} E_{\text{elev,spec}} &= 0.6 \text{ mWh}/(\text{kg} \cdot \text{m}) + \frac{30 \text{ W} \cdot 21 \text{ h} \cdot 1000 \text{ mWh/Wh}}{1000 \text{ kg} \cdot 2.0 \text{ m/s} \cdot 3 \text{ h} \cdot 3600 \text{ s/h}} \\ &= 0.63 \text{ mWh}/(\text{kg} \cdot \text{m}) \end{aligned}$$

Then, comparing this value to the limiting values of this usage category 4, it can be stated that the elevator belongs to the energy efficiency class B, as the calculated specific energy demand value is higher than the limiting maximum value of class A but lower than that of class B.

Based on the calculations and specifications above, it is possible to estimate the total annual energy used by the elevator. These are rough estimates due to the nature of the specifications. For example, the effect of acceleration and deacceleration on the time or distance traveled by the elevator is not taken into account. The energy consumed in standby throughout the year can be estimated by multiplying the daily demand by 365:

$$\begin{aligned} E_{\text{standby,annual}} &= 365 \, \frac{\text{d}}{\text{a}} \cdot 30 \text{ W} \cdot 21 \, \frac{\text{h}}{\text{d}} \\ &= 230 \, \frac{\text{kWh}}{\text{a}} \end{aligned} \tag{3}$$

Further, the energy used during travel can be estimated by multiplying the travel specific demand value with the calculated distance traveled in a day and with the nominal load. The annual energy is achieved by multiplying this daily energy use by 365, as was done with standby as well.

$$\begin{aligned} E_{\text{travel,annual}} &= 365\ \frac{\text{d}}{\text{a}} \cdot 0.6\ \frac{\text{mWh}}{\text{kg} \cdot \text{m}} \cdot \underbrace{3\ \frac{\text{h}}{\text{d}} \cdot 3600\ \frac{\text{s}}{\text{h}} \cdot 2.0\ \frac{\text{m}}{\text{s}}}_{\text{traveled distance per day}} \cdot 1000\ \text{kg} \qquad (4) \\ &= 4730\ \frac{\text{kWh}}{\text{a}} \end{aligned}$$

The total estimated energy consumption can then be calculated:

$$\begin{aligned} E_{\text{annual}} &= E_{\text{travel,annual}} + E_{\text{standby,annual}} \\ &= 4960\ \frac{\text{kWh}}{\text{a}} \end{aligned}$$

The important aspect shown in this example is that the energy consumption of an elevator has many factors, some of which are taken into account in the VDI classification guideline today. The energy consumption in different operation modes together with the usage pattern affect the annual energy demand. More examples and details of determining the energy efficiency classes can be found in the VDI guideline, and are, therefore, not dealt with more thoroughly in this section.

The VDI has also published a second part for the VDI 4707 guideline [27]. Part two addresses the energy efficiency of elevator components and offers a calculation procedure of energy demand for an elevator on the basis of the utilized components. Thus, the aim of this guideline is to give a prediction of the energy consumption of an elevator before the elevator is actually built or installed. This differs from part one, where an already built elevator is assumed. However, the component based energy efficiency is not in the scope of this thesis; therefore, the VDI 4707-2 is not inspected in more detail later in this study.

2.1.3 ISO/DIS 25745-2 standard

This section is dedicated to the upcoming ISO/DIS 25745-2 standard [8], which is currently a draft and under international review. The ISO 25745 part two is also based on the measurements introduced in the ISO 25745-1. The contents of the part two are also explained by Lorente and Barney [10], [13], [14] with some basic calculation examples. Lorente [26, Ch. 6] also demonstrates a wider theory behind this standard, but this theory is not further investigated in this thesis. The method proposed by this standard introduces a classification system with more parameters that need to be measured or estimated compared to the VDI 4707-1. It also distinguishes idle and standby powers, and the power values after a certain period of time, such as the power drawn in a so-called hibernation mode. This makes the model with its new classifications very interesting from the accuracy respective but at the same time more complex compared to the VDI guideline.

Similar to the VDI 4707-1 guideline, the ISO/DIS 25745-2 standard distinguishes the daily energy consumption into running and standing consumption. The minor differences in these two methods arise from the calculation procedure of these values. This standard gives daily run mode consumption as

$$E_{\mathrm{rd}} = \frac{n_{\mathrm{d}} \cdot \%S \cdot k_{\mathrm{L}} \cdot E_{\mathrm{rc}}}{2} \tag{5}$$

where :

- n_{d} is the number of trips per day
- $\%S$ is the average travel distance per trip in percentage of the full height of the installed elevator
- k_{L} is the load factor per trip
- E_{rc} is the measured running energy consumption of the ISO reference cycle

When comparing (5) to the VDI guideline and especially to (2) and (4) , the number of trips gains a more significant role by itself. However, the running and standby hours used by the VDI could have also been derived using the number of trips and average trip duration. The amount of travels used in this ISO method can either be known from measurements or estimated or adapted from Table 4 shown below [13]. The following tables introduce characteristics for usage categories from 1 to 5, though the actual standard also defines values for usage category 6 [8]. However, the number of travels considered by the sixth category is greater than 2000, a value to arise only on rare occasions [14].

Table 4: Number of starts per day in different usage categories according to [13].

Usage category	**1**	**2**	**3**	**4**	**5**
Usage intensity	**very low**	**low**	**medium**	**high**	**very high**
$\mathbf{n}_{\mathrm{d}}$	50	125	300	750	1500
Typical range in trips	< 75	75–200	200–500	500–1000	1000-2000

The average travel distance in percentage, $\%S$, is generally taken from the following Table 5, which clearly shows that the average travel distance is typically slightly less than half of the total height of the elevator shaft in buildings that have more than three stories.

Given with a rated load and a usage category, the load factor (k_{L}) can be derived using (6), (7), and Table 6 [13]. According to the standard, the load factor for 50% counter balanced elevator is calculated as

$$k_{\mathrm{L}} = 1 - (\%Q \cdot 0.0164) \tag{6}$$
$$\text{Range } 0.97 - 0.74.$$

Table 5: Percentage of average travel distance according to [13].

Usage category	**1 – 4**	**5**
Number of stops	**Average travel distance in percentage**	
2	100%	
3	68%	
$>$ **3**	44%	33%

Table 6: Average car load in percentage of the rated load according to [13].

Usage category	**1 – 3**	**4**	**5**
Rated load (kg)	**Average car load in percentage (%*Q*)**		
$\leq$ **800**	7.5%	9.0%	16.0%
801 – 1275	4.5%	6.0%	11.0%
1276 – 2000	3.0%	3.5%	7.0%
$>$ **2000**	2.0%	2.2%	4.5%

For traction elevators with 40% counterbalance, a different constant is used:

$$
\begin{aligned}
k_{\mathrm{L}} &= 1 - (\%Q \cdot 0.0192) \\
& \text{Range } 0.96 - 0.69.
\end{aligned} \tag{7}
$$

The standard also introduces a procedure to estimate the consumption of hydraulic elevators, but as was previously mentioned, this is not in the scope of this thesis.

A larger difference compared to the VDI guideline is in the calculation procedure of the standby energy consumption, which will be demonstrated next. The following equation can be presented in many forms depending on the type of information that is known from the elevator. Generally, the standby consumption comprises of three parts: idle, 5-minute standby, and 30-minute standby energy demand [10]. The power values that are used to determine these demands are measured and used in calculations depending on the stationary modes of the elevator. Equation (8) below is a combination of equations given in [10] and [13], and it can be declared to be more accurate than (3) used by the VDI.

$$E_{\mathrm{sd}} = (24 - \frac{n_{\mathrm{d}}}{3600} \cdot t_{\mathrm{av}})(P_{\mathrm{id}} \cdot R_{\mathrm{id}} + P_{\mathrm{st5}} \cdot R_{\mathrm{st5}} + P_{\mathrm{st30}} \cdot R_{\mathrm{st30}}) \tag{8}$$

where :

– P_{id} is the power demand in idle mode
– P_{st5} is the power consumption measured after 5 minutes of inactivity
– P_{st30} is the power consumption measured after 30 minutes of inactivity
– R_{id} is the ratio of idle time with respect to the overall time the elevator is not running
– R_{st5} is the ratio of 5-minute standby time with respect to the overall time the elevator is not running
– R_{st30} is the ratio of time that the elevator has been stationary over 30 minutes with respect to the overall time the elevator is not running
– t_{av} is the time in seconds to travel the average travel distance, including door opening/closing times

The average travel time can be estimated from the given or known information of rated speed, v, acceleration, a, jerk, j, and door operation time t_{d} [13]. The first term in (8) refers to the total standing time in hours, and naturally, if this is already known, it is needless to calculate the average travel time for this specific purpose. However, the average travel time becomes useful later in the calculation process, especially when calculating the number of trips, if that is not taken directly from Table 4. In this case, the average daily standing time of three hours is given in the VDI calculation example in the previous section, and the number of trips can be derived from this. A 35-m high elevator shaft certainly has more than three stops; therefore, the average percentage of travel distance can be derived from Table 5, and the $\%S$ will be 44%. Now, this information enables the estimation of the average travel distance and sequently the average travel time:

$$\begin{aligned} s_{\mathrm{av}} &= \%S \cdot H \\ &= 0.44 \cdot 35 \text{ m} = 15.4 \text{ m} \end{aligned}$$

$$\begin{aligned} t_{\mathrm{av}} &= \frac{s_{\mathrm{av}}}{v} + \frac{v}{a} + \frac{a}{j} + t_{\mathrm{d}} \\ &= \frac{15.4 \text{ m}}{2 \text{ m/s}} + \frac{2 \text{ m/s}}{1 \text{ m/s}^2} + \frac{1 \text{ m/s}^2}{1 \text{ m/s}^3} + 8 \text{ s} \\ &= 18.7 \text{ s} \end{aligned}$$

In the above, the magnitude of acceleration and jerk is known to be one, and the combined time of door opening and closing at the landings is measured to be eight seconds. Knowing the time of stationary to be three hours, the number of travels can be calculated as

$$\begin{aligned} n_{\mathrm{d}} &= \frac{3600 \text{ s/h} \cdot 3 \text{ h}}{t_{\mathrm{av}}} \\ &= \frac{3600 \text{ s/h} \cdot 3 \text{ h}}{18.7 \text{ s}} \\ &= 578 \end{aligned}$$

which is in the typical region of usage category 4, as can be seen in Table 4.

The ratios of different consumption times can commonly be taken from the tables provided by this standard. If the elevator is not equipped with a hibernation mode, then the two lower rows of Table 7 can be added together to form a new five-minute value.

Table 7: Standing time ratios by usage category according to [13].

Usage category		**1**	**2**	**3**	**4**	**5 − 6**
Time ratios (%)	R_{id}	13	23	36	45	42
	R_{st5}	55	45	31	19	17
	R_{st30}	32	32	33	36	41

The next part of this section focuses on calculating an energy usage example. The same elevator is considered as the one introduced in the previous section. From the usage category of 4, it could be presumed that the number of trips per day is 750, if no better information is available. However, now the value of 578 is calculated from the known and estimated data and is used for this example.

Table 6 shows that the average percentage of the rated load is 6%. Furthermore, when considering a traction elevator that is counterbalanced to 50% of the maximum load, the load factor can be calculated:

$$\begin{aligned} k_L &= 1 - (6 \cdot 0.0164) \\ &= 0.9 \end{aligned}$$

When these values, along with the measured energy consumption of the reference cycle, are put to (5), the daily running consumption becomes

$$\begin{aligned} E_{rd} &= \frac{578 \cdot 0.44 \cdot 0.9 \cdot 60 \text{ Wh}}{2} \\ &= 6.87 \text{ kWh} \end{aligned}$$

The daily standing energy consumption can in turn be calculated with (8). If the idle power consumption is measured to be 200 W and the hibernation mode consumes 20 W, then the daily standing energy usage will become the following:

$$\begin{aligned} E_{sd} &= (24 - \frac{578}{3600} \cdot 18.7)(200 \cdot 0.45 + 30 \cdot 0.19 + 20 \cdot 0.36) \\ &= 2.16 \text{ kWh} \end{aligned}$$

The total energy consumption per day will then be

$$\begin{aligned} E_d &= E_{sd} + E_{rd} \\ &= 9.03 \text{ kWh} \end{aligned}$$

If the same amount of operating days is used as with the VDI, the annual energy usage estimation of the ISO 25745 part two comes significantly lower than predicted by the VDI guideline:

$$\begin{aligned} E_{\text{annual}} &= 365 \cdot E_{\text{d}} \\ &= 3296 \text{ kWh} \end{aligned}$$

However, it should be noted that depending on the elevator system and usage pattern, the two calculation methods give greatly varying results, and this example should not be considered as a rule of thumb. The ISO/DIS 25745-2 also provides an annex that informs typical annual operating days, such as 260 for large offices, and 360 for large hotels. However, using 360 instead of 365 in the example above, would not have a large impact on the end result.

The important aspect of the standard shown in this example, was the amount of details in comparison to the VDI 4707-1, which should imply better accuracy in the consumption calculations. Furthermore, Barney and Lorente [13] have also discussed the error that is caused by the variation of the number of trips inside a certain usage category. They found that the use of the median value instead of an actual value naturally induces some error in the daily consumption estimate, but the effect of this was only found to be approximately 10% in the case study.

The energy classification of the ISO/DIS 25745-2 has a similar structure than the VDI 4707-1. Both standards introduce energy classes, or performance levels as referred in the ISO standard, for both running and standing. The idle and standing performance levels have exactly the same limit values than the VDI guideline had for standby, with levels going from one to seven instead of from A to G, as can be seen in Table 8 below.

Table 8: Performance levels for idle/standby according to [8].

Idle/standby power (W)	≤ 50	≤ 100	≤ 200	≤ 400	≤ 800	≤ 1600	> 1600
Performance level	**1**	**2**	**3**	**4**	**5**	**6**	**7**

The running performance level limits of the ISO/DIS 25745-2 are provided in Table 9, and the specific running energy of an elevator is calculated with (9)

$$E_{\text{spr}} = \frac{1000 \cdot k_{\text{L}} \cdot E_{\text{referencetrip}}}{2 \cdot Q \cdot H} \tag{9}$$

where the only possible difference is in the load factor when compared to the VDI guideline and (2). When calculating this value for the given elevator, the specific running energy becomes

Table 9: Performance levels for running according to [8].

Specific running energy for the average running cycle (mWh/kgm)	≤ 0.72	≤ 1.08	≤ 1.62	≤ 2.43	≤ 3.65	≤ 5.47	> 5.47
Performance level	**1**	**2**	**3**	**4**	**5**	**6**	**7**

$$E_{\text{spr}} = \frac{1000 \text{ mWh/Wh} \cdot 0.9 \cdot 60 \text{ Wh}}{2 \cdot 1000 \text{ kg} \cdot 35\text{m}} = 0.77 \text{ mWh/(kg} \cdot \text{m)}$$

which means a performance level of 2 for running.

The overall energy efficiency classification limits proposed by this standard are shown in Table 10 below and they can be seen to depend on both the running and standing limiting values.

Table 10: Definitions of energy efficiency classes according to [8].

Energy efficiency class	**Energy consumption per day (Wh)**
A	$E_\text{d} \leq 0.72$*Q*n_d*s_av/1000 + 50*t_nr
B	$E_\text{d} \leq 1.08$*Q*n_d*s_av/1000 + 100*t_nr
C	$E_\text{d} \leq 1.62$*Q*n_d*s_av/1000 + 200*t_nr
D	$E_\text{d} \leq 2.43$*Q*n_d*s_av/1000 + 400*t_nr
E	$E_\text{d} \leq 3.65$*Q*n_d*s_av/1000 + 800*t_nr
F	$E_\text{d} \leq 5.47$*Q*n_d*s_av/1000 + 1600*t_nr
G	$E_\text{d} > 5.47$*Q*n_d*s_av/1000 + 1600*t_nr

There are many conventions to calculate the time of not running, t_{nr}, found in the table. One method, which was also discussed earlier, is shown below:

$$t_{\text{nr}} = 24 - n_\text{d} \cdot \frac{t_{\text{av}}}{3600} = 24 \text{ h} - 578 \cdot \frac{18.7 \text{ s}}{3600 \text{ s/h}} = 21 \text{ h}$$

For the example elevator, the limiting value for energy efficiency class A would then be

$$\begin{aligned} E_{\mathrm{A_{limit}}} &= \frac{0.72 \cdot 1000 \cdot 578 \cdot 15.4}{1000} + 50 \cdot 21 \\ &= 7.46 \text{ kWh} \end{aligned}$$

and for B respectively

$$\begin{aligned} E_{\mathrm{B_{limit}}} &= \frac{1.08 \cdot 1000 \cdot 578 \cdot 15.4}{1000} + 100 \cdot 21 \\ &= 11.71 \text{ kWh} \end{aligned}$$

per day. Consequently, the energy efficiency class of the example elevator is determined to be B, as the daily consumption of the respective elevator is between the limiting values of classes A and B.

