The Economic Performance of Demand Optimized Elevator System

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Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo May 2, 2016

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SCHOOL OF ENGINEERING

ABSTRACT OF THE
MASTER'S THESIS

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Title: The Economic Performance of Demand Optimized Elevator System

Date: May 2, 2016 Language: English Number of pages: 8+77

Department of Energy Technology

Professorship: Energy Engineering

Supervisor: Prof. Risto Lahdelma

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This master's thesis ultimately frames a business case for Demand Optimized Elevator System and proposes a strategy of implementation that maximizes the economic performance of such system. The demand optimization in mid-rise and high-rise elevator systems is approached by two demand control strategies: through optimal elevator scheduling and by utilizing an energy storage. These two approaches are mutually non-exclusive and one can be implemented without another. The study suggests that demand optimized elevator system would achieve the greatest cost savings in building power system assets due to smaller feeder cables, reduced supply transformer sizing and reduced capacity requirements for back-up generators. Demand optimization would lower the load volatility of the elevator group and thus create less overall strain on the building power distribution system. These capital cost savings would primarily benefit the building constructor/developer as a result of decreased construction costs. Contrary to initial hypothesis, demand charge reductions can be only seen as a secondary benefit of Demand Optimized Elevator System. This is because the integrated demand metering that most of the utilities have in place does not encourage decreasing few second long transient power peaks. Furthermore, analysis showed that coincidence between building power demand and time-varying electricity costs can have a significant impact on the profitability of energy storage investment. In the studied case building, reducing transient peak power through elevator scheduling yielded capital cost savings of roughly 400 000€ in building power system assets. On the other hand, energy storage was estimated to achieve 18% higher transient peak power reduction than elevator scheduling and also to provide additional electricity cost savings, but these increased benefits have to be valued against the capital cost of an energy storage system. On average, the small-sized (30kWh) energy storage turned out to have the best combination of cost savings and low enough investment costs to be profitable.

Keywords: Demand Optimization, Demand Response, Elevator Systems, Group Control, Energy Storage, Demand Charge, Electricity Costs

AALTO-YLIOPISTO
INSINÖÖRITIETEIDEN KORKEAKOULU

DIPLOMITYÖN
TIIVISTELMÄ

Tekijä: Pekka Perunka

Työn nimi: Teho-optimoidun hissijärjestelmän taloudellinen kannattavuus

Päivämäärä: May 2, 2016
Kieli: Englanti
Sivumäärä: 8+77

Energia ja LVI-tekniikan laitos

Professuuri: Energiatekniikka

Työn valvoja: Prof. Risto Lahdelma

Työn ohjaaja: TkT Tapio Tyni

Tämä diplomityö käsittelee teho-optimoidun hissijärjestelmän taloudellista kannattavuutta ja analysoi sen kautta muodostuvia liiketoimintamahdollisuuksia. Työssä käsiteltävän teho-optimoidun hissijärjestelmän toiminta voidaan jakaa kahteen päätasoon: ryhmänohjaukseen perustuvaan tehopiikkien leikkaukseen ja energiavaraston avulla toteutettavaan kysyntäjoustoon. Nämä menetelmät eivät ole toisiaan poissulkevia, vaan molemmat voidaan implementoida myös erikseen. Työn tulokset osoittavat, että teho-optimointi tuottaa suurimmat kustannussäästöt kiinteistön rakennusvaiheessa johtuen mahdollisuudesta mitoittaa talon sähköjärjestelmä matalamman huippukuorman perusteella. Säästöjä syntyy tällöin muun muassa pienenevistä kaapelipaksuuksista, muuntajien kapasiteetin laskusta sekä vaadittavan varavoimakapasiteetin vähenemisestä. Toisaalta vastoin alkuperäistä tutkimushypoteesia, voidaan kysyntäjoustolla saavutettavia säästöjä sähkölaskussa pitää ainoastaan toissijaisena hyötynä. Tämä on seurausta useimpien sähköyhtiöiden käyttämästä integroidusta kysyntämittaroinnista, joka perustuu tyypillisesti 15-, 30- tai 60-min aikana mitattuun keskimääräiseen sähkötehontarpeeseen, eivätkä näin hetkittäiset vain sekunteja kestävät tehopiikit näy sähkölaskussa. Kysyntäjoustolla saavutettavat säästöt ovat toisaalta myös hyvin riippuvaisia kiinteistön kuormaprofiilin muodosta sekä hyödynnettävissä olevan energiavaraston koosta. Molemmat tekijät pitävät sisällään epävarmuustekijöitä, jotka tulee huomioida investointipäätöksessä. Työssä tarkastellun rakennuksen kohdalla, ryhmänohjaukseen perustuvalla hetkittäisten tehopiikkien leikkauksella oli saavutettavissa noin 400 000€:n kustannussäästöt rakennusvaiheessa. Toisaalta energiavaraston avulla olisi saavutettavissa vielä korkeammat kustannussäästöt, mutta johtuen korkeasta investointikustannuksesta voidaan sitä pitää kannattavana vain pienen energiavaraston kohdalla.

Avainsanat: Teho-optimointi, Hissijärjestelmä, Ryhmänohjaus, Kysyntäjousto, Tehomaksu, Sähkönhinta, Kuormanohjaus

Preface

This thesis was written in collaboration with KONE Corporation during a six month period from autumn in 2015 to spring in 2016. The thesis topic was chosen to analyze the potential for commercializing new technologies and solutions for demand optimization in the field of elevator engineering.

I would especially like to thank my instructor Tapio Tyni from KONE Corporation for his excellent guidance and help in this thesis. I am also grateful to my Professor Risto Lahdelma for our valuable conversations on the topic and help in structuring the thesis. Also, thanks to all the people at KONE Corporation who contributed to the insightful discussions that assisted me in my work. Lastly, I want to thank my family and friends for their support during the thesis writing process.

Hyvinkää, May 2, 2016

Pekka M. Perunka

Contents

Glossary

ADR Automatic Demand Response. Automated actions to reduce power demand in response to DR-signals from electric utility, ISO (RTO) or other entity with required connectivity to customer systems. 2

Aggregator A company that enlists users to participate in demand response and then sells this load reduction capacity to electric utilities and ISOs. 30

BMS Building Management System. Computer-based control system for operating and monitoring building subsystems (HVAC, lighting etc.). 26

BTS Building Traffic Simulator. Program for simulating building traffic with different elevator configurations and passenger demand. 40

DR Demand Response. Customer-side actions to reduce power demand in response to price signals or other incentives. 2

DSI Demand Side Integration. DSI encompasses also the customer-driven actions for more efficient and effective use of electricity instead of focusing only utility-driven demand side management. 9

DSO Distribution System Operator. Entity responsible for operating, maintaining and developing the distribution network for delivering electricity. 5

Electric Utility Usually a public company responsible for generating and distributing electricity in a regulated market (i.e. ConEdison). 5

EMCS Energy Management Control System. Computer-based control system for managing the energy usage in building subsystems (HVAC, lighting etc.). 22

EMS Elevator Management System. Computer-based control system for operating and monitoring elevator systems. 26

ESCO Energy Services Company. A company in a deregulated market purchasing energy from Generation Suppliers and selling it to customers. 14

ESS Energy Storage System. System for storing energy with computer-based management system. 50

Generation Supplier A company generating the electricity that customer consumes. 17

HVAC Heating, Ventilation and Air-Conditioning. The building subsystems that manage indoor environment comfort. 22

LEED Leadership in Energy and Environmental Design. A building certification system that rewards building owners for efforts in energy and environmental excellence. 26

LTO Lithium Titanate Battery. A lithium-ion battery techonology with long lifetime, high charging and discharging power and ability to withstand deep discharge cycles. 63

OpenADR Open Automatic Demand Response. A standard for demand response enablement based on automated signaling between consumers and ADR providers. 30

Retail Supplier A company purchasing electricity from Generation Suppliers and selling it to end-use consumers. 5

RTP Real-time Pricing. A rate structure that incorporates fluctuating time-varying electricity prices based on wholesale market price for electricity. 9

Smart Grid Intelligent power system that incorporates digital bilateral communication between electric utilities and consumers for more efficient, flexible and reliable power system. 9

SPS Safety Power Supply. A secondary power supply for critical building loads during outage (elevators). 24

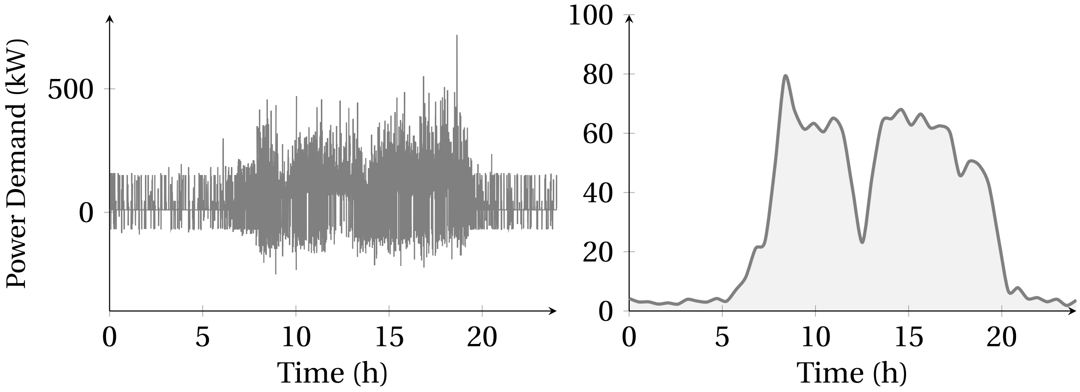
TOU Time-of-Use. A rate structure that incorporates fixed pre-specified time-of-day rates for electricity. 9

TSO Transmission System Operator. Organization responsible for managing and monitoring the transmission of electricity over long distances in a regional or national transmission grid. TSO is used mainly in Europe (ISO used in United States). 7

UPS Uninterrupted Power Supply. A secondary power supply for sensitive building loads during outage (servers and communication systems). 24

1 Introduction

In this thesis, Demand Optimized Elevator System describes an elevator system capable of optimizing its power demand through elevator scheduling or energy storage. The demand optimization in elevator systems can be approached either by optimizing transient power (in figure 1a.) or by adjusting integrated demand (in figure 1b.). In a multi-car elevator system, the transient peak power occurs only for few seconds during coincident peak power demand between multiple elevators, whereas integrated demand describes the long term fluctuations in power demand over 15- to 60-min time intervals that utilities use for metering demand. In this study, reducing transient peak power was based on optimal elevator scheduling and optimizing integrated demand was achieved by utilizing an energy storage. The analysis of demand optimization was limited to multi-car traction elevator systems in mid- and high-rise buildings, because this segment was perceived to have the highest potential for optimizing the power demand of elevator system.



(a) Transient Peak Power

(b) Integrated Demand

Figure 1: Load profiles for a high-rise elevator group in an office building

Optimizing transient power is relevant because excessive coincidence in the power demand of multiple elevators can cause unnecessarily high capacity requirements for the building power system assets. Consequently, the oversized building power system assets will increase building construction costs, making the investment less profitable for the developer. The negative effects of excessive capacity requirements can be avoided by scheduling elevators through a group control system to minimize transient peak power. On the other hand, demand optimization through energy storage also allows elevator systems to deviate from normal consumption patterns in response to high electricity prices or other incentives to reduce demand. In this thesis, both approaches to demand optimization are analyzed and evaluated for investment profitability. In literature, the reduction of peak demand in building power system through appliance scheduling has become an increasingly researched topic with the implementation of smart grids [Chen et al., 2011, Mohsenian-Rad et al., 2010, Xiong et al., 2011]. Also, optimizing building peak demand by utilizing a local battery storage has recently become more common and its popularity can be expected to keep growing with the declining cost for batteries [Leadbetter and Swan, 2012, Nykvist and Nilsson, 2015].

However, optimizing transient power in building power distribution systems hasn't received nearly as much attention as optimizing integrated demand. This can be attributed to the fact that transient peak power has no significant impact on the supply network and mainly affects the portion of the power network behind the utilization transformers. Thus, utilities have no incentive to charge customers for short durations of transient peak power and as a result it has no impact on customer's electricity bill. Utilities often make use of rate structures that define peak demand in terms of average demand for a period of 15- to 60-min. In addition, the transient power demand of an elevator system is uniquely volatile and thus transient peak power is mainly a problem of buildings with large-scale elevator installations.

> In an elevator context, Transient Peak Power affects the capacity requirements for building power system, whereas Integrated Peak Demand influences the amount of demand charges in an electricity bill.

Recently, the increased integration of renewable and distributed generation has made utilities to seek more control over demand side resources. This demand side participation in which customers adjust their integrated demand in response to price signals or other incentives has been named - Demand Response. Demand Response (DR) is considered to be an essential asset in the utilities' toolbox to meet the growing challenge of balancing supply and demand [Eurelectric, 2015]. On the demand side, the commercial building sector is playing a vital role in Demand Response because it can account for over half of the peak demand in US during the period of highest consumption. Furthermore, the global spending on Automated Demand Response (ADR) in the commercial sector is estimated to grow from $278 million in 2012 to over $712 million in 2018. At the same time, the demand response market is expanding from large businesses and institutional customers to also include small and medium-sized customers. This transition is further complemented with the implementation of more automated controls (hence ADR), which have recently become more popular among commercial facilities. Currently the commercial DR market is dominated by United States but other countries and areas such as Asian Pacific are catching up fast. [Pike Research, 2012]. The growing interest of building owners towards demand response also opens up market opportunities for equipment manufacturers, whom by developing DR-enabling equipment can help their customers to benefit from the growing demand response market.

1.1 Background

[Xiong et al., 2011] studied optimization for Demand Response in smart grids by considering two groups of appliances: "real-time" and "schedulable". Real-time appliances require immediate power supply and cannot be scheduled to operate in later time, whereas schedulable appliances can be shifted to become active with a delay. The existing elevator systems (without energy storage) can be considered "real-time" in the sense that they require immediate power supply to carry out service requests. Also, currently any attempt to deviate from this need for real-time power supply will most likely negatively impact the transportation capacity of the elevator system. In a multi-car elevator system, demand optimization through elevator scheduling would allow slight deviation from the normal intermittent consumption patterns by enabling control over the transient power of an elevator system. On the other hand, for a multi-car elevator system to deviate from normal integrated demand patterns it could either turn-off individual elevators, adjust driving parameters or control demand through an energy storage. Turning off elevators or adjusting their driving parameters would both negatively influence the transportation capacity of the elevator system. Only with an energy storage could the integrated demand be optimized without impacting the provided service level. The main functionality of an energy storage would be to filter any excessive fluctuations in power demand and optimize the load profile for measured integrated demand. Such active buffering through an energy storage could bring the same benefits in capacity reductions for building power system assets as elevator scheduling but also additional savings by reducing electricity costs and by providing additional back-up power supply during power loss. It should be also noted that these two approaches to demand optimization are mutually non-exclusive and one can be implemented without another.

- Elevator scheduling
- Adjusting driving parameters
- Turning-off elevators
- Coupling elevator system with energy storage

Figure 2: Demand control strategies in elevator systems

The benefits of reducing transient peak power in elevator systems have not been studied in existing literature and this thesis will provide a much needed assessment of the possible upsides. Utilizing an energy storage to reduce electricity costs in elevator systems has received minor interest in the academia but comprehensive studies are still missing on the topic. [White et al., 2010] introduced the topic of reducing electrical costs for elevators by arguing that in order to minimize the cost of operating electrical equipment, it is necessary to study the energy consumption, the rate at which the energy is consumed and the time at which the energy is consumed. In this thesis, the focus will be mainly on the demand portion of the electricity costs. Load profiles were simulated for different demand control strategies to understand the rate and time at which energy is consumed. The key difference between this study and vast majority of existing research is to not focus on improving energy efficiency of an elevator system but rather examine the implications of optimizing power demand in elevator systems. The focus is on the rate and time at which the energy is consumed, not on the total amount of energy consumption. This perspective opens up new possibilities for finding ways to reduce electricity costs and to minimize the imposed building power system costs by an elevator system. Ultimately, the aim of this study is to frame a business case for minimizing the customer's capital investment and operating costs through demand optimization in elevator systems.

Why to optimize demand? Matching supply and demand at all times is crucial for well-functioning electric system. If the demand for electricity keeps changing then the grid operators have to adapt into these changing circumstances rapidly. Under predictable demand and power supply from large power plants, the grid operators can maintain balance with relative ease by simply dispatching sufficient generation. This is however about to change as more and more intermittent renewable generation is introduced to the grid. Maintaining balance is becoming increasingly difficult under the new circumstances. [Eurelectric, 2015]. The responsible balancing authorities need more than just supply-side flexibility to overcome the problem of grid stability and that is why demand response has become such an industry buzzword. Especially in the urban centers, big commercial buildings can have a significant impact on the electric demand and grid stability [US Green Building Council, 2012]. The demand side flexibility of these large customers is a great asset that can be utilized through participation in demand response. Also, the European Commission has recognized the values of demand response and has taken an active role in promoting demand response enablement. [Eurelectric, 2015]

1.2 Thesis Structure and Methodology

The chapter 2. gives an overview of electricity markets in New York and London and illustrates the common rate structures and tariff plans applicable for large customers in these market areas. The chapter 3. will analyze different control strategies and requirements for demand optimization in buildings. The next chapter 4. will illuminate the basics of elevator systems that will lay the basis for understanding the characteristics of power demand in elevator systems. In chapter 5. at first traffic simulations and power demand model are created and then a set of simulations are carried out to analyze the impact of optimizing power demand in elevator systems. The results of demand optimization are evaluated in chapters 6. and 7. for cost savings and investment profitability. Final chapter 8. will draw a conclusion from the findings and recommend next steps for the future.

Optimizing transient power in elevator systems is based on a method of optimal elevator scheduling in multi-elevator systems. The implementation of such control algorithm was not studied in this thesis and instead a functional algorithm was assumed to have been applied to the group control system that was capable of realizing the desired reduction in transient peak power. In the case of optimizing integrated demand through an energy storage, a control algorithm was written to optimize the operating of the energy storage system in relation to the time-varying electricity prices. The implemented optimization method for the operating of the energy storage system will be based on a multi-objective genetic algorithm. The integrated demand optimization is carried out for three energy storage sizes under two different rate structures. Additional benefits from participating in demand response programs are analysed qualitatively but excluded from the quantitative cost-benefit analysis due to uncertainties in the eligibility for program participation.

The capital costs savings in building power system assets are evaluated for feeder cables, transformers and back-up generators. The analysis was limited to the portion of the building power network that elevator systems are connected to. The capacity requirements for power system assets were partially obtained from electrical drawings for the case building and in part estimated based on the building size. The price information for power system assets and battery storage were collected from various online source and then often approximated on cost per kVA/kW or per kWh basis. The electricity costs from operating the elevator system were calculated as a portion of the total building electricity costs. The case building was expected to be billed on the basis of a single metering point and served under a combined contract for electricity supply and distribution. All electricity was assumed to be bought on the day-ahead market price, while distribution costs, surcharges, levies and taxes were calculated according to the available information from local operators.