It should be noted that the ISO/DIS 25745-2 standard, which was used as the basis of this example, is currently under public evaluation; thus, it can change in the future, resulting in different calculations and classifications. Nevertheless, the main content is expected to retain.

The energy classes are important both for the manufacturer from the marketing perspective and for the buyer who wants be sure that the building has energy efficient appliances [26, Ch. 13]. The buyer aims to minimize the used annual energy to achieve lower costs of operation. The energy efficiency class with the usage category provides maybe the most valuable information regarding the buyer's purchase decision.

2.1.4 KONE EnerCal tool

KONE EnerCal is an energy calculation tool which provides fast estimation of the energy consumption of elevators. It generates lifecycle energy cost assesments from the input data given by the user. This data includes the new elevator type, information on the possible replaceable elevator system, and the characteristics of the building. Similar to the ISO 25745-1 standard, the tool excludes energy consumed by the shaft and machine room. [56]

KONE EnerCal is a hybrid system with a calculation methodology comprising multiple steps utilizing various information sources. One of the sources embeds the the efficiencies and energy consumption properties of various components used in the specific elevator set-up to the calculations. Thus, the methodology includes the energy consumption model of the elevator. To calculate the energy usage, the methodology also requires information on the building type, i.e., the volume of traffic and the structure of the shaft. The estimated or known annual trip amount is set by the user, and the methodology presumes the share of up-and-down trips to be equal. The load spectrum, presented in Table 11, is considered to be the same as suggested by the VDI guideline. [56]

The tool calculates the total annual energy consumption as the sum of energy used by hoisting, brake, control panel, and car lighting:

$$E_{\mathrm{total}} = E_{\mathrm{hoist}} + E_{\mathrm{brake}} + E_{\mathrm{control}} + E_{\mathrm{light}} \tag{10}$$

Table 11: Trip ratio by various loads according to [7].

Load in % of the nominal load	**Trip ratio** in %
0	50
25	30
50	10
75	10
100	0

Typically, when computing the savings in cost of energy with EnerCal in a case of modernization, the clearest percentual energy saving comes from replacing the lighting system with more energy efficient technology, such as light emitting diodes (LEDs).

2.2 Previous consumption reports and studies on elevators

Multiple studies and reports have been conducted on the energy consumption of elevators, but they have been regional and not comprehensive. The most known monitoring campaign in Europe, called the Energy-Efficient Elevators and Escalators (E4) Project [5], has shown that there is quite a lot of variation both regionally and elevatorwise [28]. For example, the measurements done in this project show that the variation in the ratio of standby energy is large with measured ratios ranging from 4 to 90 percent. The E4 Project also suggests that elevators can account for three to eight percent of the total electricity consumption of a building, but these values have large variance between buildings. The large dependence on the building type, used technologies, and region specific factors is shown when examining two not E4-related case studies from Norway [29] and Shanghai [30]. In a low-energy office building in Trondheim, Norway, the elevators were measured to consume around 0.3 kWh per square meter of the building, contributing to a near 0.6 percent of the total electrity consumption of the building [29]. An opposite result was found in a case of a commercial building in Shanghai, where the elevators accounted for 14 to 22% of the total energy consumption depending on the time of the year. This high figure most likely results from the older elevator technology, and the high-rise properties of the building, as the specific energy consumption could be calculated to be close to 19 kWh/m^2. However, the elevators in Shanghai were only measured for one day, and the yearly consumption was derived from this, leaving some uncertainty to the results. Though the E4 Project was conducted in multiple countries with different types of elevators, it still does not present completely satisfiable results regarding the annual consumption of elevators. This is due to consumption values being extrapolated from short-time measurements, which may be the reason for the large variances in their measurements between different measurement sites.

Another wide research project [31], executed in Switzerland, was concluded in 2005 with 33 measured elevators from a variety of manufacturers. The project finding was that the standby energy accounted for 25 to 80 percent of the total consumption. These figures are in line with the E4 findings and prove that the standby demand is a notable factor in the overall consumption of an elevator. High standby usage ratio derives from the typically low usage of an elevator, as can be realized from Table 2 on page 8. However, modern elevators tend to have low standby consumption ratio in usage categories four and up, as can be seen in [26, Annex B], but these elevators have been scarce in the previous measurement projects. The project paper [31] also presents some energy consumptions of typical traction elevators in certain type of buildings based on the research findings. These can be seen in Table 12 below. A typical traction elevator technology in this case has a permanent magnet motor with frequency converter and a gearless drive. However,

Table 12: Energy consumptions of typical traction elevators according to [31].

Type of building/purpose	**kWh p.a.**
Small apartment building	950
Office or medium sized apartment building	4350
Hospital or large office building	17 700

it should be taken into account that these values are also projections based on a calculation method of a Swiss standard [32] using a travel-cycle meter. Thus, the energy consumption is not actually measured over the year. Despite of this, when comparing the last two values with figures presented in a case study by Schindler [33] for elevators with corresponding usages, it can be seen that the values are quite close to each other. The case study presents kWh values of 4246 and 25 267, which are calculated with the VDI process introduced earlier.

A short study report [34] on the energy consumption of three measurement sites in British Columbia, Canada, is one of the few reports to study the effect of regenerative drives on the energy usage profile. The paper shows that in some elevator systems there are trips where the overall energy consumption is negative, that is, the elevator is producing energy. Naturally, the elevator cannot be a net producer of energy in normal traffic conditions, due to the losses in the mechanical and electrical system. If there were no losses, and the same people would go up and down, the net consumed energy would be zero [35]. The study report also shows, that the technology used in an elevator has a crucial impact on the energy consumption behavior. In this case, the measurements were taken both before and after retrofitting the control and drive system. When comparing the measurements, two of the retrofitted sites were noticed to generate energy during upward travels, while before they were always consuming. However, the effect of the retrofit on the trip down was negligible. Instead, the third site was measured to use over 200% more energy going up, while saving 40% going down, when comparing to the situation before the retrofitting. One possible explanation to the difference may be the used traction machine technology, because the third site was the only one with gearless direct current (DC) machinery. However, all the elevators had significantly improved their standby energy efficiency.

A paper analyzing the energy efficiency potentials of elevators and escalators [36] concludes from the basis of the E4 Project that if all the elevators currently installed in Europe would be modernized or replaced with the best available technology, the savings in energy consumption would be around 60% or 11.5 TWh. This is equivalent to around 14% of the entire electricity consumption of Finland in 2012 [37]. In other words, though the electricity consumption of elevators can be seen as relatively low, it is still considerable, and the energy consumption should not be neglected. In addition, as other energy users, such as lighting, Heating, Ventilation, and Air-Conditioning (HVAC) reduce their demand in the future, the percentage used by elevators will rise, attracting attention [38], [39].

The literature review done for this thesis revealed that there is no strong long-time measurement data of the energy consumption of elevators easily available. Nevertheless, the estimates and projections given by different studies are in line with each other, suggesting that the long-time measurements should indeed give similar results compared to calculation methods based on short-time measurements. However, regional studies include local usage patterns making, for example, the correction factors given in the studies not completely applicable worldwide [38].

3 Materials and methods

This chapter defines the methods and materials used in the process of gathering and modifying the needed data from the metering sites. In addition, the elevators selected for the measurement campaign are introduced to provide background information to the energy classification process and annual consumption calculations. The last sections present useful data that is applied to the results part of this thesis. This data includes the usage statistics of the elevators under examination, energy consumption profiles of the pilot building, and solar energy production curves.

This chapter also introduces the chosen meters, their accuracy and method of installation. There was a clear need to analyze the energy consumption in two different time scales: short-term and long-term, as both of them have their benefits and drawbacks regarding different requirements in the measured data. Both short- and long-term measuring devices were tested against a calibrated NORMA D6100 Power Analyzer at the laboratory of the university. The short-term readings can be considered to be more accurate and are used to find the error in the readings of the long-term measuring system. The error in the long-term data can then be compensated with this information.

3.1 Measuring technology

Suitable equipment was carefully selected to carry out the measurements. Elevators are equipped with variety of technologies from different eras, affecting the characteristics of the electrical system, which causes a challenge to the measuring system. Moreover, the practical issues concerning installation and data transfer vary from one building to another.

3.1.1 Challenges in measuring the energy consumption of elevators

Actual measuring principle of elevators can be considered to be fairly simple, but, in practice, the overall functioning of the system and its installation raises many challenges. With modern lighting and control equipment, the elevators have a relatively low standby power demand, and typically for a large proportion of the time, the elevators are in some sort of standby mode [5]. Measuring low electric currents would not be an issue by itself, but the high demand during travel, and especially when the elevator is accelerating, causes very high currents. Therefore, the current measuring unit needs to be capable of handling both situations with suitable accuracy. Moreover, standby modes typically introduce high amounts of harmonics in electric currents particularly in modern elevator systems that have frequency converters and other power electronics [56]. These harmonics cause ripple in the electric current waveform, inducing uncertainty to the measurements. Furthermore, the first on-site measurements revealed that in standby the elevators may have most of the electrical load on one phase, while the rest of the phases are only slightly loaded, and the consumption in these phases may not be noticed by the measuring device at all. Nevertheless, the absolute error in the energy consumption readings will still remain in accectable boundaries. In addition to measuring the energy consumption, the measuring system needs to be able to act with negative electric powers, if the elevator is equipped with a regenerative unit and line braking capabilities [11].

Naturally, safety issues have to be considered when installing the measuring system. For example, the measuring equipment is typically placed inside an enclosure to protect users from electric shocks, and the access of people into the elevators must be prevented when undergoing the reference cycle runs [11]. One aspect to notice when planning the installation is to secure the power supply to the elevators, i.e., the normal operation and especially malfunctioning of the measuring system must not interfere with the usability of the elevator system.

Another part of the measurements is the data itself. Vast amounts of data are needed first of all to be recorded, transferred, processed, and finally interpreted. The recording rate needs to be set to a level which allows storing enough useful information, while keeping the amount of data workable and analyzable. The remote monitoring and reading of the recorded values raises an issue as the machine or the electrical room may not offer suitable communication systems or is located in an area that has a low quality or no mobile network available. Establishing a reliable and robust communication network requires much designing, and even with the remote features, the system should also be equipped with a local data storage, such as a memory card.

3.1.2 Short-term measurements

An accurate three-phase power quality monitor with fast sampling and recording rate was needed for the short-term measurements. Fluke 1760 Three-Phase Power Quality Recorder was chosen and tested to be suitable for the power and energy monitoring task. Furthermore, the Fluke complies to the IEC 61000-4-30 Class-A, fulfilling the accuracy requirements set by the ISO 25745-1. Laboratory testing in various situations against high-end equipment confirmed the error to be clearly under 1% in active and reactive energies. The laboratory testing process and equipment are further introduced in Appendix A. Another conclusion found by testing was that the low demand in standby mode may not be an issue as there was no clear difference in measuring currents, power, or energy with current clamps having 5 or 50 A primary winding. Therefore, measuring low powers with the higher current clamp introduces no significant error to the readings of the chosen short-term measuring device.

Fluke 1760 was planned to monitor one elevator for a few days storing high-quality data on power and energy. It would also provide the reference cycle energy consumption readings executed after the installation of the measuring equipment. The data gathered from the Fluke at the installation site was considered to be without error and could be used to determine the error in the long-term measurement device. This error-determining process would contain the comparison of concurrent readings stored by the Fluke and lower-end measuring equipment that are installed to the supply of the same elevator. This type of procedure, demonstrated in Figure 3, was considered to allow the compensation of error introduced by the elevator environment to the lower-end measuring equipment. Short-term reading was decided to

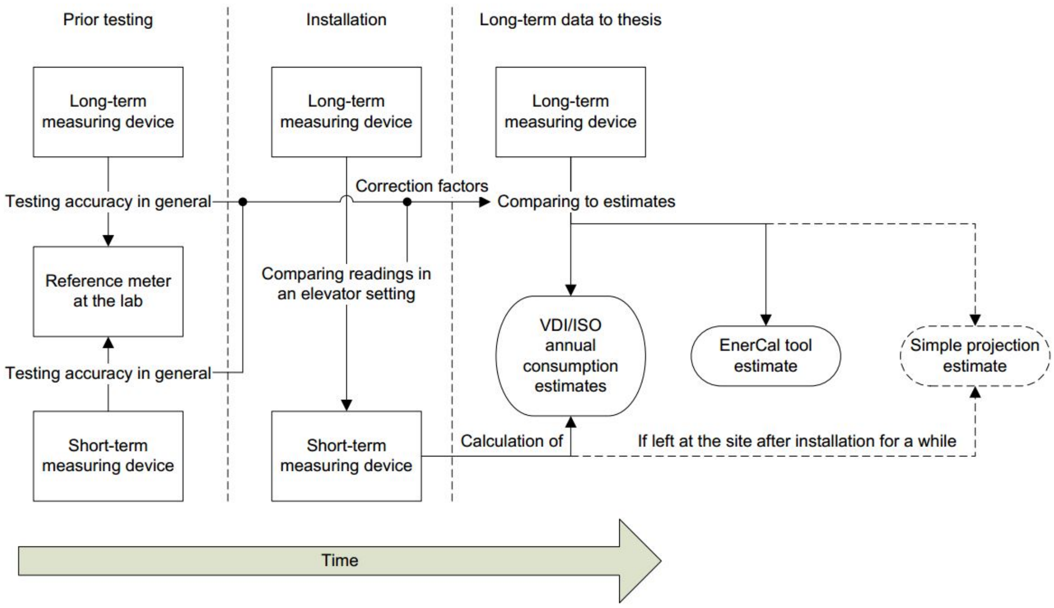

Figure 3: General measuring plan for determining the accuracy and behavior of the metering devices.

be performed on-site, though Fluke 1760 offers multiple communication possibilities.

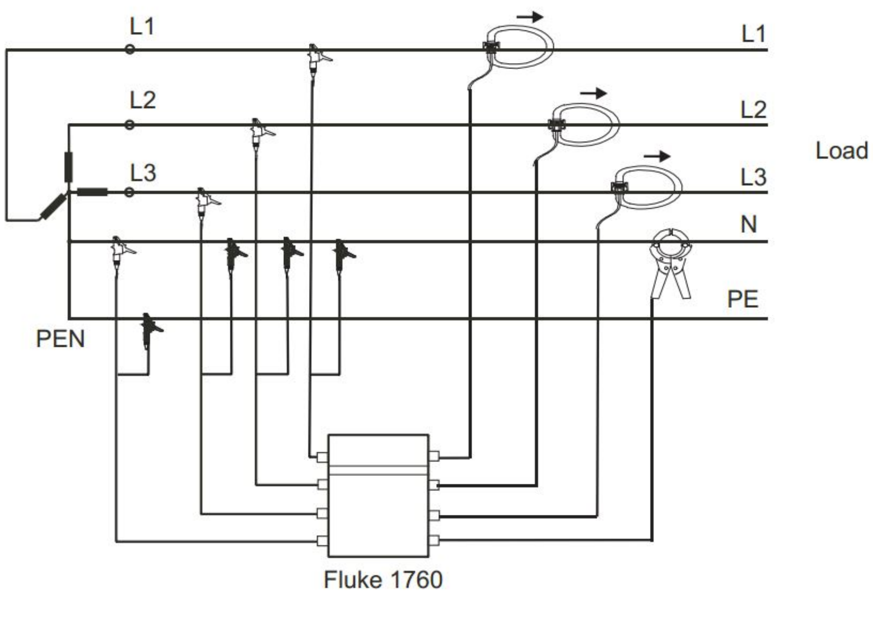

Figure 4: Fluke 1760 measuring principle on one elevator [40].