2 Electricity Markets and Pricing

This chapter will illuminate the existing electricity market conditions and pricing methodologies under two specific market areas. The purpose of this chapter is to explain how and why electricity costs are formed for large commercial buildings. The focus of market study will be on the city of New York in US and London in UK. Both areas are given a short overview of local wholesale and retail markets, rate structures, tariff plans and current electricity price level. The different rate structures that utilities apply for commercial customers are an essential part of understanding the composition of their electricity costs. The benefit of optimizing integrated demand in elevator systems ultimately relies on the incentives generated by time-varying electricity prices and demand charges. In the end of this chapter, a typical electricity bill for a large commercial building will be decomposed under both market areas. The purpose of decomposing electricity costs into indivual price components is to identify the demand based charges in the electricity bill.

2.1 Electricity Market Overview

The electricity markets of New York City (NYC) in US and London in UK operate both under their own particular electricity market models. In general, the electricity markets in US are more disintegrated than in UK. In US, the electricity markets are generally more disintegrated than in UK. Several independent regional market areas compose the US markets, whereas in UK the whole country can be considered as a single market area. Both in NYC and London the markets have been liberalized so that customers can choose their own Retail Supplier. The main difference between the market areas lies in the level of government regulation. In NYC, the local public service commission has more regulatory oversight on tariffs plans when compared to the government regulation in London. Since large commercial customers often procure their electricity through wholesale market price based contracts, it is important to understand the volatilities and price level in the local wholesale markets. Customers in NYC are part of larger wholesale market that is operated by regional transmission operator NYISO, whereas in UK the wholesale trading takes place at two power exchanges: APX and Nordpool.

United States has three independently synchronized and weakly interconnected electric grids in the continental area and these can be further divided into 107 areas with independent balancing authorities. More than 3100 electric utilities operate in the United States, of which 73% are investor owned utilities (IOU), 15% are municipal utilities and 12% are electric cooperatives. [Koivisto, 2014] argues that the aftermath of California electricity crisis of 2000-2001 severely slowed down the market reform and has led different parts of the United States in very different stages of unbundling and market deregulation. Currently, two thirds of the country is covered by competitive wholesale markets and one third by vertically integrated monopolies. Furthermore, retail market reform has reached even less far with only 15 states and District of Columbia having adapted competitive retail markets. The electric power policies and regulatory practices are heavily influenced by the states, which has created varying and complex operating frameworks in the electric power industry. Electric utilities have to get an approval to charge their customers a certain electricity rate and depending on the ownership structure of the Electric Utility the approval will be acquired from different entities. [Koivisto, 2014]

Europe has the centralized regulatory authority European Commission, which can be seen to some extent analogous to the role of U.S. Federal Government in policy and regulatory decision-making. However, in EU unlike in the United States, electric power is not seen as a heavily regulated public utility but as a commodity that should be subject to the same competition as other commodities. Instead of focusing on national level power systems, the European Union promotes a bigger perspective of harmonized and competitive European electricity markets. In order to enable competition of generation and supply, the system requires sufficient cross-border transmission capacity and harmonized national regulation. EU thrives for electricity market reform by issuing regulations to support unbundling of transmission system operations and adaptation of competitive retail markets. Interestingly EU has currently more power over the member countries than U.S. has over its individual member states to control the market reform. The EU directives for unbundling of transmission and generation and rollout of smart metering systems are evidence of this. [Koivisto, 2014]

Electricity Retail Markets can, from the point of view of a customer, be simplified by using two basic market models. Both of these models are retail supplier centric, which means that customers mainly interact only with the retail supplier. The difference between the two models is in the relationship between customer, retail supplier and Distribution System Operator (DSO). In general, customers do not interact with Transmission System Operator (TSO) and transmission charges are passed through by retail supplier or DSO. In the first option, customer has a contract only with the retail supplier and thus the DSO acts as a subcontractor for the retail supplier providing network services needed by the customer [Therese and Svensson, 2014]. This kind of single contact point between customer and service provider avoids unnecessary confusion to the customers. Contrary to subcontractor model, the other market model involves visible separation between retail supplier and DSO, in which both have their own contract with the customer [Therese and Svensson, 2014]. Electricity markets in Nordic countries are a good example of such a market model. However, no matter the differences between different electricity market models, when it comes to billing, the customer often deals only with the retail supplier.

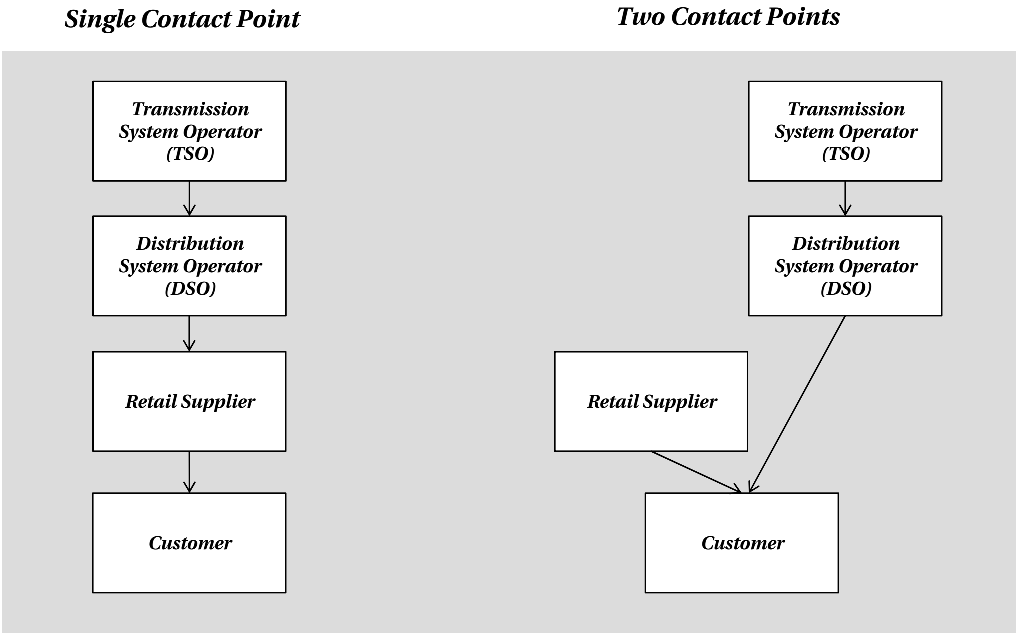


Figure 3: Two market models and relationship between Customer, Retail Supplier, DSO and TSO. Based on: [Eurelectric, 2013]

New York is famous for the long history of its electric grid but also well known for its past problems in ensuring secure electric supply. Compared to other cities in US, the power system of New York stands on its own with 3 million customers and peak demand of 11 GW reaching almost twice as high as the second largest city, Los Angeles. The electricity prices in the city are among highest in the country with total revenues amounting up to $15 billion. The electric demand is reduced during the winter due to the fact that 65% of the heating demand in the city is fueled by natural gas. [The City of New York, 2013]. It should be noted that the relatively low share of electricity in heating will increase elevators' share of the total building electric demand. Climate change together with the threat of disruptive outages caused by natural catastrophes such as hurricane Sandy in 2012, have pushed NYC to aggressively take on initiatives to reduce peak demand for electricity [The City of New York, 2013]. A single day without electricity can result in economic losses of more than $1 billion for the city. Demand response programs are playing a key role in the government's plan for a more resilient New York and over the recent years the local TSO and eletric utility have accumulated together roughly 500MW of DR capacity (5% of grid peak demand). Furthermore, the threat of power outages also increases the need for backup generation in case of emergency. [The City of New York, 2013]. These particular circumstances and regulatory factors have made NYC a very potential ground for equipment manufacturers and other stakeholders to pilot demand response projects.

NYC has liberalized electricity retail market, which means that customers can choose their electricity supply either from their local electric utility (such as ConEdison) or from Energy Service Company through retail access program. The State of New York Public Service Commission mandates utilities to provide market-based hourly pricing for their non-domestic customers. As a result, some utilities like ConEdison have a mandatory real-time pricing for certain customer segments. Though, the industrial and business customers that wish to mitigate the risk from price volatility can still enroll on fixed tariffs through retail access. [Kim, 2013]. On the distribution side, ConEdison is the primary electric utility in NYC and it is under the regulatory oversight of Public Service Commission. The New York Independent System Operator (NYISO) operates the transmission network in the state. [The New York City, 2011]

London is the capital of United Kingdom and an economic powerhouse of the country. The London Power Network serves over two million customers in the most densely populated urban center of UK. The peak power demand for the London region is estimated to be slightly more than 5 GW and planned to grow for roughly 1,5 GW in the next 15 years. The space limitations in central London area are projected to influence construction to focus more on larger and taller buildings with very high electric demand. It is likely that a significant amount of network reinforcements are required in the London power network to cope with the high peak demand for electricity. In addition, the increasing electric demand together with rising electricity prices is expected to have a significant impact on customers' electricity bill. The London Plan and Smart London Plan are initiatives that aim to mitigate the negative effects of increasing electric demand by supporting decentralized energy, demand management and infrastructure development. [Stephen Jones Associates. South East Economics, 2014]. Although London is not pushing for demand response as aggressively as NYC does, the projected increase in peak demand and electricity costs will create circumstances that clearly promote more demand side management in the city.

Britain has fully competitive electricity retail market with 59 active electricity retail suppliers serving non-domestic customers. The biggest retail suppliers for large consumers in the non-domestic market are EDF, Npower and E.ON with 21%, 19% and 13% market shares, respectively. The energy company EDF also holds a dominant market share of electric supply in the London region. The electricity market model in UK is supplier-centric and customers interact only with the retail supplier when dealing with contracts, tariffs, invoicing etc. The contracts between retail supplier and business customers are often based on bi-lateral contracts and prices aren't disclosed to public. The large customers are usually under half-hour metering and prices are aligned to changes in the wholesale market. [ofgem, 2015]. On the distribution side, there are 14 distribution system operators (DSO) in Britain of which the UK Power Networks operates in the London region. The transmission network is owned and operated by National Grid. Transmission and distribution networks are largely natural monopolies and thus subjected to price control regulation. On average the distribution charges are lower in London compared to rest of Britain.

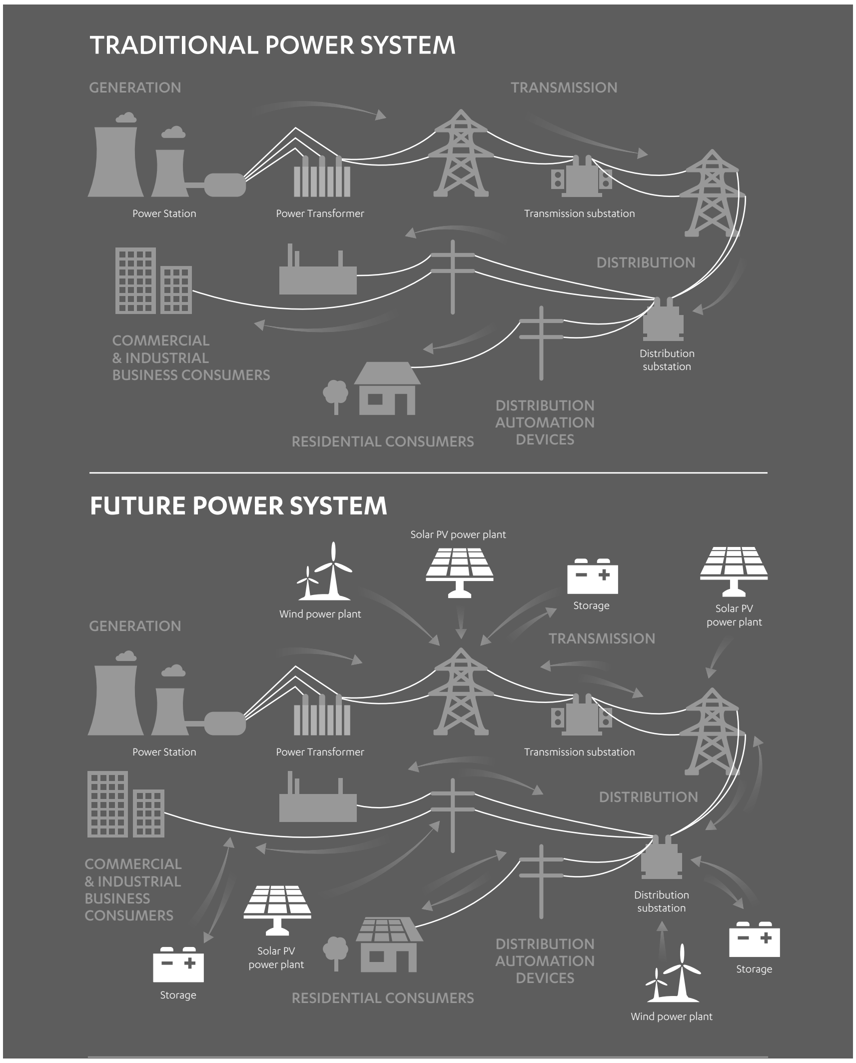


Figure 4: Layout for traditional and future power system [National Infrastructure Commission, 2016]

2.2 Rate Structures

All customers; residential, commercial and industrial, are charged both for energy (kWh) and demand (kW), but residential customers often pay only one rate due to the little variation in electricity use between different households. However, with commercial and industrial customers the consumption patterns vary greatly, which means that the electric utilities are compelled to charge the customers based on their individual demand profiles. [National Grid, 2012]. In their study of reducing electricity costs, [Xu and Li, 2014] state that utilities mainly charge for electricity on the basis of energy consumption and peak demand. The relative importance of demand based charges increases if the billed customer's peak demand to average demand ratio increases. In order to measure the actual individual demand, electric utilities will usually install meters at customer's facilities to record the average demand over every 15-minute period. [Xu and Li, 2014]. The concept of average interval demand that utilities apply in their billing is also known as the integrated demand as it is mainly referred in this thesis. The customers who are responsible for creating the demand peaks in the power system are also responsible for covering the cost of providing supply during the peak hours. These expenses are collected as the demand component part of the electricity rate [National Grid, 2012].

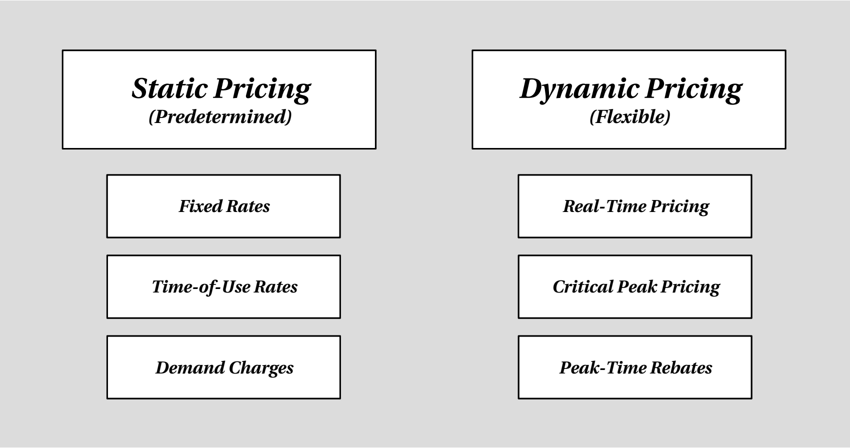


Figure 5: The common rate structures for electricity billing

This review of electricity rates will mainly focus on different rate structures that electric utilities use to manage peak demand and encourage peak demand mitigation on the customer side. The utility rates are divided into two main categories, which are static rates and dynamic pricing. The static rates are defined upfront and require no advanced communication systems, whereas dynamic pricing rates are defined more or less according to the real-time wholesale market prices and necessitate bi-lateral communication between consumer and electric utility. These are the general characteristics of utility rate structures, which can be altered and combined to fit the specific needs of each electric utility. In practice, there is a wide variety of seemingly different rate structures but their objective is largely the same. These rate structures often try to model the real cost of delivering power when it is actually used. This often means making the pricing time-dependent instead of flat rate. The electricity price will fluctuate or move in incremental steps according to system-wide demand for electricity. [Newsham and Bowker, 2010]

Fixed Rates refers to a flat rate for electricity in which the electric utility charges based on the amount of electricity consumed, independent of the time of use and peak demand. A traditional approach especially with the residential customers has been to use a flat rate per kWh. [Hledik, 2014] argues that this has been partly due to the lack of sufficient metering infrastructure, which would allow the use of demand charges based on individual demand. The downside of flat rate is that they can be inadequate in recovering the fixed costs imposed on electric utilities, because they incentivize only energy efficiency and not demand management [Hledik, 2014]. Under flat rate structures, the customers with load profiles that coincide with the system peak demand are subsidized by customers with less volatile load profiles. Therefore resulting in an unfair allocation of costs, which doesn't reflect the real-time cost of electricity. [Newsham and Bowker, 2010]

Seasonal flat rates take into account the long-term changes in electric demand by varying the fixed rate according to the season in question. Seasonal changes in electricity rates are necessary because electricity consumption usually varies seasonally partly due to the increased demand in heating or cooling during different seasons. [Wang and Li, 2015] state that in U.S. the peak demand often occurs during summer, which is echoed in the study of U.S. utilities by [Ong et al., 2010], which confirms that seasonal flat rates have typically higher rates during summer than winter months.

Time-of-Use Pricing (TOU) is a rate structure, in which the price for electricity varies between different blocks of time during the day [Newsham and Bowker, 2010]. These blocks of time are typically longer than one hour and they are set rates that reflect the average cost of generating and delivering power during those time periods [U.S. Federal Energy Regulatory Commission, 2012]. A typical TOU rate is divided into two to four tiers per day with low cost during night, high cost during late afternoon and moderate cost during mornings and evenings. The block of time with highest price is referred as “on-peak” and block with lowest price as “off-peak”. [Ong et al., 2010]. [Wang and Li, 2015] argues that Time-of-Use pricing is the easiest way to encourage customers to manage demand and it requires the least amount of technological adaptation. This is largely due to the simplicity of TOU pricing; fewer price changes result in slower response time, and therefore lower threshold to participate in demand response. TOU pricing can be seen as the natural intermediate step that customers can take before moving towards more dynamic real-time pricing. [Wang and Li, 2015]. However, regardless of growing interest in real-time pricing and its benefits, variations of TOU pricing are still far more common among utility rate structures.

Demand Charges are described by [Hledik, 2014] as “a charge based on the customer's maximum demand over a specified time period – typically the monthly billing cycle”. Demand charges mirror the fixed cost of making the electricity available for sale. This is in contrast to the energy costs, which are related to the actual generation of energy. They are necessary in order to allocate the costs adequately to the customers with inconsistent loads causing most strain to the electric grid. In addition, demand charges are meant to incentivize demand reduction during peak hours and demand shifting from on-peak hours to non-peak hours. [Duke Energy, 2013, Hledik, 2014]. The maximum demand is calculated as price per kilowatt and either independently of time of use or only during the hours with the highest system-wide demand [Hledik, 2014]. E.g. [National Grid, 2012] calculates demand charges for the highest average demand over a 15-min interval during the billing period. It is common for utilities to measure demand in intervals of 15-, 30- or 60-min.