The basic measuring principle used with the Fluke is demonstrated in Figure 4. If protective earth (PE), and zero conductor (N) are not separated but form a PEN wire, the fourth voltage probe can be removed. Measuring the electric current in the zero conductor is optional but might offer some useful knowledge on the functioning of the elevator. However, zero conductor currents are not examined in this thesis.

3.1.3 Long-term measurements

In this thesis, the major focus is on the long-term measurements when estimating the annual energy consumption of the elevators. Long-term measurements require equipment that is cost-efficient, reasonably accurate, and has suitable communication systems and data storing capabilities.

The aim of this thesis was to design, install, and verify the functioning of the long-term measuring system and create a measuring concept that could be modified to be used in an international elevator consumption measuring campaign. The equipment gathered at the university prior to the project was found to be insufficient in terms of data recording and readability. Moreover, the cost of the measuring units and the required supporting systems proved to be expensive, which would hinder the expansion of the measuring campaign. An idea was considered to develop a cost-friendly system that could be left at the site for multiple months or years. At the early stage of the project, it was decided that after extensive laboratory testing, the long-term measuring system would be installed to the first office building, demonstrated in Section 3.2, as a pilot.

After extensive development with Asema Electronics Ltd, a meter manufacturer, a cost-friendly meter was tested at the laboratory, and the accuracy proved to be suitable for long-term active energy metering. Appendix B introduces some of the test results of Asema M2 meters and the basic concept of the designed measuring system. Due to the uncertainty of capabilities of the created system in actual elevator environment, a backup plan was taken into action to use more expensive meters in series with the created measuring equipment in order to verify the functioning of the designed metering system or at least to collect actual energy consumption readings of elevators in the first building.

EMU Professional three-phase kWh meters were purchased and their basic functionality and accuracy were verified at the laboratory of the university. Due to flexibility and communication aspects, an M-Bus version of the meters was chosen with M-Bus datalogger [41]. In addition, 100 A current clamps were attained to be used at the first measurement site. The basic principle of operation is presented in Figure 5. The M-Bus can be constructed using basic paired cable or similar, and the communication between the router and the server can be established using, for example, a 3G modem. The M-Bus Logger was set to send the measurement data to the server using Smart Message Language (SML). The smart-me.com server then provides reports and statistics of the connected meters to the users. More detailed data can be fetched directly from the M-Bus Logger using a Dynamic Domain Name System (DDNS). DDNS was enabled, due to the likely change in the public IP address of the 3G router after every restart of the router.

Both the developed meters and the meters from EMU have cumulative energy registers. Therefore, the energy consumption or generation within a certain period of time is found by calculating the difference in the register values. The logging interval

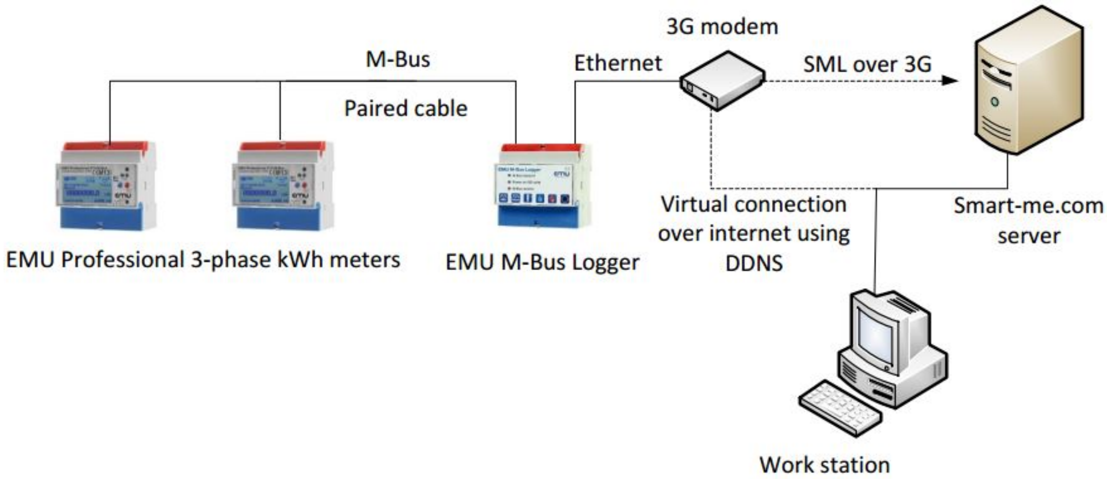

Figure 5: An example diagram of the basic structure of the measuring system built around EMU Professionals using an M-Bus data logger. Meter and logger figures fetched from [41].

of the developed and EMU meters was set to two and five minutes, respectively. The timely segregation of energy usage in the smart-me service is built automatically depending on the type of consumption. Thus, the energy consumption profiles can appear to be slightly different when comparing to the plain M-Bus Logger data.

A shorter test run, similar to the one presented in Appendix B, was conducted also for the EMU Professional meters. Table 13 introduces the overall accuracy of the EMU devices compared to the developed low-end metering system. The EMU meters can be seen to have less variation between the readings but somewhat more error in certain data registers than the developed system. The larger error can be explained with not calibrating the meter for the testing setup or due to the fact that larger current clamps were used with relatively low testing electric currents. Thus, the EMU meters are thought to be more stable in their accuracy between different electrical devices, and they could offer a more realiable reading in the elevator environment and fulfill the 10%-accuracy requirement proposed by [24] in various situations. Furthermore, the variation in accuracy between phases was noticed to be clearly smaller with EMU devices than with the Asema devices, which could derive from the difference in the method of measuring the voltages of the second and third phases. EMU Professional measures every phase voltage, while the developed meter only measures voltage in the first phase. More detailed description of this is presented in Appendix B. Both metering systems are capable of recording inductive and capacitive reactive energies, but these measurements are not included in this thesis. Therefore, the accuracy comparison of these registers is not introduced. Both measuring systems were equipped with openable-core current transformers (CTs), inducing some excess error compared to solid-core current transformers [42], but simplifying the installation procedure at the measurement site.

Table 13: Error percentages in total energy of the tested meters

Developed meter	**Phase sum error%**	**EMU Professional**	**Phase sum error%**
Consumed energy (inductive load)			
M1	-2.0	**EMU1**	2.9
M2	2.1	**EMU2**	1.0
M3	4.6	**EMU3**	1.6
M4	-0.2	**EMU4**	0.2
Consumed energy (capacitive load)			
M1	-9.3	**EMU1**	-5.6
M2	-6.2	**EMU2**	-5.8
M3	-8.0	**EMU3**	-5.3
M4	-7.0	**EMU4**	-4.9
Generated energy (inductive load)			
M1	0.5	**EMU1**	-10.2
M2	-1.5	**EMU2**	-8.0
M3	-21.6	**EMU3**	-8.1
M4	0.7	**EMU4**	-5.8
Generated energy (capacitive load)			
M1	8.4	**EMU1**	-0.1
M2	10.6	**EMU2**	-0.3
M3	2.6	**EMU3**	-0.5
M4	10.6	**EMU4**	-0.6

3.2 Measurement sites

The time period reserved for this thesis allowed the elevator measurements of one mid-rise office building in Espoo. The building, later denoted as Building 1, was mostly occupied by only one company and acted as a pilot site for the metering systems introduced in Section 3.1.3. A plan was to verify the functionality of the developed and EMU measuring systems in both consumption and generation states. However, the first installation site was discovered not to have a regenerative unit; therefore, this thesis does not identify the prospects of energy production of elevators based on actual measurements but discusses them in general.

Building 1 is equipped with an elevator group with four elevator cars, and the usage can be considered to be evenly distributed between the cars. One of the elevators is fed from a reserve power supply enabling service use. Table 14 shows the characteristics of the elevator group in Building 1. This information enables the calculation and estimation of key parameters requested by the VDI 4707-1 [7] and ISO/DIS 25745-2 [8] energy classification schemes introduced in Sections 2.1.2 and 2.1.3, respectively. The defined parameters are presented in Table 15.

The first three elevators were fed through a common three-phase electricity sup-

Table 14: Characteristics of the elevator group in Building 1.

Number of cars	4
Nominal load	1500 kg
Counterbalance	50%
Nominal speed	2.5 m/s
Full lifting height	59.1 m
Number of floors	16
Machinery	Gearless PMSM

Table 15: VDI 4707-1 and ISO/DIS 25745-2 parameters derived from elevator characteristics of Building 1.

Scheme	**VDI**	**ISO**
Usage category	4	4
Load factor	0.7	0.9426
Average travel distance	n/a	26 m
Number of travels per day	n/a	750
Average standby time	21 h	n/a
Average travel time	3 h	n/a

ply, limiting the voltage measurement points to only three. The fourth elevator required another three voltage measuring points, as it was connected to a separate supply. One EMU and one developed meter were installed to each elevator supply. The EMU devices were set to measure voltages from every phase, but the developed meters were only connected to the first phase voltage.

The VDI guideline states that the energy usage of the group dispatching system should be measured and evenly distributed between the elevators. In addition, the consumption of car cooling, heating, and, for example, call panels should be determined and documented. However, Building 1 caused a challenge in verifying whether these consumers were behind the elevator supply or whether they were fed by some other supply. Furthermore, the ISO/DIS 25745-2 does not cover these consumers when determing the energy consumption of elevators.

3.3 Comparison material

This section presents material that is required when inspecting the results of this thesis. The first two sections introduce the usage patterns of the elevators in Building 1 as well as the total electricity consumption statistics of the building. The third section examines solar power generation characteristics in Finland, and this information is later, in Chapter 4 and Chapter 5, used to identify the prospects of utilizing solar power with elevator systems.

3.3.1 Usage statistics of elevators

A critical source of information for this thesis and the project in general was KONE Elink, an application reporting the operation statistics of the elevators. Reports can include the number of starts in total, the number of starts with different loads, and travel time. This information is later utilized in Chapter 4, where the consumption data is analyzed against travel statistics.

Typically, the arrival rate of passengers or the usage rate is distributed to five-minute sections [15, Sec. 3.2], and this method is also used in this thesis. Figure 6 presents a common arrival rate in an office building, and the amount of arrivals can be seen to peak around five minutes before the deadline, for example, start of work or lunch. However, presently, many work places have flexible working hours, but as

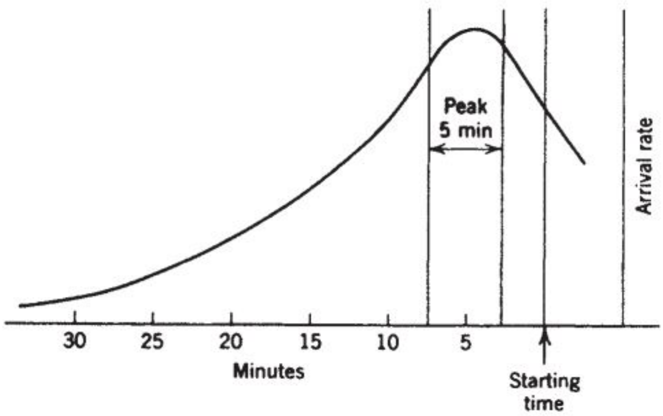

Figure 6: Typical arrival rate in an office building [15].

[15] states, the use of five-minute periods for studying the peak traffic of elevators has been found suitable in every building type. In addition, the profile provided by Figure 7 supports the passenger behavior suggested by the arrival rate theory. The figure also reveals the average loading profile of one elevator in Building 1 on both weekdays and weekend based on data derived from Elink start load statistics in March 2014. If an average person is presumed to have a mass of 80 kg, then the highest peak of the figure shows that the average amount of people traveling on a weekday between 10:55 and 11:00 is almost 18. A similar profile, in Figure 8, but without any knowledge of cargo, is formed by plotting the average number of travels for one elevator. The profiles seem to have similarities in peaking, but the effect of transporting different amount of people during certain periods is clear. For example, the morning peak has around the same amount of trips as the lunch hour,

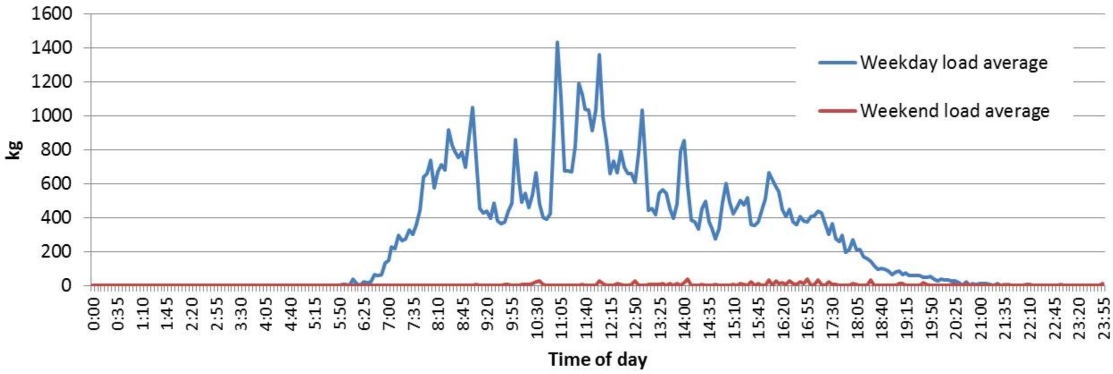

Figure 7: Average mass carried during a 5-minute period per elevator in March: Building 1.

but has, on average, less people inside the elevator. This may derive from people having a tendency to go for lunch in larger groups.

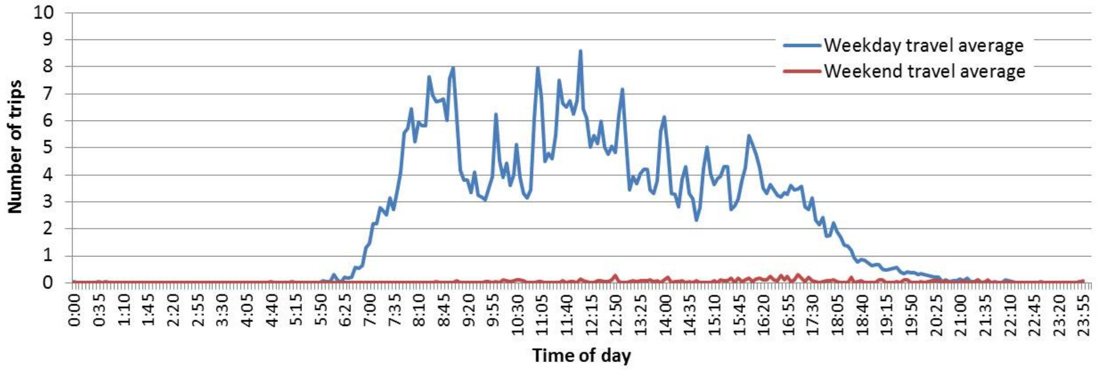

Figure 8: Average number of trips per elevator based on 5-minute averages in March: Building 1.

Other important values given by the Elink were the average travel time and the amount of total starts derived from statistics of over nine months. The variables required by the standards then became as follows:

$$\begin{aligned} t_{\mathrm{av}} &= 24.2 \text{ s} \\ n_{\mathrm{d}} &= 400 \\ t_{\mathrm{nr/standby}} &= 21.3 \text{ h} \\ t_{\mathrm{r/travel}} &= 2.7 \text{ h} \end{aligned}$$

for each elevator in the group. The average daily travel value of 400 is calculated for every day not just for working days. The average weekday value was noticed to be 550. Another piece of statistics provided by the nine-month data is the ratio of travels under certain loads presented by Table 16, showing that a major portion of the travels is performed on near-empty cargo.

Table 16: Ratios of travels with different loads according to 9-month data from Elink in Building 1.

Percentage of maximum load Q	**0–20%**	**20–40%**	**40–60%**	**60–80%**	**80–100%**
Ratio of starts	96.46%	3.29%	0.23%	0.02%	0.0002%

3.3.2 Energy consumption of pilot building

One aim of this thesis is to analyze the correlation of energy consumption of buildings and elevators within them. This section introduces the electrical energy consumption profiles of the first building under elevator measurements. This data is gathered by the kWh meters that electricity companies use to bill the user of the building.

The monthly electricity consumption of Building 1 is provided in Figure 9, where the monthly usage has been calculated as an average based on years 2012 and 2013. Variation between months can be seen to be minor, and is most likely dependent on

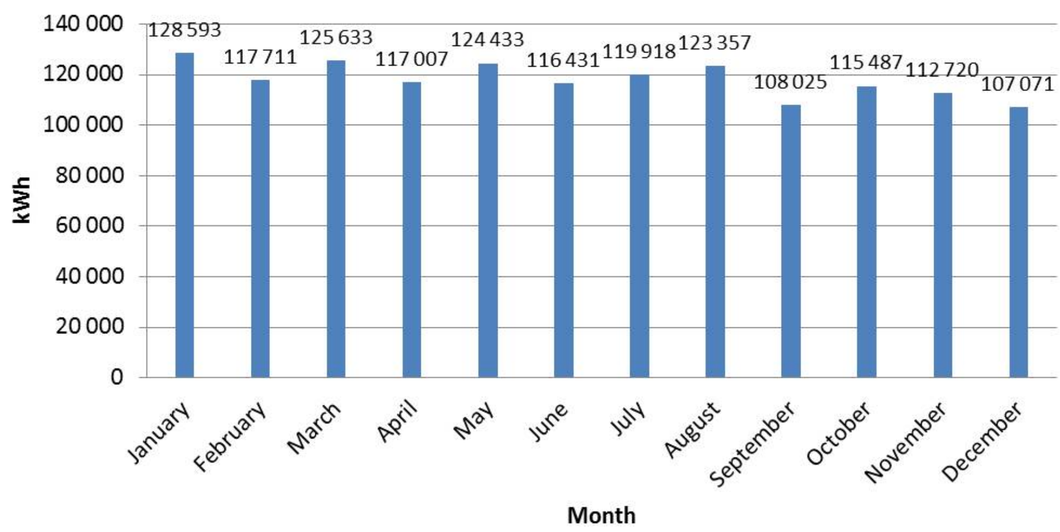

Figure 9: Electricity consumption of Building 1 by month as average values based on years 2012 and 2013.

the number of days, especially working days, in a month. The average annual total electrical energy usage by Building 1 during these two years was calculated as 1.42

GWh. The monthly variation between the two years was noticed to be considerable (between -15% and +9%), but the total annual usages did not differ greatly.

Figure 10 shows the electricity usage profile of the building in February prior to the elevator measurements. Weekdays can be seen to resemble each others, while the weekend clearly has, on average, low consumption, not much different from the night time demand. This type of profile is typical of office buildings [43, Sec. 6.1]. A more detailed daily consumption profile of a normal weekday is presented in the

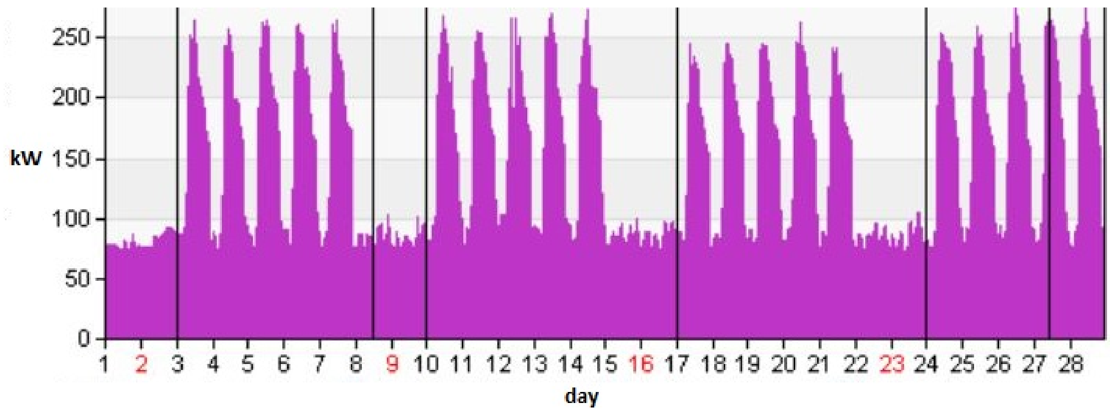

Figure 10: Energy consumption profile in February 2014 of Building 1.

results section of this thesis.

3.3.3 Photovoltaic power generation model

This section introduces some results of a power generation model [44] for photovoltaics in Southern Finland to provide background for the analysis of the prospective uses of photovoltaics in elevator systems. Three different tilt angles are investigated: 0° (horizontal), 42° , and 90° (vertical).

Figure 11 reveals that the vertically mounted panel will yield a more stable monthly production over a year, while the horizontal panel will produce most of the energy during the summer months and negligible amounts during the winter. For most of the year, a 42° tilted panel is between these two options in terms of power generation. According to the model, most electricity is annually produced by the 42° system although the differences are minor, as can be seen in Table 17.

Most likely, the wisest mounting angle for a building from these three options is the 42-degree angle because it offers the most annual energy and the peak production is during hot summer months that require much electricity for cooling. The production potential profile of the tilted panel is investigated next. The focus is on the shape of a theoretical energy production curve, which is presented in the form of power indices. The actual power can be derived when the power index values are divided by thousand and multiplied by the nominal power of the solar module system [44]:

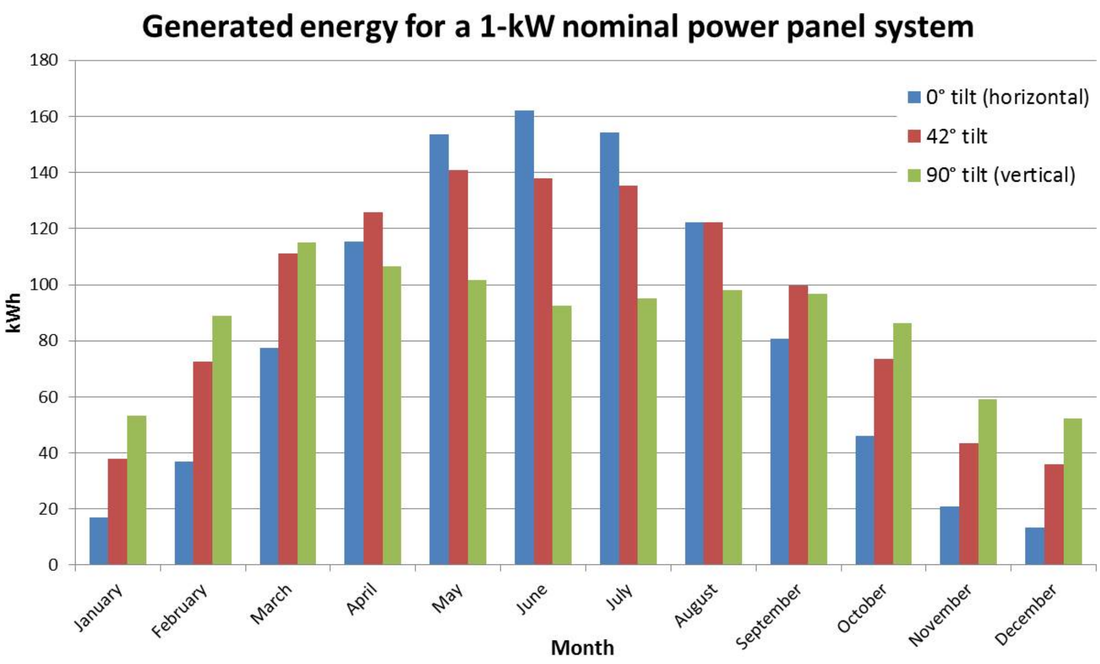

Figure 11: Monthly generated energy for horizontal, tilted, and vertical 1-kW panel systems adapted from [44].

Table 17: Annual electricity production of 1-kW nominal power photovoltaic systems in different tilt angles adapted from [44].

Panel mounting angle	kWh p.a.
0°	999
42°	1136
90°	1046

$$P_{\text{m,h}} = \eta_{\text{eff}} \cdot P_{\text{max}} \frac{p_{\text{index}}}{1000} \tag{11}$$

When comparing the Figures 11–12 to the plots presented in [44], it can be seen that there are some minor differences which arise from the use of sunshine hour ratio denoted as sunshine hour value, t_{ssh}. This thesis uses a sunshine hour value of 0.437 for every month, which produces a realistic average value of annual energy [44]. Figure 12 shows that a halfway tilted panel brings the monthly curves relatively close to each other with peak power around noon. However, the winter months can be clearly seen to yield little energy and have a peak power of about half of the summer months.

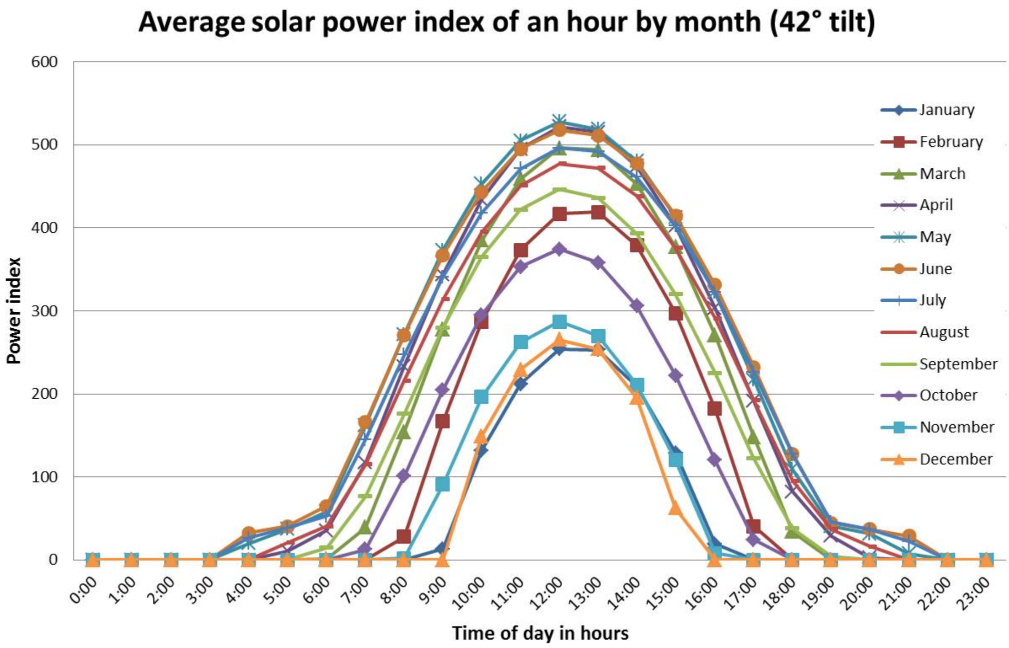

Figure 12: Hourly power index values by month for 42° tilted panel adapted from [44].

4 Results

This chapter presents the results gathered from the first measurement site. Readings from the short-term measuring device are introduced first, and they form the base for calculating the estimates and energy efficiency classes according to the VDI guideline and ISO/DIS-25745-2 standard. The long-term energy consumption data is then utilized to identify the differences and similarities of the estimates and actual readings. Furthermore, this chapter identifies the proportion of the elevators in the total consumption of the building, designs a plausible photovoltaic system to be used with the elevator group, and determines the correlation between energy usage and passenger traffic.

4.1 Short-term measuring device readings

Fluke 1760 was installed as depicted in Chapter 3, and read after a reference cycle and a couple of days, depending on the data need. The Fluke recordings include phase voltages and currents, harmonics, and reactive and active powers and energies per phase. However, only the active powers and energies are presented below, as they are in the scope of this thesis.

4.1.1 Reference cycle measurement

Reference cycle, depicted in Section 2.1.1, was performed with elevator 1 in Building 1, and the power profile during 11 travel cycles is shown in Figure 13, where the high peaks are caused by the car traveling downwards, as the drive system has to lift the counterweight. The ISO 25745-1 standard suggests the test to be run with no load, but due to the nature of the elevator controllers, the test in Building 1 was conducted with one person weighing 75 kg inside the car. Nevertheless, this only comprises five percent of the nominal load and should not be a significant factor in the end results. The elevator was seen not to have any energy saving modes; thus the idle and standby demand were measured to be equal. Table 18 presents all the results identified with the reference readings. Every elevator in the same group was considered to have the same consumption properties, and this presumption was seen relatively accurate by measurements from long-term measuring devices.

Table 18: Results of ISO 25745-1 reference cycle measurements in Building 1.

Idle demand	172 W
Standby demand	172 W
Average reference cycle consumption	140 Wh

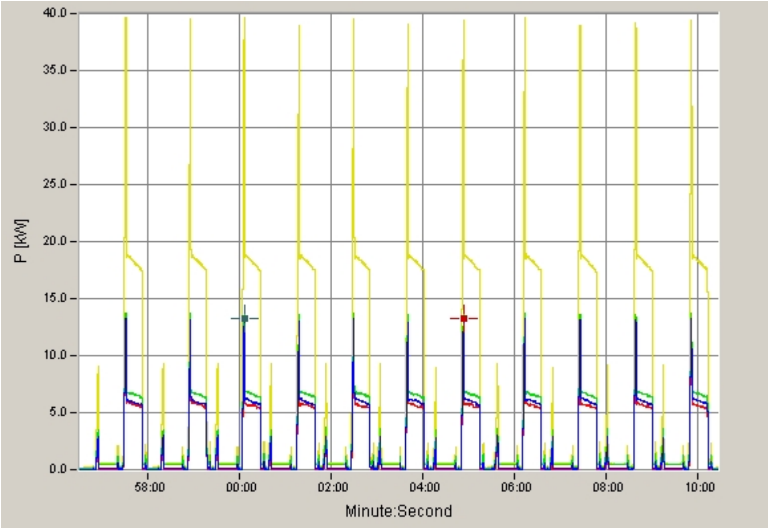

Figure 13: Power profile of one elevator in Building 1 attained from Fluke 1760. Yellow color represents the total power of the three phases.

4.1.2 Simple projection of annual consumption

Fluke 1760 was left at the pilot site to measure elevator 4 for three days, and after that elevator 1 for another three days. A simple annual projection estimate for the entire elevator group was calculated on the basis of the information provided by these six days, by multiplying the average weekday and daily weekend consumption with 260 and 104, respectively. Naturally, the number of working days is somewhat lower than the number of weekdays, but some weekends also have more activity balancing this deficiency in the presumption. The following short-term annual consumption estimate was derived for the entire elevator group:

$$\begin{aligned} E_{\mathrm{a}} &= 4 \cdot (260 \cdot E_{\mathrm{weekday}} + 104 \cdot E_{\mathrm{weekend}}) \\ &= 4 \cdot (260 \cdot 20.0 \text{ kWh} + 104 \cdot 5.2 \text{ kWh}) \\ &= 22\,963 \text{ kWh} \end{aligned}$$

Section 4.3 compares this figure to estimates provided by the VDI guideline, ISO/DIS 25745-2 standard, and to the annual consumption projection provided by long-term measurements. The annual projection value of the Fluke could have been slightly improved by checking the amount of travels on the measurement dates to the average daily amount of travels of a year. However, this would not have been so straightforward because the elevators always have a large standby consumption as well.

4.2 Long-term measurements

This section introduces energy consumption readings gathered by the long-term measurement setups. The first part determines the plausible error in the measured figures and proposes a compensation method that is used to calculate the actual energy consumptions of elevators.