Demand charges are often only imposed on commercial and industrial customers due to the lack of necessary metering infrastructure with small customers [Hledik, 2014]. For example, [National Grid, 2012] will install demand meter and begin billing demand whenever the customer's electricity consumption surpasses 2000 kWh per month for four consecutive months. The amount of demand charges in the electric bill can vary greatly depending on the customer's demand profile and rate offered by electric utility. Rate structures with high demand charges and low energy charges are often applicable to consumers with much higher loads compared to buildings with load profiles between 100 to 200 kW [Ong et al., 2010]. [Hledik, 2014] identifies a lack of consistency across existing demand charges in U.S. and shows that the rate design can have a substantial impact on the electricity bill.

Demand Ratchet Demand ratchet is a rate design, which minimizes the risk of providing services for customers with highly varying demand. It is based on actual demand or on a percentage of the highest demand in preceding months. For example, if customer's peak demand reaches 100 kW in January with demand ratchet set at 80% or 80kW in this case, for the following 11 months the customer's demand charge is based on this 80kW even if actual demand would be lower. Demand ratchet is used in billing in order to cover the cost of maintaining and investing in generation, transmission and distribution. [Duke Energy, 2013]

Dynamic Pricing is a form of price-based demand response or also known as implicit demand response. Dynamic pricing strategies aim to incentivize peak demand mitigation and load shifting by the electricity consumers. They also allow utility rates to connect with the wholesale market prices, thus better mirroring the real-time cost of delivering power. [Hu et al., 2015]. By default dynamic pricing is more complicated and requires more participation from the customers than fixed rates. Furthermore, adjusting consumption to time-varying prices presents high potential rewards but also high risks to customers. Due to the lack of necessary metering infrastructure, price-based demand response has not been possible until lately [Herter et al., 2007]. Currently, dynamic pricing is still in its introductory stage with little over 10 years under deployment [Hu et al., 2015]. Nevertheless, some utilities have already mandatory hourly-pricing for certain large customers [Consolidated Edison Company of New York, Inc., 2016b].

Real-time Pricing (RTP) Real-time pricing is a form of dynamic pricing that is the most closely tied to the real-time market cost of delivering energy. The prices vary hourly and the range between demand peaks and lows can be much greater compared to CPP. [Newsham and Bowker, 2010]. In order to link together the hourly price and hourly changes in the cost of power, real-time pricing requires technology, which allows two-way communication between the consumer and electric utility. It is considered to be the most advanced form of demand response and also less common one. It has received far less research compared to TOU and CPP partly due to the lack of customer acceptance. [Hu et al., 2015].

Critical Peak Pricing (CPP) When the reliability of power system is at risk, electric utilities can call upon critical peak pricing with significantly higher tariffs [Hu et al., 2015]. Critical peak pricing (CPP) is one form of price-based demand response, but different from flat rates and TOU pricing, it uses dynamic rates that allow utilities to change prices on short notice (Herter, McAuliffe et al. 2007). Utilities forecast the days with particularly high demand and CPP is usually called day-ahead before “event days” when the rate is applied (Newsham, Bowker 2010). Therefore its timing is mostly unknown to the customer beforehand. In addition, CPP is limited to fewer hours per year and has a higher price compared to normal peak prices. [Hu et al., 2015]. CPP often uses real-time prices during high peak demand overlaid on top of TOU or flat pricing [Hu et al., 2015]. On the other hand, (Newsham, Bowker 2010) explain how the same rate structure is used every time the CPP is called on. In US, critical peak pricing is a less commonly enrolled rate structure compared to real-time pricing or time-of-use rates.

Peak-time Rebates (PTR) Peak time rebates are the least common form of dynamic pricing when compared to TOU, CPP and RTP [Hu et al., 2015]. [Hu et al., 2015] describe peak time rebates as the payments customers get for not using power during highest demand. The customer demand is compared against previously established household-specific baseline, based on which the reimbursement will be determined. PTR tariffs can be seen as the inverse form of CPP [Hu et al., 2015].

Future Trends in Rate Structures should be considered in order to anticipate the future changes in electricity costs and possible variations in price composition. The environmental initiatives are pushing power systems towards reduced amount of regulating capacity such as coal power plants and more towards variable production such as wind power. This will have an increasing effect on the cost of local and system-wide peak demand, thus making it even more important to find measures to adjust demand and reduce peak loads. The new tariff components that address this issue will be passed to the end-user through system operator tariffs, transmission network tariffs and distribution tariffs. It can be argued that tariff designs based on capacity, peak load or adjustable load, which aim to shift demand to another time period, will increase in the future. [Similä et al., 2011]. [Partanen, 2012] also predicts that improvements in energy efficiency and energy storages will have an impact on the amount of transmitted energy and peak demand in the power grid. Consequently, under energy charge based tariff schemes, distribution system operators will not only face increased costs but also loss of revenues.

In order to address these changes in the energy system, the tariff schemes will have to be transformed to guarantee sufficient revenue streams for the DSOs. [Partanen, 2012]

The computerization of power systems via Smart Grids will have a major effect on the electric grid and cause significant changes in the relationship between electric utilities and consumers. The Smart Grids of the future are designed to utilize bi-lateral communication technologies and remote control systems to enable a more efficient, flexible and reliable power system. As a result, Smart Grids can be estimated to further accelerate Demand Side Integration (DSI) by activating also the smaller consumers to participate in demand response. The added customer-side demand flexibility will potentially benefit all stakeholders. Moreover, there are many possibilities to incorporate the opportunities brought by automatic meter reading and two-way communications into network tariff designs. The automatic delivery of information will enable the end-user to respond to the price signals and optimize consumption based on the tariff plan. [Similä et al., 2011]

Currently TOU remains as the most commonly applied tariff in U.S. as can be seen in figure 6. even if it encourages only little changes in the load curves of industrial customers [Hu et al., 2015]. In addition, [Hu et al., 2015] argue that “it is urgent and important for Europe to find alternative price mechanisms other than TOU.” In U.S electricity rates are expected to increase due to network investments and higher power costs from increased share of renewables [Kassakian et al., 2011]. [Borenstein et al., 2002] believe that price-based demand response will eventually provide the power system with enough reliability to surpass emergency load curtailment programs. The increase of enabling technologies is seen as integral part of demand response but not sufficient alone. The developments in demand response are tightly tied together with the adaptation of smart grids. In a smart grid study, [U.S. Energy Information Administration, 2011] illustrate how number of states in U.S have taken actions to implement dynamic pricing in the past years and i.e. New York and California have already mandates that utilities have to offer dynamic pricing. [Kassakian et al., 2011] argue that an ideal utility rate structure would eliminate the need to recover network costs through kWh charges, but instead energy would be charged according to the locational marginal prices during specific time at each distribution node. The remaining network costs would be recovered by fixed charges. However, the current power system is far from realizing such an ideal solution.

2.3 Tariff Plans

Electricity tariff plans are the specific fees that electric utilities use to charge customers on their electricity bill. In general, the tariff plans can be divided into supply, distribution and transmission tariffs. Also, there is a variety of different tariff schemes that vary between different electric utilities and local regulatory practices. For supply tariffs, the commercial customers can often choose between fixed contracts, flexible market price –based contracts or some combination of the two. Fixed price supply tariffs protect customers against changes in future electricity prices. The average electricity costs

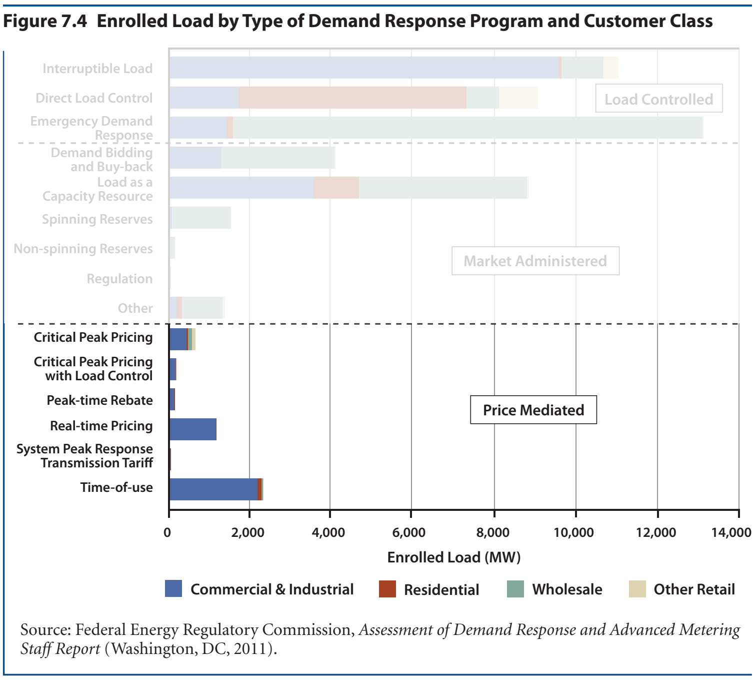


Figure 7.4 Enrolled Load by Type of Demand Response Program and Customer Class

Source: Federal Energy Regulatory Commission, *Assessment of Demand Response and Advanced Metering Staff Report* (Washington, DC, 2011).