4.2.1 Reliability analysis of long-term consumption results

In order to determine the functionality and performance of the long-term measuring equipment, the accuracy testing, mentioned in Section 3.1.2, was performed with elevator number four in Building 1, and the register values were proven to fulfill the accuracy requirements of 10% in long-term energy consumption measurements, as can be seen in Table 19. The overall accuracy was performed during the first day and night after the installation. The standby readings during the night were seen to have a relatively constant error of -13 to -18 percent, which amplifies the assumption of the difficulty of measuring low standby demand. Nevertheless, the significance of the standby error was mitigated during peak demand hours, as the error during morning peak demand was determined to be between -3 to -6 percent. A plausible reason for the registers having values below the actual amounts may be the issue of measuring low currents discussed previously in Section 3.1.1. In addition, low-end measuring equipment commonly have a cut limit in low power situations, where the measured value is set to 0 W instead of, for example, 9 W. This scenario was identified in the laboratory testing, but it does not fully explain the difference, especially during the peak demand. The result of gaining moderately lower values at the installation site is reasserted by the laboratory testing, as the Fluke revealed the elevators in Building 1 to be slightly capacitive in standby, and only shortly inductive during travel, and all of the installed meters were tested to have a negative error in consumed energy register with capacitive load, which was already seen in Table 13 in the previous chapter.

Table 19: Error percentages in total energy consumption against Fluke 1760.

Developed meter	**Phase sum error%**	**EMU Professional**	**Phase sum error%**
M4	-5.2	**EMU4**	-6.9

The metering units in elevators one to three in Building 1 were considered to have similar accuracy properties as the units installed to fourth elevator, since the EMU devices were determined to have similar error behavior in laboratory testing as was shown in the previous chapter. Table 20 shows the reading comparisons of the developed and EMU meters in elevators one to three and reveals that both metering systems are capable of reliable long-term measuring. However, the following result sections are based on data gathered by EMU devices, as M2 had some issue of determining the positive direction in the setup phase, due to the low standby electric current. This issue was resolved for the next measurement site by fixing the positive and negative power directions to be based on the direction of the clamps. The M2 register value for Table 20 was taken from the negative energy side, i.e., the generated active energy register. The following method was performed in the subsequent long-term result sections to compensate the determined error in the readings of the EMU Professional meters: the power values of under 300 W were divided by a factor of 0.865, while other results were divided by a factor of 0.948. The accuracy determining and error compensation process is further discussed in Chapter 7 which recommends possible fine tuning aspects to the process.

Table 20: Consumption energy register values after first overnight reading.

Developed meter	**Phase sum (kWh)**	**EMU Professional**	**Phase sum (kWh)**	**Ratio Mx/EMUx**
M1	14.89	**EMU1**	14.85	1.003
M2	18.62	**EMU2**	17.38	1.071
M3	16.56	**EMU3**	16.61	0.997

As mentioned in Section 3.2, it was slightly uncertain whether the energy consumption of heating, cooling, call panels and the group controller were included in the measurements as required by the VDI, and on the contrary, excluded by the ISO 25745 part two. Nevertheless, the electric schematics indicated that nearly everything associated with the elevator group was fed from the supplies that were under measurement. For example, the Elink traffic reporting tool was noticed to be connected to an uninterruptible power supply (UPS) device that was powered by the elevator system. Though the following results may lack some information, the difference in consumption figures should not be significant. Futhermore, this difference should not affect the analysis of utilizing the energy consumption standards. A major effect could plausibly be the change in the energy efficiency class.

4.2.2 Consumption over examining period

As was presumed, the elevators in Building 1 were used in quite equal amounts, as can be seen in Figure 14 that shows the consumption division in a seven-day period. This thesis used a five-week examining period for the long-term measurement data gathering, and this length can be considered relatively long when compared to most studies but is far from a 52-week year. Nevertheless, the extrapolation method should give good preliminary results of the annual consumption of the elevators that were measured. The long-term reading equipment was left at the measurement sites to gather more information for further studies.

EMU Professional devices installed at Building 1 recorded a kWh value of 2350 kWh during the five-week measuring period in March and early April 2014. This figure has been error compensated with the method described in the previous section, and can, therefore, be considered as the best knowledge available when projecting the annual consumption of the elevator group.

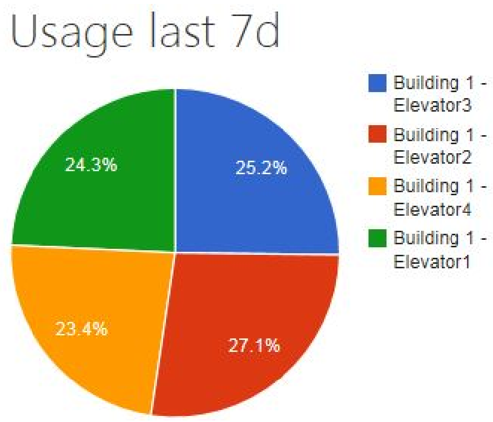

Figure 14: Division of energy consumption inside the elevator group of Building 1 as given by smart-me.com.

4.2.3 Energy demand pattern

In order to identify the energy usage behavior of elevators, an energy demand profile is needed. Depending on the type of the building, the profiles can be constructed in various forms. This thesis uses a basic weekday–weekend segregation, which is a viable option in office buildings. Lorente Lafuente [26] used eight different day types in her models, but for the measuring period of Building 1, the use of Monday–Friday and Saturday–Sunday segregation proved to be sufficient, since the days within the same group were seen very identical.

Figure 15 presents the average weekday (working days) and weekend (out-of-office days) power demand profiles of one elevator. The profiles have been derived from error compensated five-minute averages measured by the EMU Professional devices during March 2014. Hence, the profiles are more jagged than a common profile based on hourly averages, but the overall shape of the weekday profile can be seen to resemble the hourly figure presented and explained in more detail later in Sections 4.4.1 and 4.4.2.

Researchers and literature have been discussing the ratio of weekend consumption in relation to weekdays [26], [57]. Previously, the usage of elevators in office buildings on a weekend day have been considered to be around half of that of a weekday [26]. Naturally, this ratio depends on the work customs of a region the elevator is located in. For the elevators in Building 1, located in Finland, the ratio of travels during weekends was only around five percent according to the Elink statistics. The energy usage ratio of weekends was calculated to be 20%, and this result is also supported by the Figure 15. The larger energy consumption ratio compared to travel ratio derives from the standby demand which is always present in the current configuration of the elevator group in the pilot measurement site.

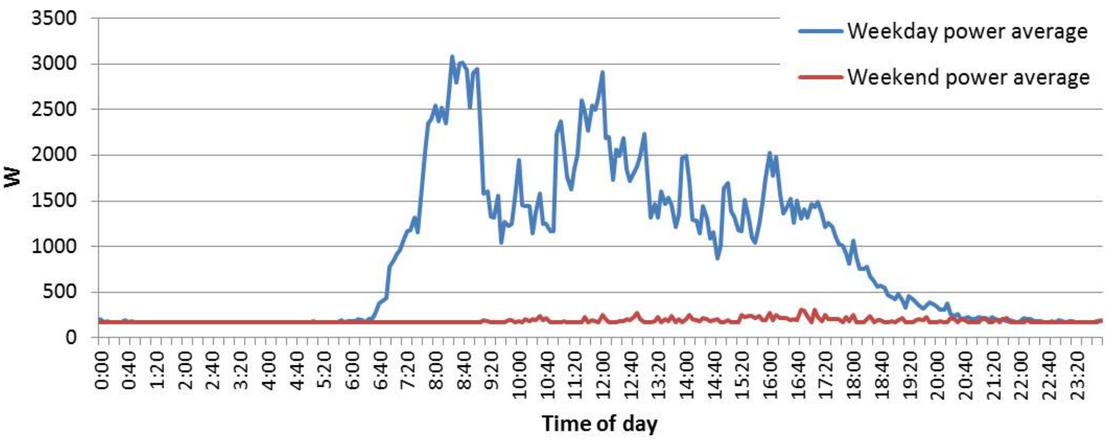

Figure 15: Electricity power demand profile per elevator based on 5-minute averages: Building 1.

4.3 Projections and estimates provided by consumption models

Table 21 on the next page presents the annual estimates provided by the VDI guideline and ISO/DIS 25745-2 standard with various calculation methods based on different source knowledge from the usage statistics of Building 1. As mentioned on page 16, the VDI typically utilizes 365 operating days in its calculations, while the ISO standard also discusses using 260 operating days for large offices. Elink data was used to calculate average standby and travel times more accurately than standards provide as default values. The average travel time has also been used in the default ISO/DIS 25745-2 calculations, as the jerk and door operation times of the elevators in Building 1 were not known. However, the average travel distance was calculated as guided in the standard. The effect of using Elink average travel time with the number of travels suggested by the ISO 25745-2 for elevators in category 4 buildings resulted in both absolutely and relatively lower standby energy usage than with the default standard values, as the time of not running, t_{nr}, became as 19 h instead of 21 or 21.3 h that were introduced earlier.

EnerCal estimated annual electricity usage with input elevator characteristics and a yearly travel amount of 146000 per elevator, a figure derived from Elink statistics over a period of nine months. EMU readings have been compensated with the method presented in Section 4.2.1, and the Asema M2 value has been extrapolated from a kWh consumption figure after 16 days and divided by a compensation factor of 0.948 based on the error percentage introduced in Table 19 previously. The difference in the annual projections of the long-term devices seems to be notable. The largest reliability issue to Asema devices resulted from the meter in the second elevator having difficulties determining the positive power direction, as discussed earlier. If Asema consumption data would have been compensated with the same power method as EMU readings, the Asema M2 estimate would have also slightly

Table 21: Annual consumption estimates and projections for elevator group in Building 1.

Method	**Operating days used in calculation**	E_{annual} (kWh)	**Ratio** $E_{\text{annual}}/E_{\text{EMU}}$
VDI	365	37 957	1.553
VDI$_{\text{ISO2}}$	260	27 038	1.106
VDI$_{\text{Elink}}$	365	34 764	1.422
ISO	260	26 036	1.065
ISO$_{\text{VDI}}$	365	36 551	1.496
ISO$_{\text{Elink}}$	365	22 306	0.913
Tool	**Usage method**	E_{annual} (kWh)	**Ratio** $E_{\text{annual}}/E_{\text{EMU}}$
EnerCal	146000 trips/a	33 852	1.385
Fluke	6-day projection	22 963	0.9460
Asema M2	16-day extrap.	20 990	0.859
EMU	5-week extrap.	24 440	1.000

risen, as the low consumption values during weekends would have increased relatively more than on weekdays when the error percentage was determined. Furthermore, the 16 days used in the extrapolation included two extra weekend days, lowering the simple projection outcome by nine percent, if the weekend consumption ratio is presumed to be 20%, a figure presented in the previous section. Thus, the actual difference in recorded annual energy usage between the two long-term measuring systems can be considered to be minor. On the other hand, also the short-term projection method, demonstrated in Section 4.1.2, seems to offer a good alternative to long-term readings, as discussed on page 21.

The estimation method of the ISO standard seems to give the best result both with basic presumptions and with Elink travel information. Instead, the VDI guideline provides near accurate estimate when used with operating days suggested by the ISO standard, but fails with the basic presumptions and with the Elink travel information. Moreover, EnerCal provided a greatly higher estimate than actual for the elevator group in Building 1. One plausible factor may have been a mistake in choosing the right components and features of the elevator for the EnerCal input data. Nevertheless, both EnerCal and VDI estimates with Elink travel amount provided similar figures. The results are analyzed in Section 5.1 in more detail.

Figure 16 reveals the standby and travel ratios calculated by the standards and the average daily (including weekdays and weekends) kWh value in both modes for one elevator. EMU Professional and Fluke values were derived by categorizing all five-minute average power values as standby, if the power value was under 200 W. As the five-minute values that were categorized as travel generally still contain times of standing, the EMU and Fluke travel consumption ratios will yield to a relatively higher figure than actual. Furthermore, if the standby demand is con-

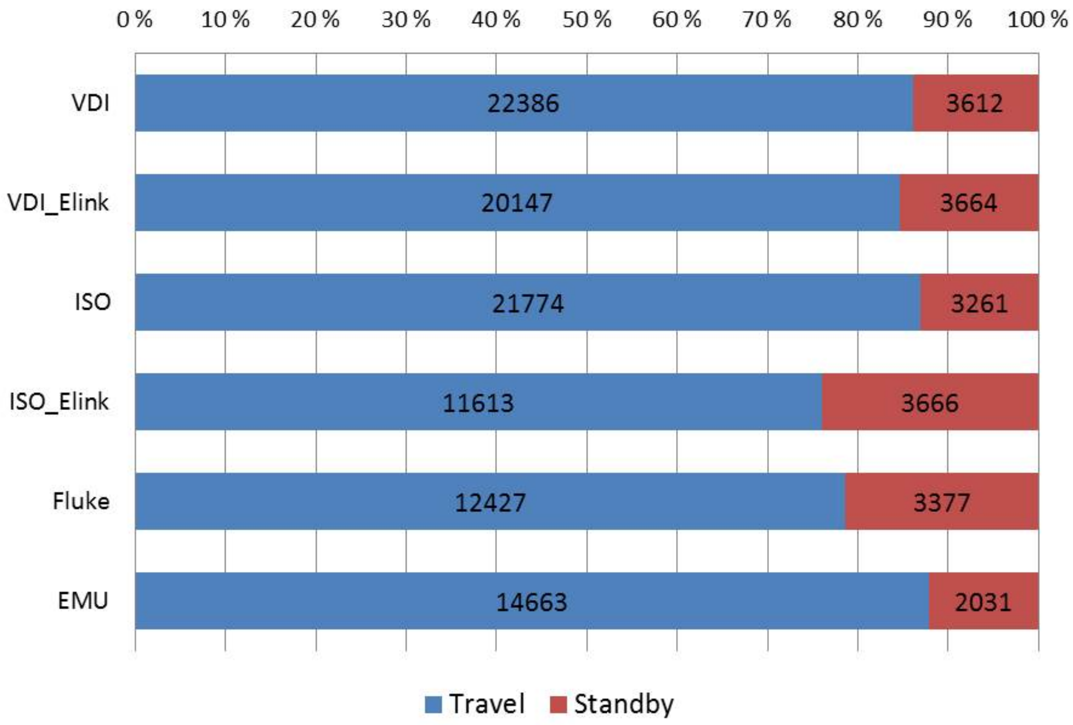

Figure 16: The ratio of standby and travel consumption with average daily kWh values for an elevator in Building 1.

sidered to be always present as the base demand, and the travel consumption is seen to be the consumption that exceeds the standby threshold, here 172 W, the standby consumption ratio becomes significantly higher. With EMU readings, this ratio in total becomes as 25%. For a weekday and weekend, this ratio was found to be 19% and 94%, respectively. All of the ratios determined by this process yield to higher ratios than proposed by Figure 16 for EMU. Nevertheless, the average ratio of 25% is approximately the same as the ratio provided by the ISO standard with Elink statistics, which is no surprise, as it uses actual travel amounts with actual measured consumptions from the reference cycle.

Travel and standby ratios of the EnerCal tool have not been introduced here, as the tool does not provide these figures. However, similar tools providing similar annual estimates seem to present the ratios in reverse compared to the above figure: travel 0.3 and standby 0.7, for example. This difference may result from componentwise calculation methods dividing the consumption of individual components into standby and travel or from the difference in defining various operating modes as standby or travel. Moreover, EnerCal considers only one elevator, and the electricity usage of the control system is calculated for the elevator. However, Building 1 having four elevators results in the energy usage of the control system to be divided between four units, decreasing the total consumption in comparison to multiplying the EnerCal estimate by four. However, this effect is presumed to be minor.

With regards to the energy efficiency classes, all six VDI and ISO calculations produced almost equal classifications in Building 1. This is due to travel and energy efficiency classes having dynamic border definitions. Naturally, the standby class was the third best (C or 3) because of the stationary demand being between 100 and 200 W, and both of the energy classification schemes having same border values for standby power. The total energy efficiency classes were determined to be category B in every scenario. The only minor difference was in running classification, as the VDI suggested class A for travel, while, as with the ISO/DIS 25745-2 method, the class was calculated one performance level worse (2). Nevertheless, when examining the calculated figures, both of the VDI and ISO standards were very near to their class A border, and the difference of the determined classes may change if the intermediate values were rounded differently.

4.4 Comparing the energy profiles of buildings, elevators, and solar panels

This section is dedicated to examine the correlation between the energy consumption of buildings and elevators. In addition, the section utilizes the solar energy production curves presented in Section 3.3.3 to see similarities to the energy consumption behavior of elevators.

4.4.1 Energy consumption of buildings against elevator data

To determine the portion of elevators in the total electricity usage of buildings, this section uses the electricity data from Building 1, introduced in Section 3.3.2, along with the energy consumption readings of the EMU Professional meters installed to the electricity supplies of the elevator group in Building 1. Figure 17 compares the concurrent electricity usage by hourly averages of Building 1 against the consumption of the elevator group. The profiles can be seen to peak within the same hours, but at the same time, the effect of elevator usage can be stated to be minor on the overall consumption of the building. This statement is supported by Figure 18 showing the average hourly ratio of the elevator group in total consumption. The momentary power ratios can be considered to fluctuate from the average, as the total demand of the building is typically more stable than the usage of the elevators. The hourly ratio is at its largest during peak traffic hours at the start and end of the workday and during lunch time when people are moving from their floor to the restaurant. The overall consumption ratio on this particular Monday was calculated to be 2.35%, a value little less than determined by the E4 Project. When regarding the entire month of March 2014, the ratio of elevators in the total consumption was

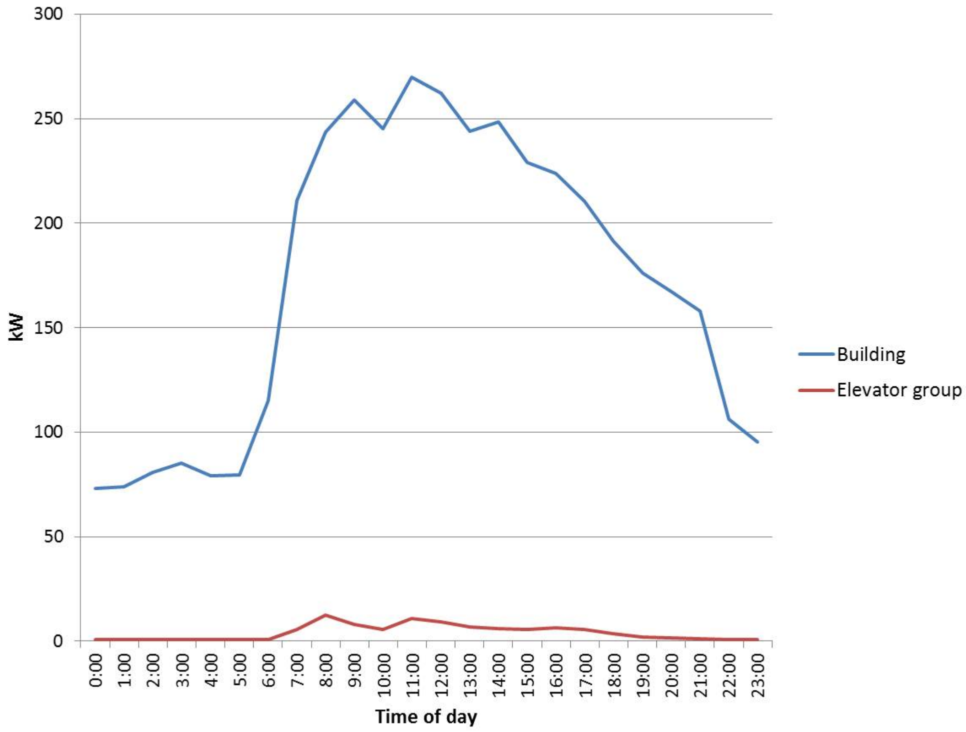

Figure 17: Electricity usage in Building 1 with concurrent total consumption of the elevator group on one Monday in March.

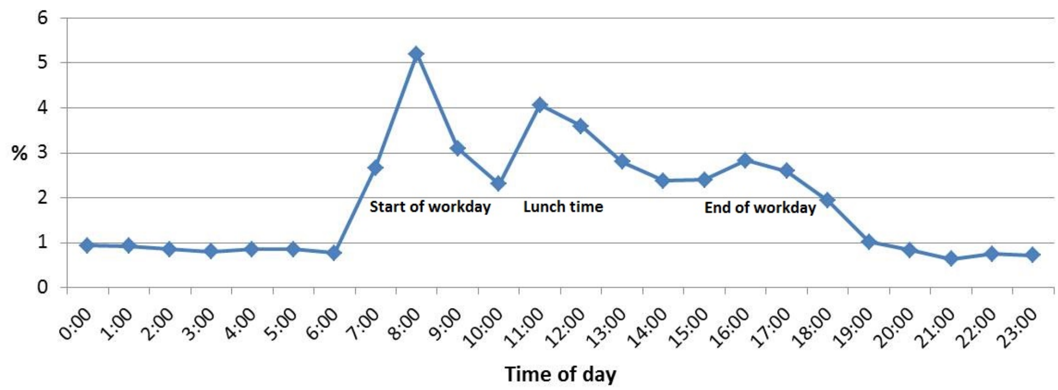

Figure 18: Ratio of elevators in the total consumption of Building 1 on one Monday in March.

calculated to be

$$
\begin{aligned}
r_{\text{el.group}} &= \frac{E_{\text{el.group,March}}}{E_{\text{building,March}}} \cdot 100 \\
r_{\text{el.group}} &= \frac{1996 \text{ kWh}}{104\ 338 \text{ kWh}} \cdot 100 \\
r_{\text{el.group}} &= 1.9\%,
\end{aligned}
$$

which signals an even lower consumption ratio for elevators in Building 1. The consumption of the elevator group was attained from error compensated EMU Professional figures during March 2014, and the concurrent Building 1 data was collected from an application provided by the electricity company. Electricity usage in March 2014 can be noticed to be clearly smaller than presented in Section 3.3.2; therefore, the ratio could be even less in another year.

If the annual electricity consumption of Building 1 is presumed to be as defined in Section 3.3.2, and the annual estimate given by EMU Professional meters presented earlier in Table 21 is considered, the annual consumption ratio of the elevator group in Building 1 can be determined to be

$$\begin{aligned} r_{\text{el.group}} &= \frac{E_{\text{EMU}}}{E_{\text{building,a}}} \cdot 100 \\ r_{\text{el.group}} &= \frac{24\ 440\ \text{kWh}}{1.42 \cdot 10^6\ \text{kWh}} \cdot 100 \\ r_{\text{el.group}} &= 1.7\% \end{aligned}$$

When inspecting all the three ratios identified in this section, they are all in the same region, and most likely the actual ratio is, on average, slightly under two percent annually, if the usage of the elevators or the consumption of the building would not substantially change in long-term. Though this figure is slightly lower than suggested by the E4 Project, it is in line with findings from Finland [45].

4.4.2 Solar power production against elevator data

This section identifies the needed battery sizes in terms of electrical energy in a situation where the consumption of the elevator group in Building 1 is powered totally by photovoltaics (PVs). The energy storage efficiency of the battery system is presumed to be 100% [46], which may be considered exaggerated but serves as a best-case situation. This calculation also considers the PVs to perform as depicted in Section 3.3.3 and the elevator consumption pattern to be recurrent. The example examines energy production of three months: March, June, and December. These months resemble the average, the best, and the worst times of the year for a PV with a 42-degree tilt in terms of electricity production.

The total average weekly consumption of the elevator group in Building 1 was measured to be 470 kWh, and to fulfill this demand, the needed photovoltaic sizes in kilowatts for March, June, and December should be 19, 15, and 59 kW, respectively. If the nominal power of the installed photovoltaic system is 20 kW, it will be sufficient for half of the year between March and August, with the lowest production in March, as can be seen in previous Figure 11. Figure 19 presents an average weekday consumption of the elevator group in Building 1, and the PV power profile for a 20-kW system in March. With this setup, the PV system is not capable of generating enough energy within the same day, though the lunch hour peak is satisfied. Nevertheless, when the battery system is scaled to enable the utilization of sunshine during weekends, a 20-kW system is clearly sufficient, which can also be

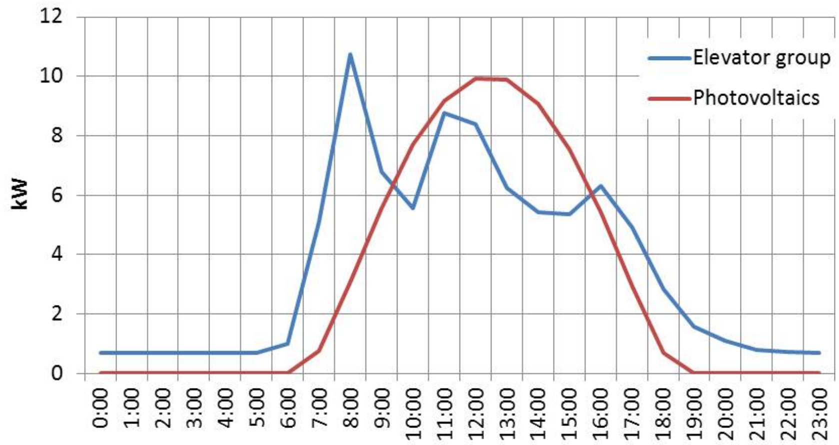

Figure 19: Photovoltaic power generation profile for a 20-kW system and elevator group consumption on a weekday in March.

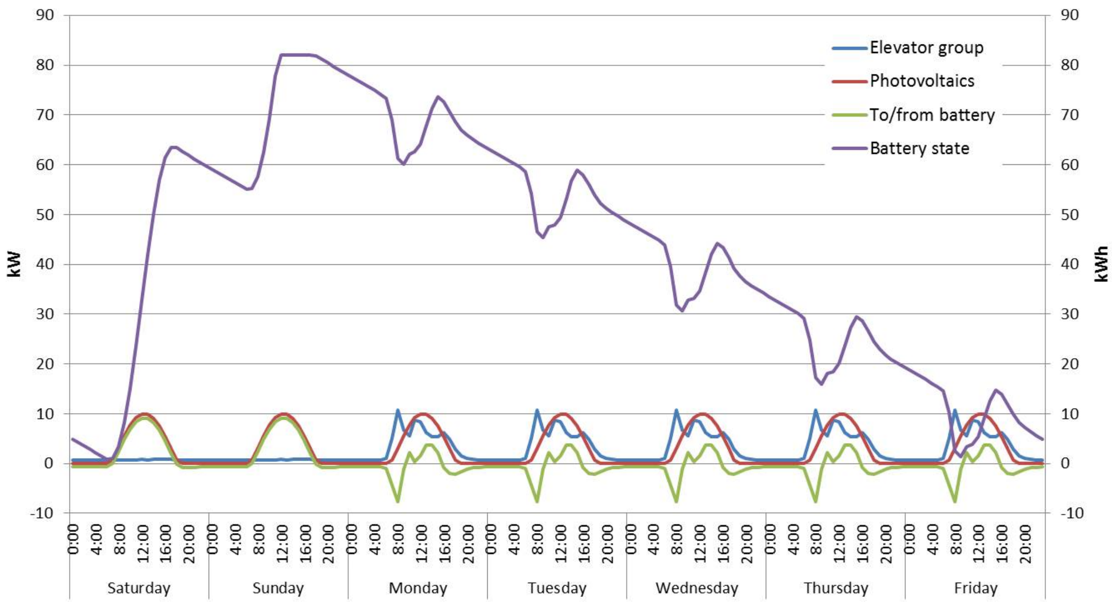

Figure 20: An illustration of a net zero PV (20-kW) and battery system (82-kWh) in March for elevators in Building 1.

seen in Figure 20, which reveals that the net zero system is achieved with 82-kWh battery storage. This amount of storage equals to nearly five Opel Amperas having a common 16-kWh battery capacity [47].

4.5 Impact of traffic on the energy usage of elevators

To analyze the effect of passenger traffic on the energy consumption of elevators, this section utilizes the loading and travel profiles introduced in Section 3.3.1 having characteristics similar to the consumption profile presented on page 40 and identifies their resemblance.

When the loading and consumption profiles are put on top of each other, in Figure 21, the resemblance between the two is clear, though the time syncronization caused some challenge to the data handling process. Standby power demand causes the base level of the power profile to be around 172 W, while, naturally, the loading during standby is zero. With five-minute average values, the correlation coefficient

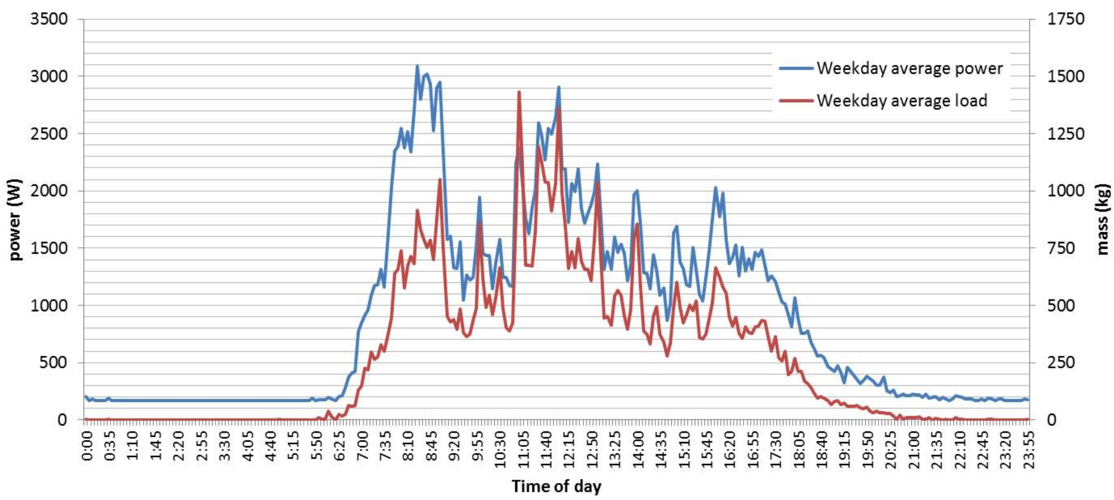

Figure 21: Weekday 5-minute averages of power demand and loading per elevator in Building 1.

was calculated to be 0.96, which verifies the large dependence of energy consumption on passenger volume. The figure also indicates the effect of using a heavy (50%) counterbalance, as the lunch hour peaks of the profiles are more similar than start or end of workday peaks. Though the lunch hour loading is significantly higher than during the rest of the day, the energy consumption is less than in the morning peak. This results from the morning having generally always an empty car traveling down to pick up only a few passengers, while at lunch time, more people are traveling with the same car, lowering the net mass that is needed to be moved by the motor of the elevator. Therefore, the impact of the counterbalance on the correlation of traffic and energy usage of elevators could explain some of the 0.04 gap in the correlation coefficient.

When examing plain travel amount data against the consumption profile, in Figure 22, even clearer resemblance can be identified between the profiles than by examing loading statistics. One factor may be the counterbalance which affects the energy consumption depending on concurrent loading and the direction the elevator is traveling; thus, the loading itself is not the only variable affecting the consumption. Moreover, high correlation between travel and energy consumption, 0.986, can be easily accepted, as the loading is commonly minor in contrast to the nominal load, as explained in the following paragraph, and due to the tendency of the elevator to travel equally upwards and downwards. Therefore, the travels, on average, tend to consume the same amount of energy, resulting the consumption to depend highly on the number of trips.

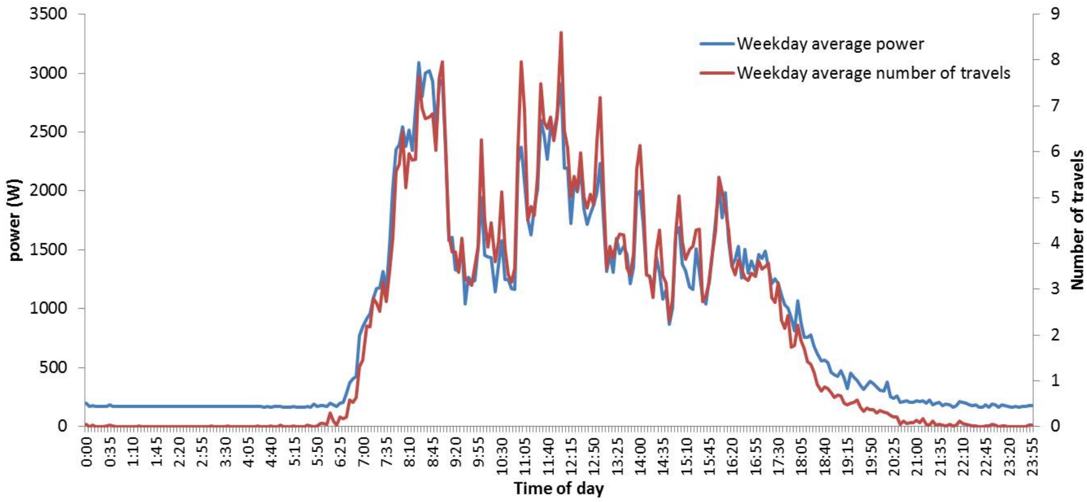

Figure 22: Weekday 5-minute averages of power demand and amount of travels per elevator in Building 1.