Figure 6: Enrolled load under price mediated demand response in U.S. [Kassakian et al., 2011]

under flexible supply tariffs are often comparatively cheaper to fixed supply tariffs but then customers also need more advanced metering infrastructure to provide electric utilities sufficient data for billing. In general, the distribution and transmission tariffs have charging policies for both use-of-system charges and connection charging. These charges cover the cost of using the electricity distribution network and establishing a new connection to the grid. Since, distribution and transmission can be considered natural monopolies under most circumstances, the distribution and transmission tariffs are generally heavily regulated by government. Government can also influence the tariff planning from its own objectives by for example limiting the amount of allowed profits for utilities and by subsidizing certain customer segments.

New York has the New York State Public Service Commission, which regulates and approves the electricity tariffs in New York, which means that the contracted electricity rate and its terms and conditions are under its supervision. Customers are obligated to purchase distribution from the local electric utility but the supply tariffs are open for competition due to deregulation and customer can choose buy electricity supply from the local electric utility or to be served by ESCO (Energy Services Company / Electric Suppliers). Customers are often categorized by their end-use purpose, connected voltage and maximum demand level. For example, ConEdison serves general customers with peak demand in excess of 10 kW under the Service Classification 9, General – Large. The supply part of this tariff is based on either standard fixed supply rate or time-varying prices. In case that customers purchase supply from ConEdison and their monthly maximum demand exceeds 1500 kW then they will be served under mandatory hourly pricing tariff called Rider M. Rider M is based on the day-ahead market price and fluctuates hourly. [Consolidated Edison Company of New York, Inc., 2016b]

Most of the customers in NYC are charged for network services by ConEdison, which is the biggest distribution company in the city [The New York City, 2011]. ConEdison's distribution tariff consists of five main components: Demand Delivery Charges ($/kW), Energy Delivery Charge ($/kWh), Metering Charges ($/month), Reactive Power Demand Charge ($/kVar) and Additional Delivery Charges and Adjustments. In addition, applicable customers who are not served under mandatory Time-of-use pricing have the chance to choose between TOU rates and fixed rate structure for the demand delivery charges. [Consolidated Edison Company of New York, Inc., 2016b]

New York State imposes variety of taxes and levies on utilities, which are incorporated to the price that consumers pay for their electricity. Sales tax is imposed on customers who purchase supply or delivery of electricity, whereas Gross Receipt Tax is collected from the utilities' revenues. In addition, surcharges for incentivizing renewables, energy efficiency and social subsidies are included in the price that customers pay for electricity.

The connection charges, due to establishing a new electricity connection from building premises to distribution network, are often case-specific and depend on the type of connection and location of the connection point. These contracts are also often not disclosed publicly and remain bespoke between utilities and customers.

London has a variety of different market players offering electric services to consumers. Companies such as EDF provide fixed, flexible and performance based energy contracts for customers. For example, EDF explains their pricing policy in terms of Unit price, Pass through charges and Other factors. Unit price consists of energy costs (cost of purchasing electricity), infrastructure costs (cost of transmission and distribution of electricity) and cost to serve (management costs). Pass through charges are combination of charges that incur due to delivering electricity to customer. These charges are Standing Charge for installing and maintaining the distribution network, Availability Charge for covering investment and maintenance of the electricity grid, Reactive Power charge for losses in power efficiency, Combined Half Hourly Data Charge for metering costs and Settlement Agency Fee for balancing the costs between different stakeholders. Other factors in electricity costs include Renewable obligation, which support the implementation of renewable electricity projects. [EDF, 2013]

In UK, the natural monopolies of electricity distribution and transmission are regulated by electricity market regulator – Ofgem. It has the responsibility of making sure that customers are charged in appropriate way for their new connection to the electric grid and its usage. The charging methodology divides customers according to their connection voltage level (low-voltage, high-voltage or extra high-voltage) and metering interval (half-hourly or non-half hourly). The large commercial building studied in this thesis would fall under the category of high-voltage customer, which is subjected to Common Distribution Charging Methdology (CDCM). [ofgem, 2016, Energy Networks

Association, 2014]

Neither production, transmission or distribution of electricity has specific taxes in UK, but they are subjected to the standard turnover taxation - VAT rate of 20% (in some cases reduced rate of 5% for non-business use). However, most of the paid VAT charges can be reclaimed in commercial sector. Even though supply itself is not taxed, the retail suppliers have to collect tax based on the consumption of electricity. [Eurelectric, 2012]. Customers are also charged policy support costs (Levies) in an increasing manner as a result of policies which aim to mitigate climate change and promote the implementation of renewable energy sources. Compared to other European countries, UK has one of the lowest levels of total taxes and levies. [Eurelectric, 2014]

Connection charges can be allocated into three groups, which are, the costs paid by customer, the costs divided between customer and DSO and the costs covered fully by DSO. According to London Power Networks, all the extension assets that have to be installed in order to deliver electricity to new premises are charged fully to customer. The costs from reinforcing the existing system so that it will benefit also other system users are apportioned between customer and DSO. DSO will cover all the costs beyond one voltage level higher than the customer connection point is at. The connection charges are bespoke and depend on the specific customer requirements, but DSOs publish examples to illustrate pricing methodology and cost ranges. For example, a new 600kVA connection to commercial premises could cost around 70 000€ (inc. cables, substations, joints and meter panels). More than half of the total costs can be allocated to the installation of high-voltage and low-voltage cables (45 000€), and almost all the rest goes to the cost of substation (22 000€). [UK Power Networks, 2012]

2.4 Wholesale and Retail Prices

The commercial and industrial customers can differ quite a lot from the residential customers in how they purchase electricity. The more the customer consumes electricity the more important an optimal strategy for procuring that electricity becomes. A typical non-domestic customer in UK has total annual electricity consumption of 11 000 MWh and electricity costs of roughly 1,4 M€ [Stephen Jones Associates. South East Economics, 2014]. Thus, it is evident that these facilities pay or at least should pay close attention to how they purchase electricity and whether that is the most cost-efficient strategy. Depending on the level of development in the local electricity markets, the customers have a variety of options including whether they buy electricity on a fixed price or on the wholesale market price. Also, a combination of the two can be a beneficial option for some customers due to ability to mitigate risk against fluctuations in market prices. These contracts between an electric utility and a customer are often bespoke and not public information. Thus, for the sake of simplicity, we will disregard the more complicated schemes of purchasing electricity and instead rely on the wholesale market prices for the year of 2015 and expect customers to procure all of their electricity supply through market price based contract.

An important distinction regarding this study is the difference between energy (kWh) related costs, demand (kW) related costs and fixed costs. The rate structures under the studied tariff schemes can have around 15 different price components that are incorporated into the price that customer eventually pays for electricity. The detailed analysis of these individual components isn't relevant regarding the scope of this study and its goals. Instead, the price components are laid out in a way that will visualize how the different components can be divided into meaningful categories such as into consumption based *Commodity Charges* or use-of-system based *Delivery Charges*. The Commodity Charges incur from purchasing electricity from Generation Suppliers and can fluctuate in response to wholesale market prices, whereas Delivery Charges refer to the portion of the electricity bill that covers the cost of delivering electricity to customer. However, division into Commodity and Delivery Charges does not reveal sufficient information about the tariff structure for managing electricity costs. Thus, electricity costs were divided into energy, demand and fixed cost components, which yields much more relevant information about how the customer's demand profile impacts the electricity bill. In order to determine the potential savings from optimizing demand (kW), it is essential to understand the weight of demand component (kW) in the electricity costs. Figure 7. illustrates main components of an electricity bill for a large consumer, following the above mentioned cost allocation principles.

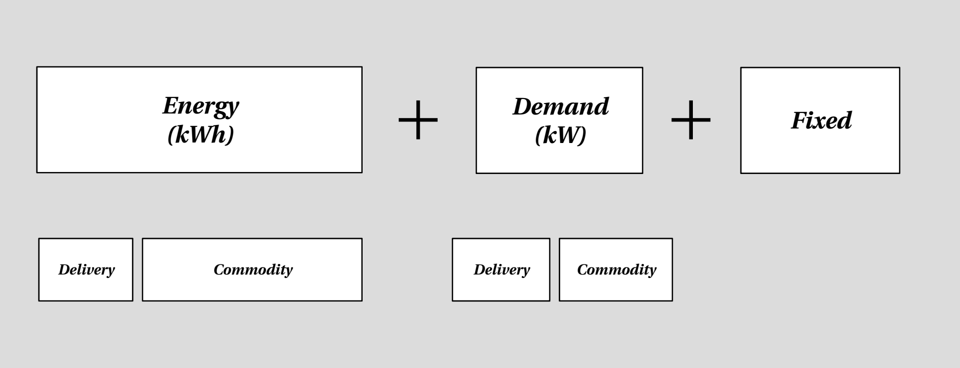
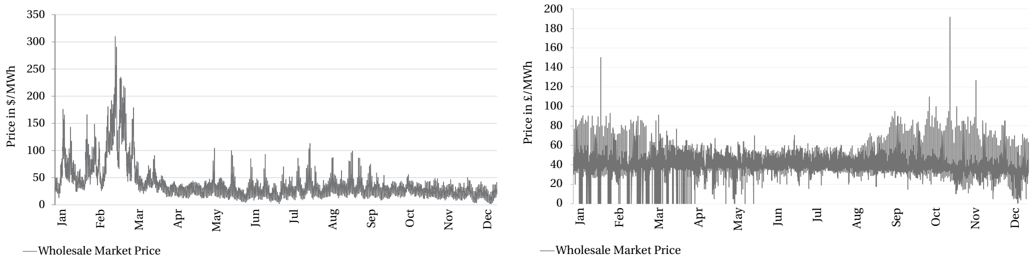


Figure 7: Breakdown of electricity bill into its main components

The composition of individual price components on an electricity bill varies greatly among different utilities and thus comparing them without first labeling them into meaningful groups isn't useful. The majority of comparisons in this study will be carried out by composing electricity costs from the three top-level groups in this hierarchy: energy, demand and fixed costs. Identifying the demand based costs in the electricity bill is essential in order to evaluate the profitability of demand response measures.