The use of a heavy counterbalance can be questioned when investigating the statisctics recorded by the Elink. Table 16 on page 31 clearly verifies that a major share of the travels is done with a near-empty cargo, and the high loads are encountered in negligible amounts. This piece of information suggests that the counterweight could be chosen significantly smaller, reducing the energy consumed by the empty car traveling down, which comprises about a quarter of the total travels [7], and is responsible for a major portion of the energy demand during the weekday morning peak consumption, for example. Nevertheless, the use of a large counterbalance lessens the requirements set to the drive and motor, enabling cost-efficient sizing without compromising reliability of the elevator systems in high-load situations [48].

5 Discussion

This chapter analyzes the possible factors affecting the presented annual consumption estimates and projections and inspects the prospects of utilizing photovoltaics and energy storages in elevator systems.

5.1 Analysis of annual consumption estimates

On the basis of the precision and reliability analyses, it can be stated that when the errors have been compensated as described earlier, the readings from EMU devices can be consired to be of good quality, while the Asema devices have some issues with data logging in Building 1 affecting their results.

As a presumption, the method proposed by the ISO 25745 part two can be considered to be the most accurate one, especially if used with the actual statistics of elevator usage. Therefore, annual energy consumption by the ISO standard using Elink data is seen as the most promising estimation method in general. However, the VDI should not differ greatly from the ISO estimate, as the elevators in Building 1 possessed no energy saving modes, and the largest difference could be considered to derive from the used load factor k or k_{L}. However, though the load factor of the ISO standard has been calculated higher than the factor of the VDI, the ISO standard suggests a slightly lower energy usage for travel, as was shown in Figure 16 in the results section, though (5) reveals that the effect is the opposite. Therefore, probably the most significant factors affecting this difference are the use of the average travel distance, $\%S$, in (5) and the negligence of acceleration and door operation times by (4). Furthermore, a trip based calculation method, such as suggested by the ISO/DIS 25745-2, can easily be accepted according to the results which verified high correlation between travels and energy usage of elevators. Actually, the $\mathrm{ISO}_{\mathrm{Elink}}$ estimate would become even closer to the annual projection calculated from EMU readings, if the amount of average daily travels in March is used instead of the nine-month Elink data. The number of daily travels (weighted by five weekdays and two weekend days) in March 2014 was 440, and with this figure, the $\mathrm{ISO}_{\mathrm{Elink}}$ estimate would be 23 934 kWh, and the error would only be -2.1% instead of -8.7% presented in Table 21. On the other hand, the $\mathrm{VDI}_{\mathrm{Elink}}$ estimate would increase, worsening its accuracy. Due to March having higher average daily travel value than derived from the nine-month Elink data, the annual projections calculated on the basis of the meter readings, especially of EMU devices, have yielded to somewhat higher figures than maybe the actual. This further proves the observation that most of the estimates overshoot in the case of Building 1.

The VDI guideline generally presumes 365 similar days, and this concept is viable, if the average number of trips per day is actually known. The VDI states that this figure is calculated by dividing the number of annual trips by 365. The suggestion by the ISO/DIS 25745-2 to use 260 days with office buildings may be fundamentally incorrect, due to the nature of most elevators consuming standby energies throughout nights and weekends. Nevertheless, the standard also allows applying any number of days, but does not clearly state the calculation method for elevators that are mostly in standby on certain days of the week. This thesis indicates that when applying the basic calculation methods given by the ISO/DIS 25745-2 standard, the use of 365 days can be seen proper, if the actual long-term travel amount is known. On the other hand, the VDI guideline performed more accurately with plain multiplier change from 365 to 260 than with known travel amount, at least in the case of Building 1. In fact, the ISO and VDI estimates with basic presumptions and the same amount of operating days yield to relatively similar figures.

The VDI and ISO methods also generally consider only one elevator. Thus, Building 1 having four elevators results in overcapacity and a lower travel amount value than standards suggest as default presumptions, as the amount of total travels is divided between four units. Therefore, both the VDI and the ISO standard with basic presumptions were noticed to overestimate the travel consumption, and, consequently, the annual energy usage of the elevator group in Building 1.

EnerCal did not agree with the actual results of Building 1, though the amount of trips per year was derived from Elink statistics and used also with the VDI and ISO estimation methods. The VDI with Elink information and EnerCal delivered similar estimates, which was expected, due to EnerCal utilizing certain calculations provided by the VDI guideline. However, both estimates were further from the most probable value than the ISO part two with Elink travel data.

The presented EMU Professional values may have been overcompensated on high demand five-minute periods, as the accuracy was determined from a longer time period containing more standby. Moreover, the Asema and Fluke projections seem to support this overshoot. However, their projections are formed from less data, and cannot be directly compared. Another aspect to be noted is that the error compensation factors were presumed to be the same for each elevator, which may have induced some additional error to the overall results of the EMU Professional devices at the pilot measurement site, though this effect is expected to be minor. Nevertheless, regardless of which metering system or estimate is utilized, the result seems to be in line with findings of [31], reporting elevators in a large office building to consume 17 700 kWh a year.

5.2 Prospects of using solar power and energy storages with elevators

Solar energy can clearly be used to supply most of the consumption needs of elevators, especially during summer months, and the use of energy storages, mainly batteries, would clearly emphasize that the solar energy is actually used by the elevator system. However, in the example calculation presented in Section 4.4.2, the power generation of the PV system can never exceed the power demand of the entire building. Thus, the use of energy storages can be questioned because even though the utilization of the locally produced energy is more cost-efficient than selling it back to the grid and purchasing it later, a large office building is generally always capable of consuming the produced local energy instantly. However, line braking and selling the energy back to the grid may require some additional equipment or contracts with the electricity distribution company.

The variation of solar irradiance throughout the year should be noted when considering the use of solar energy. Furthermore, the solar panel generation model introduced by this thesis presumed the sunshine hour ratio to be constant through the year, though actually the ratio is clearly smaller in winter than in summer [44]. With regards to the calculation example and the graphs presented in Section 3.3.3, this alternating ratio would mean that the production would increase in April–August and decrease during other months.

Another local generation prospect rises from elevators with regenerative capabilities. This thesis did not inspect the actual production profiles of regenerative elevator systems but they have been analyzed, for example in [45] and [49]. The energy savings induced by a regenerative drive have been measured to be 30% by [49]. However, the savings potential naturally varies between buildings, elevators, and storage methods. Due to the nature of the power generation profile having fast but high-power production peaks, the usefulness of a supercapacitor cannot be neglected. However, electric vehicles (EVs), possessing similar braking capabilities as an elevator, are commonly equipped only with batteries, and is seen as a more proven technology. Moreover, as with photovoltaics, the building is typically more than capable of utilizing the generated energy, diminishing the need for any energy storage, presuming that line-braking has been enabled. Nevertheless, an integrated supercapacitor [50] or battery system could bring added value to the elevator, making it more appealing to customers.

6 Conclusions

This chapter sums up the findings of this thesis and analyzes the overall situation regarding the energy consumption of elevators. This thesis revealed many issues in the actual energy consumption measuring process of elevators, discovered multiple differencies in the current consumption models, and also achieved its main targets.

Elevator itself is a very energy efficient device as the mass moved up also tends to come down. The net electricity demand derives from a process where the energy is turned into heat with the effect of brakings or losses in the mechanical and electrical system. With regenerative drives, the energy generated in braking modes can be utilized more effectively. It can be stored, transformed to another form of energy, used inside of the building by another appliance demanding power at the same time, or fed back to the grid, if the momentary generated power exceeds the concurrent consumption of the building, a situation unlikely to occur. The first installation site was measured for five weeks giving an annual electricity consumption projection of 24 440 kWh, which resembles the consumption of a standard Finnish detached house using electric heating [51]. The determined electricity usage can be considered to be small in comparison to the entire office building, as the annual consumption ratio of elevators was estimated to remain under two percent.

The energy consumption in standby is a major factor in the total energy consumption of an elevator in the currently installed elevator stock. Previous studies suggest that the excess lighting may account for most of this usage. Modern elevators are equipped with frequency converters and control systems that also contribute to the standby demand and typically use energy saving LEDs. This means that the ratio of lighting is decreased. However, the fact that a large share of the energy consumption of an elevator goes to lighting in the currently installed stock of elevators just amplifies the importance of lighting as one of the major contributors to the energy consumption of buildings [52]. The elevators measured during this thesis were calculated to use 75% of the used electricity for travels and 25% for standby, if the standby consumption is considered to be always present as the bottom layer of usage. However, the energy usage of elevators almost directly correlates with its travel pattern, as the correlation coefficient between travel amount and consumption was calculated to be 0.986 in Building 1.

During this thesis, the use of a heavy (40 to 50%) counterweight was questioned in terms of energy efficiency, as the actual cargo inside a large office elevator rarely exceeds even 25 percent of the nominal load. Especially in upward travels, elevators without any regenerative properties cannot turn the excess mass into useful energy other than heat, which is rarely utilized. Furthermore, downward trips require more energy with a heavy counterweight and a low cargo. Nevertheless, the heavy counterbalance allows lower nominal requirements for the motor and drive of the elevator, as the peak resultative load can only be around half of the nominal load of the elevator [48]. Therefore, the heavy counterbalance is justified, enabling lower starting currents and smaller, less expensive motor and drive units.

Determining the energy classes with different usage characteristics did not seem to cause issues to the energy classification schemes, as they both produced almost equal energy classes to the elevator group in Building 1. However, more measuring locations with various usage should be analyzed in the future to verify the resemblance of the two schemes in terms of classification. Moreover, the results from the first measuring site indicate that the upcoming ISO/DIS 25745-2 provides more accurate results than the VDI 4707-1 guideline and the EnerCal tool but to confirm this and to find the actual differences, the research needs to be continued in multiple locations with different shaft heights, technology, and travel patterns. Currently, this thesis indicates that the VDI and ISO methods provide highly similar travel and standby ratios and daily energy usage estimates with their basic presumptions, whereas EnerCal may use ratios that are almost reverse in its calculations. Nevertheless, the annual energy consumption estimate provided by the EnerCal tool is close to the VDI estimate with the same travel amount input, indicating that the difference in the travel and standby ratios may merely derive from the definitions of the operating states.

When comparing the functionality of the standards and the EnerCal tool, the standards can quite easily be utilized by examining the building type, basic characteristics of the elevator, and performing the reference cycle measurements; thus, the standards provide energy consumption estimates and performance classifications even without any knowledge of the used elevator technology. On the other hand, EnerCal calculations can be performed without any measurements, if the elevator type, characteristics, and features are known and a reasonable trip amount value is used.

This thesis succeeded to create a low-end measuring system that could be left at the measurement site for long-term measurements and also found a commercial solution with similar functioning. The research will continue in the office building measured for this thesis, while the measuring campaign keeps expanding to other locations utilizing both of the long-term metering systems. The following chapter examines some plausible points of improvement, raises issues to be considered, and suggests future areas of research.

7 Recommendations

During this thesis, multiple beneficial pieces of knowledge were attained of choosing and installing measuring equipment and handling and interpreting the gathered data. This chapter raises some of the key aspects of these observations and suggests a policy to continue the measurement project and the research in general.

Two different 3G routers were used during the pilot testing: a 3G Wifi router with an integrated SIM card reader and a normal router with capability of using an external 3G modem. The latter seemed to be more reliable and is equipped with LAN ports, which are used by the EMU system. However, both of these routers are designed to be used in a normal household and did not prove to be completely robust in longer use. EMU Data Logger stores data even without any ethernet or internet connection, but should a more stable remote monitoring system be needed, an industrial router with multiple SIM card slots or self-booting capabilities may be an alternative. In addition, at measurement sites located abroad, the functionality of the remote monitoring systems needs to be checked. Most likely, in some areas, the mobile connection calls for rethinking, i.e., the 3G modem needs to have correct technologies and frequency areas, and the SIM card could be attained from a local operator to prevent high transmission costs.

The developed cost-efficient energy monitoring system presented good promise, and the Asema devices should be further tested at a measuring site that also possesses regenerative properties. If the system is decided to be used in the measurement campaign in the future, the overall realibility of the system should be improved. The functioning of the router should not affect the data storing, and seemingly the only way to secure the data logging was to develop the central unit to store the values. This update will be performed on Asema E at the second installation location, which is not discussed in this thesis, and the data backup will be gathered to a standard memory card. If the central unit would also be cabable of opening the VPN connection, introduced in Appendix B, the external laptop would become redundant, decreasing the system costs. In the current situation, the requirement of external knowhow in establishing suitable connections and installing proper software proved to increase the costs of the developed metering system to a level close to the EMU devices in measurement sites with only a few elevators.

With the above circumstances and options, the EMU devices are to be preferred at most of the measurement locations, as they are also easier to use and more stable than the developed system. At one-elevator locations, a TCP/IP version of the EMU Professional should be installed, if its functioning is first verified regarding the data reading, as it will become far cheaper than acquiring the expensive data logger in addition to the EMU Professional with M-Bus connectivity. The plausibility of using TCP/IP version in systems with two or three elevators or escalators could also be examined. EMU also provides another metering unit, EMU Allrounder, whose capabilities in plain energy consumption monitoring should be investigated, as Allrounder is more affordable for sites with simpler measurement requirements. Surely, for basic kWh-energy monitoring with one-hour resolution, a number of cost-friendly meters can be found on the market, but this thesis did not inspect these devices, as it was not in the scope of this thesis.

The error compensation methods, introduced in Section 4.2.1, should be revised to determine whether they should be based on power or on energy. One-week accuracy determination of energy may be a solution, though on the other hand, the power method can be performed faster and perhaps even at the same time the installations are implemented. To achieve the most reliable determination of accuracy, the determination process should include all the devices that are analyzed. However, moving the reference meter, for example Fluke 1760, to every device can be burdensome or even impossible.

Though this thesis identified several sources inducing large differences in the estimates given by the standards, more thorough sensitivity analyses should be performed for multiple variables to see their actual effect on the end-results. Also statistical techniques, such as correlation of various variables and the consumption pattern of the elevators, should be utilized in the data sets to deepen the understanding of the shape of the energy consumption profile.

The measuring campaign needs to be expanded greatly to achieve more data and knowledge of the electricity usage behavior. A qualified electrician should be contacted to perform the installation, in case the KONE group service people are not capable or qualified to install the measuring equipment. The measurement campaign can also be extented to escalators and moving walks, as the pilot tested devices can also be used in them. The escalators can be considered as simple versions of elevators in terms of modeling [53], [54], and they have a classification standard [12] that is planned to be published in 2015.

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A Laboratory testing equipment

This appendix introduces the laboratory equipment that was used in the testing process of the used meters. Figure A1 presents the basic structure of the laboratory equipment used to test the energy meters. The three-phase line supply voltage was controlled by using a variable-voltage transformer and was typically set between 220 and 230 volts. A recently calibrated NORMA D6100 Power Analyzer attached to a PC was used to gain reference values that were used in finding out the accuracy of the tested meters. Simple testing to examine the basic functionality of the meters was executed with a three-phase resistor whose resistance could be varied. More thorough testing was done with an induction motor assembly where the load could be varied using a voltage-controlled frequency converter. The control voltage could also be set so that the induction machine was driven as a generator, allowing the testing of negative powers and exported energy. The operation of the meters under capacitive situations was examined by adding a desirable amount of capacitance by a three-phase adjustable capacitor.