Wholesale Market Prices for the half-hourly day-ahead market in NYISO Market and UK APX are illustrated for the year 2015 in figures [8a,8b]. The prices are defined for each half-hour interval so that every day has 48 spot prices that are given one day in advance. In UK, the price level increase in colder seasons can be accounted for increased demand during fall and winter periods. Similar phenomenon can be seen also occurring in NYC during cold winter months. The wholesale market prices in northeast US correlate heavily with natural gas prices and February price spike can most likely be attributed for supply scarcity. The rare price spikes also manifest the volatile nature of spot prices for electricity. In case that customers choose to be served under market based tariffs, then they have a great incentive to reduce consumption during these highly priced periods.



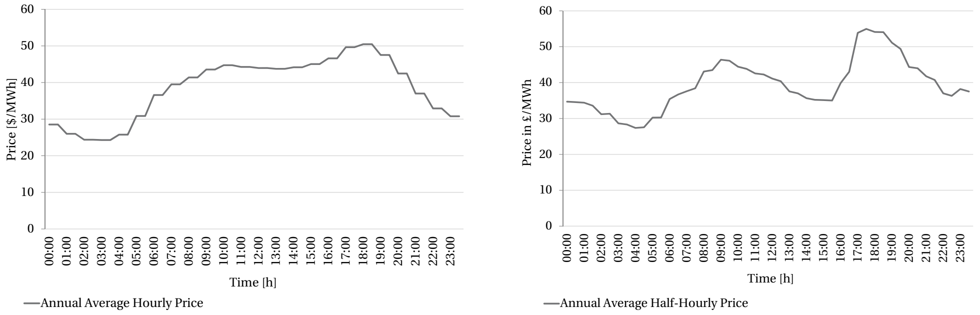
(a) NYC

(b) UK

Figure 8: Wholesale Half-Hour Day-Ahead Market Prices for electricity in 2015 [APX - Power Spot Exchange, 2016, NYISO, 2016]

The average daily prices in figures [9a,9b] show that the most expensive hours usually occur during late afternoon around 5-6pm. This can be attributed to the common lifestyle in which people work for 9am to 5pm and then return home causing a surge in domestic consumption. The cheapest hours occur during 3-4am when most of the people are at sleep and businesses stay closed. Interestingly, the wholesale price in UK declines during afternoon and only surges back up around 5pm. Such phenomenon doesn't happen in NYC where the price level will remain at constant high throughout the afternoon until it also surges up around 5pm. It can be most likely explained by the particular character of NYC, which is densely populated by offices that have very high demand during working hours.

Typical commercial electricity bill in London and NYC consist of multiple charges that have been illustrated in figures [11,10]. The price components can be allocated on the basis of whether they are charged according to demand ($/kW) or energy ($/kWh) and also separated into delivery and commodity costs. The different price components might also have time-of-use rates applied to them instead of just a fixed rate for given billing period. For example, the case building in this study is subjected to ConEdison tariff that has time-of-use rates for Energy Demand and Market Supply Charge. As a result, the demand costs in NYC are heavily dependent on the coincidence between peak demand and the most expensive time periods in the time-of-use rates. On the other hand, the case building in UK is not subjected to similar time-of-use rates in demand charges but instead has a fixed rate per day.



(a) NYC (b) UK

Figure 9: Average Daily Half-Hour Day-Ahead Market Prices in 2015 [APX - Power Spot Exchange, 2016, NYISO, 2016]

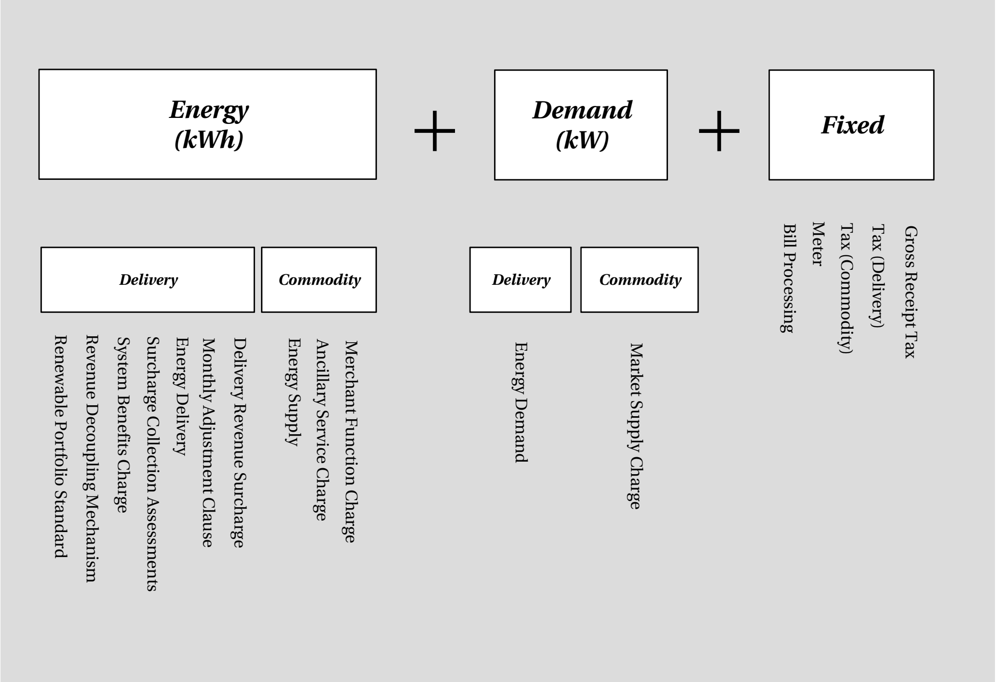


Figure 10: Electricity bill breakdown for a typical commercial customer in NYC

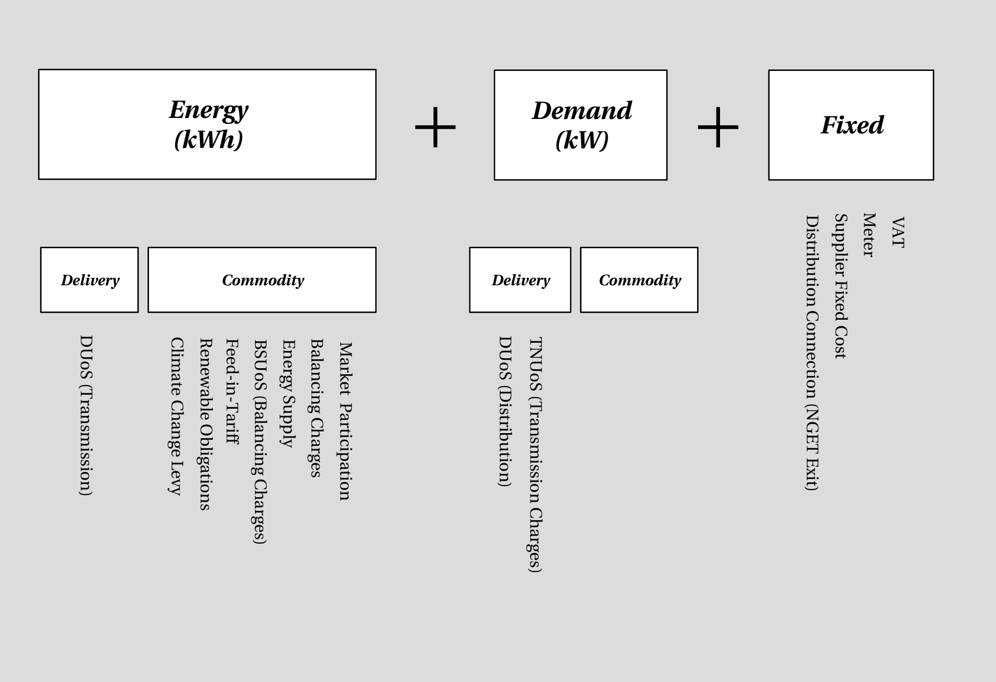


Figure 11: Electricity bill breakdown for a typical commercial customer in London

3 Demand Optimization in Buildings

There is a great potential for demand reductions in commercial buildings. [Kiliccote et al., 2006] refer to a study stating that commercial buildings account on average for 45% of the summer peak demand in U.S. [Pike Research, 2012] place the figure even higher, stating that more than half of the peak demand in US can be attributed to commercial building sector. Nonetheless, commercial buildings are still only a minor participant in demand response programs while big industrial customers dominate most of the demand response programs. Large industrial customers are an obvious target for Demand Response programs due to their high peak-to-average ratio, which indicates high momentary peaks in demand. The large customers are also more likely to have existing building and energy management systems that are a requirement for many demand response programs. However, the current trend is giving more and more emphasis on the commercial and even residential level demand response. Studies have shown a potential to reduce peak demand by 5-10% in buildings with enabling Energy Management Control Systems (EMCS) [Kiliccote et al., 2006]. EMCS is a tool for operating building subsystems to maximize energy-efficiency and to achieve demand reductions in building power demand. Figure 12. shows the impact of different demand response strategies on building power demand.