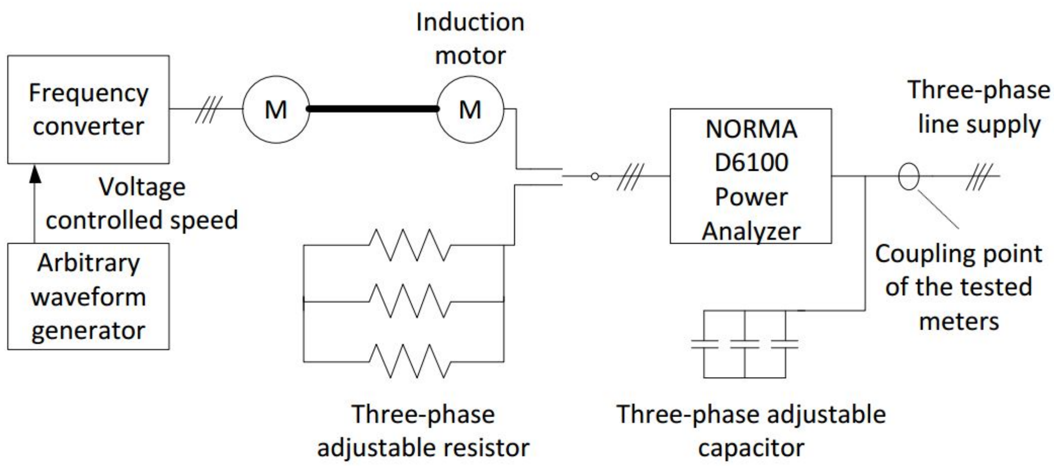

Figure A1: Illustration of the laboratory setup used during testing of the energy meters.

B Designed low-end long-term metering setup

This appendix gives detailed information on the built long-term measurement setup. The testing and building of the measurement device setup, for the purpose of this research, was a joint effort by the meter manufacturer and the university. The devices from Asema Electronics Ltd were reprogrammed and optimized for this specific research.

B.1 Structure and working principle

This setup has one 3-phase power meter for each elevator. The Asema M2 power meter measures the phase currents from all three phases and one phase voltage. Therefore, the meter presumes that the magnitude of the phase voltages is the same with 120-degree phase shifts between phases, adding some inaccuracy to the power measurement reading of the phases whose voltages are not actually measured.

The basic working principle of the created low-end measuring system is shown in Figure B1. The figure demonstrates the use of radiowaves as the communication method between the energy meters and the central controller, Asema E, and the actual data is stored in a laptop computer acting as a data logger. The readings can be remotely monitored or fetched from a work station via the SSH connection through the server. A future area of development would be to modify the central controller to act as the data logger with SSH functionality to prevent the use of an external laptop.

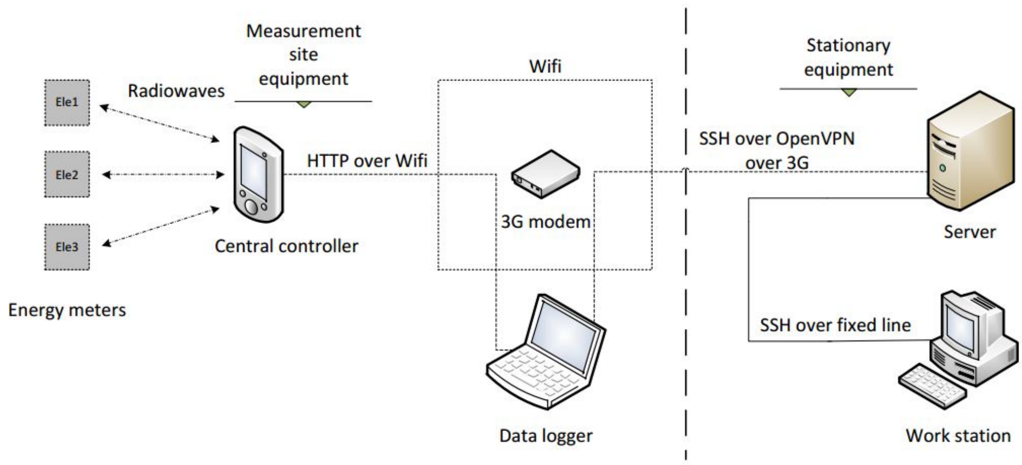

Figure B1: Diagram of the basic functionality of the designed long-term metering system.

The system is designed to work with a plug-in principle, i.e., the connections are established automatically as the meters, central controller, 3G modem, and the laptop are switched on. Establishing a connection to a device behind a mobile network is a challenging task. This issue has been solved by setting the laptop to contact the server with fixed IP address to open a Virtual Private Network (VPN) between the laptop and the server. The user of a regular work station can then gather the wanted information from the data logger using basic SSH commands.

B.2 Testing the accuracy

The accuracy of the device was tested on multiple levels. The values given by the tested meters, later denoted as M1, M2, M3, and M4, were compared with the reference value measured by NORMA D6100 power analyzer, which was considered to be without error. The readings from the NORMA D6100 and meters M1 to M4 were stored to separate files at different stages of testing to achieve a high amount of comparable results.

The last tests with the final product focused on the energy readings, and the next part of this appendix introduces the contents and the results of these tests. During the test, the meters had current clamps capable of measuring electric current up to 80 amperes. Clamps with nominal current of 150 A were not tested as extensively at the laboratory, but their performance was planned to be analyzed at the second measurement site.

B.2.1 Inductive test

The inductive test was performed with the inductive motor setup, and the capacitive load was adjusted to zero. Figure B2 shows the used repeating active and reactive power cycle achieved with a sinusoidal waveform set for the arbitrary waveform generator introduced in Appendix A. It can be seen that there was some fluctuation in the reactive power, but it remained constantly around 550 var. The active power, instead, was set to cycle between negative and positive values. Therefore, one aspect of the test was to see the performance of the meters with the varying power sign commonly found in, for example, elevators equipped with a regenerative unit.

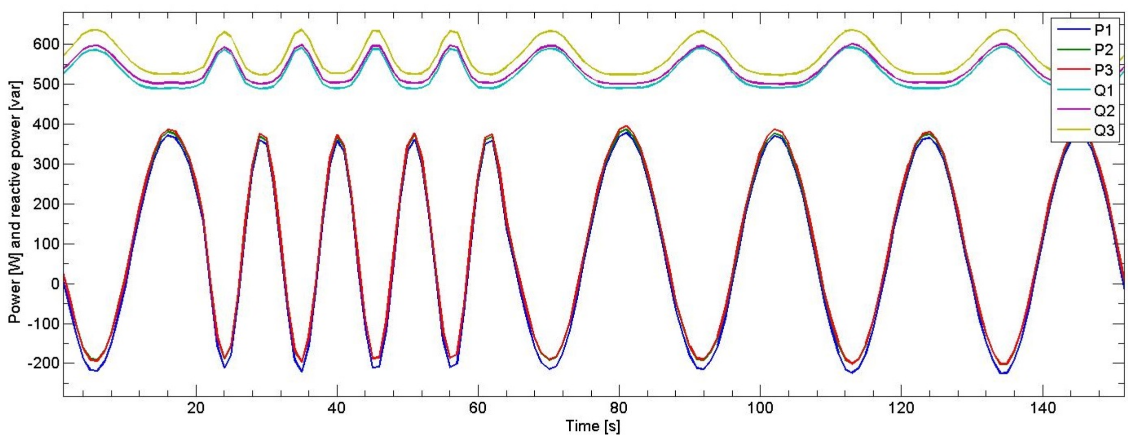

Figure B2: Active and reactive power cycles used during the inductive test.

The following error percentages, shown in Table B1, were derived from the test that lasted over 17 hours. These can be considered to represent the accuracy of the device in the laboratory environment with the specific test setup. The most significant value to examine in the table is the error in the sum of the phase registers, as that reveals the total error introduced by the measurement setup. Commonly, issues in the phase accuracy can be seen to even out in the calculation of the total energy. Large variation between the first and the second phase in generated energy registers may derive from the calibration or from some yet unknown programming issue. This issue was not considered to be major because the elevators at the pilot installation site were said not to have regenerative capabilities, and the calibration could be performed later.

Table B1: Error percentages of different energy registers in the tested meters with inductive load.

Meter	**Phase 1 error%**	**Phase 2 error%**	**Phase 3 error%**	**Phase sum error%**
		Consumed energy		
M1	6.6	-9.9	-1.9	-1.9
M2	10.8	-5.7	1.5	2
M3	13.9	-0.6	1.0	4.6
M4	5.6	-5.8	0.2	-0.2
		Generated energy		
M1	-30.6	43.6	-5.3	0.5
M2	-33.6	42.9	-7.1	-1.5
M3	-52.5	0.5	-5.8	-21.6
M4	-26.7	40.0	3.6	0.7
		Inductive energy		
M1	2.6	-6.0	-1.6	-1.7
M2	0.9	0.5	-0.6	0.3
M3	-2.1	-0.6	-0.2	-1.0
M4	2.9	0.7	1.3	1.6

Meter number three seems to have a clear problem with calibration, as the positive and especially the negative active energy register has a significant error in phase 1 that also contributes to the sum of the phases. Despite of this, the meter was decided to be installed, as the calibration parameters could be changed at site if needed. Moreover, the capacitive test, introduced in the next section, for M3 was clearly successful, signifying that the calibration process cannot be considered necessarily so straightforward. Common calibration issues are explained, e.g., in [55].

One aspect examined during the test was the development of the error in time. The error should not increase percentagewise, as this would mean exponential increase in the absolute error. Figure B3 depicts the positive energy register values of

M1 against the values recorded by the PC connected to the NORMA D6100 within one hour of the inductive test run. The figure confirms that the absolute errors

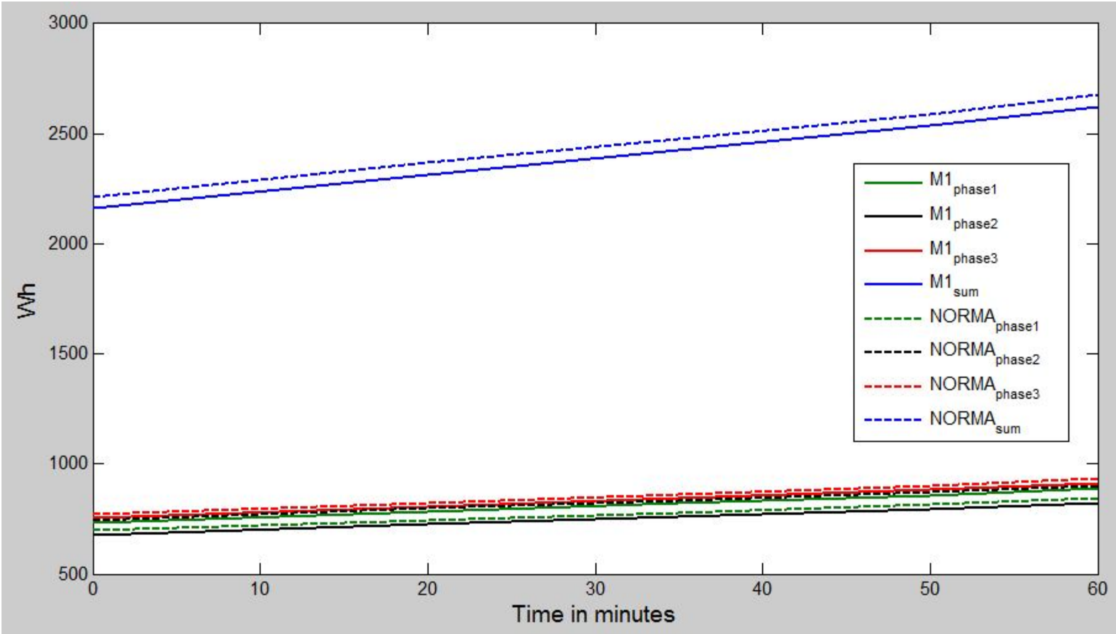

Figure B3: Positive energy register values of M1 against the reference meter of the laboratory within an example hour.

seem to be constant or slowly linearly changing, and this is also supported by the the findings of Table B1.

B.2.2 Capacitive test

In capacitive test, a suitable amount of capacitance was added to achieve the power cycles shown in Figure B4. The figure reveals that the reactive power remained on the negative side, i.e., all the reactive energy was capacitive in nature. The active power was cycling with a higher amplitude than in the inductive test, but the shape of the waveform remained the same.

Table B2 presents the calculated accuracies of the tested meters in a four-hour test. During this test, the M3 meter was set to measure the same equipment as the rest of the meters, but it had seven times the current compared to the others, and this was achieved with looping the conductor seven times around the clamps. The higher current enables more accurate determination between capacitive and inductive current, and this clearly shows in the table of accuracies. Despite of this, even M3 still had also recorded a considerable amount of inductive energy, and the sum of capacitive and inductive energy registers was clearly higher than it should have been. Nevertheless, as the primary task was to develop a two-way kWh meter, this issue was not further tackled in this thesis. Furthermore, the consumed and generated energy registers were discovered to work sufficiently enough with

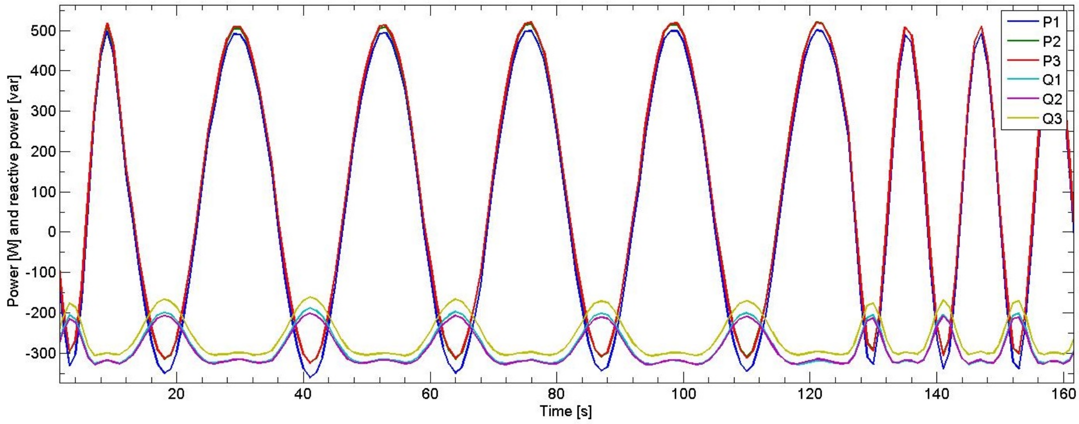

Figure B4: Active and reactive power cycles used during the capacitive test.

capacitive loads, and prior to the first installation, elevators were presumed to be only slightly capacitive during standby, and highly inductive during travel [56].

Table B2: Error percentages of different energy registers in the tested meters with capacitive load.

Meter	Phase 1 error%	Phase 2 error%	Phase 3 error%	Phase sum error%
		Consumed energy		
M1	-18.7	-2.8	-7.0	-9.3
M2	-15.8	0.3	-3.4	-6.1
M3	-21.7	-0.9	-2.4	-8.0
M4	-18.2	-0.1	-3.5	-7.0
		Generated energy		
M1	7.8	13.3	4.1	8.4
M2	9.9	18.1	3.8	10.6
M3	4.4	1.7	1.3	2.6
M4	9.5	15.1	7.5	10.6
		Capacitive energy		
M1	-38.2	-68.8	-60.9	-56.2
M2	-37.0	-45.3	-61.5	-47.5
M3	1.7	2.7	-5.8	-2.2
M4	-52.5	-63.4	-65.7	-60.4

In theory, the first phase should, on average, be the most accurate one, as the other phase voltages are not actually measured. However, as Table B2 revealed, the consumed energy registers of phase one had considerably more error than other phases, and this error remained in the overall sum of the phases. This is most likely a calibrational issue, as the devices were calibrated with an inductive load. Furthermore, the laboratory test could not emulate an actual elevator environment, and the power peaks were significantly lower than in actual elevator systems. Therefore, the success of the pilot testing at the first installation site was considered to be the defining factor for the use of the developed measuring system in the future.