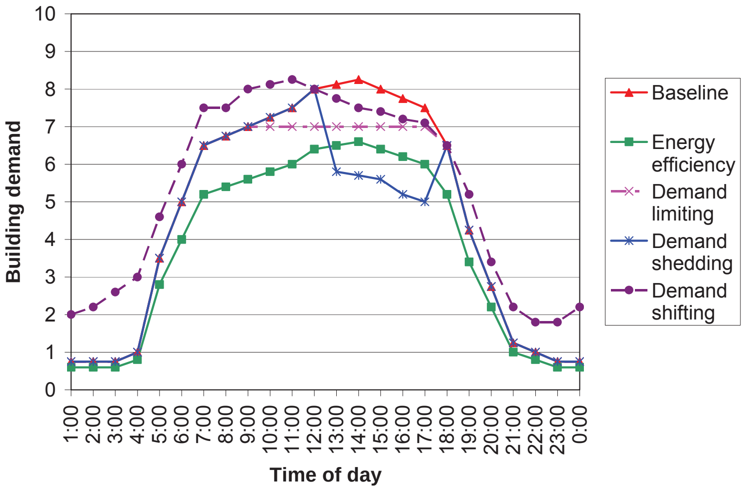


Figure 12: Illustrative load profiles under Demand Response [Motegi et al., 2007]

The demand management strategies and technologies vary to a great extent depending on the building characteristics, but main focus has been on controlling HVAC and lighting systems. This is because i.e. HVAC loads are considered to some extent shiftable, which makes them especially suitable for demand response. HVAC equipment can be momentarily turned-off or operated at partial load in order to reduce building power demand as long as normal operation is restored before indoor environment quality decreases below unacceptable threshold. In some occasions, facility's integrated demand can be substantially reduced for even several hours by effectively controlling these shiftable building loads. Contrary to HVAC loads, elevator systems and other loads that require real-time power supply are not considered to be shiftable in the same sense. Even though, elevator systems consisting of multiple elevator cars can be scheduled to reduce transient peak power on a timescale of few seconds, they cannot achieve demand optimization on a timescale of minutes to hours without sacrificing transportation capacity. Unless coupled with an auxiliary energy storage, which would keep providing real-time power supply to the elevator system. Other means of adjusting integrated demand of an elevator system could only be achieved on the expense of lowered service level. However, under some circumstances the momentary reduction in service level could be considered acceptable if the facility owner would receive sufficient financial compensation for the demand reduction. Currently, some commercial buildings have adapted demand management strategies in which they would turn off some of the elevators during demand response event [Motegi et al., 2007]. This certainly isn't an optimal strategy for enabling elevator systems to participate in demand response. Another method would be to only control the elevators' rated speed and acceleration so that decent transportation capacity is maintained despite the lowered power supply. Nevertheless, currently the facility managers do not have the necessary access or controls to carry out such demand control strategy.

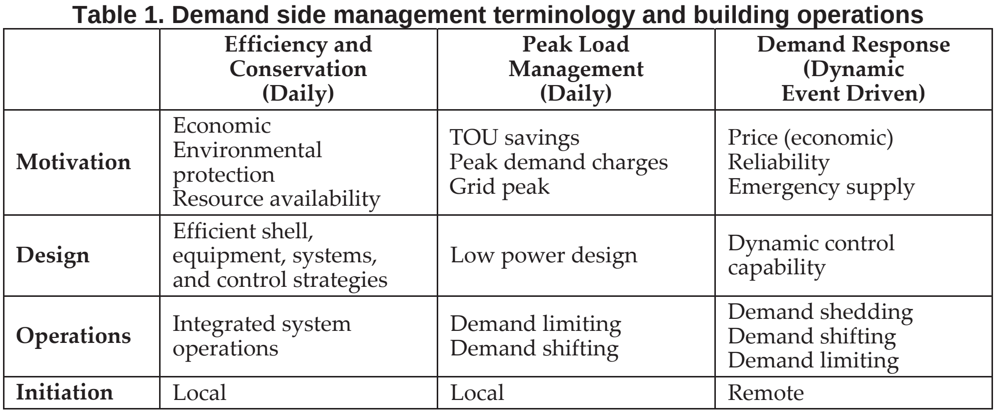


Table 1. Demand side management terminology and building operations

	Efficiency and Conservation (Daily)	Peak Load Management (Daily)	Demand Response (Dynamic Event Driven)
Motivation	Economic Environmental protection Resource availability	TOU savings Peak demand charges Grid peak	Price (economic) Reliability Emergency supply
Design	Efficient shell, equipment, systems, and control strategies	Low power design	Dynamic control capability
Operations	Integrated system operations	Demand limiting Demand shifting	Demand shedding Demand shifting Demand limiting
Initiation	Local	Local	Remote

Figure 13: Demand side management terminology and building operations. [Motegi et al., 2007]

Figure 13. outlines the different levels of demand side management in buildings and proposes a framework for analyzing the building operations from the perspective of Demand Response. This thesis will refrain from analyzing the energy efficiency and conservation strategies, because the topic has been well covered in previous studies. Instead this study will mainly focus on how Peak Load Management and Demand Response relate to the elevator context. In their analysis, [Kiliccote et al., 2006] divide demand control activities into three main features: Demand Limiting, Demand Shifting and Demand Shedding. The influence of these strategies on building demand were illustrated in Figure 12.

Demand limiting refers to momentary load reductions, which prevent the system from exceeding certain pre-determined demand limit. After the control event the demand will be restored back to normal.

Demand shifting refers to control strategies that will shift electricity consumption to another time period.

Demand shedding refers to temporary reduction in demand in response to a control signal.

[Kiliccote et al., 2006] propose that demand shifting would be a realistic approach if i.e. thermal storage could be used to offset demand to a cheaper time period. This could either be achieved by utilizing an active heat storage (chilled water, ice storage) or by passive heat storage (pre-cooling building) [Kiliccote et al., 2006]. Also a battery storage could be used to store electricity when demand is lowest and then discharged when demand is highest. Even though, battery storage has many magnitudes lower capability to store energy relative to investment costs than heat storage. We will later utilize the same framework that [Kiliccote et al., 2006] proposed for demand management and adapt it to the requirements of elevator systems.

3.1 Building Power System

In this study, the analysis is limited to the portion of the power network that lies between a primary feeder and an elevator system. [Harvey, 2012] states that large commercial buildings usually purchase electricity directly from medium-voltage distribution grid (4-35kV) and use step-down transformers on site to transform it down to the utilization voltage level. The primary function of building power distribution system is to distribute electrical power throughout the building. A power distribution system in a commercial building is usually a three-phase system consisting of low-voltage circuits and step-down transformers that connect them to the primary feeders [Naval Facilities Engineering Command, 1990]. This step-down process can be typically attributed to lose 3-5 % of the delivered electricity [Harvey, 2012]. The common utilization voltage levels are 400V (line-to-line) in Northern Europe and 480V (line-to-line) in US.

The building power distribution system can be configured in a variety of ways that take into account i.e. reliability issues, location of large loads and investment costs [Naval Facilities Engineering Command, 1990]. However, the main distinction should be made between central and distributed low-voltage supply. Central supply describes a situation in which transformers are feeding into different parts of the distribution network whereas distributed supply has transformers placed closer to load centers for a more evenly distributed installation. In a paper by [Siemens, 2015], it is argued that an economical power range to transport energy in a low-voltage grid is roughly between 50kVA to 250kVA due to power losses, power quality and voltage drop. Thus, it makes sense to place the step-down transformers near primary loads in order to minimize transporting energy in a low-voltage grid for excessive distances. Locating transformers near the primary loads will also have the benefit of reducing requirements for secondary cables [M., 1999].

As previously explained, a normal power supply to a building can be fed through a direct connection to the public low-voltage grid or from the medium-voltage network by utilizing public or local substations in the building. In case of emergency safety power supply (SPS), back-up generators can be utilized to provide standby service whereas local energy storage can provide uninterruptible power supply (UPS) for sensitive emergency systems. For example, firefighting elevators are often connected to the SPS whereas emergency lighting is connected to the UPS. [Siemens, 2015]. [Siemens, 2015] suggests that SPS and UPS systems are designed to meet 30% and 15% of building total power demand, respectively.

Figure 14. illustrates a typical network planning example for a high-rise building with more than twenty floors and required power of less or equal to 2000kW. The network planning is based on design suggestion for different building modules made by [Siemens, 2015]. The distribution system has one central supply section and six 800kVA supply transformers. Thus, the total rated capacity of supply transformers in the building is 4800kVA, which means that the transformers are mainly operated at partial load. The supply transformers are placed near the primary loads, which are the elevator system and HVAC. The firefighting elevators are connected to SPS through a secondary feeder cable.

When dimensioning an elevator system, one should be concerned with the capacity of the power supply transformer, size of the feeder cables and current rating for circuit breakers. The distribution assets have to be dimensioned to handle the load currents caused by elevator system loading. [Harvey, 2012] refers to a study in which a survey of 43 buildings resulted in average transformer load to be only 16% of rated capacity. The available power ratings for power supply transformers move in incremental steps. Dry-type transformers are more preferable for inside building-use than oil-immersed transformers. Three-phase dry-type distribution transformers are identified in EN 50541-1 (VDE 0532-241) to have the following nominal power ratings in kVA: 100, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150. However, transformers can momentarily achieve higher than normal output if additional ventilation is used. [Siemens, 2015]. In the case building of this study, the low-voltage feeder cables that provide normal power supply for both elevator groups are typical $240 mm^2 XLPE/PVC$ copper cables and SPS is fed through $95 mm^2 XLPE/PVC$ copper cables. This implies that the elevator systems can operate only at partial load under SPS (e.g. in the case study building 4 out of 12 elevators can remain operational during outage). As a result, some of the elevators would have to be turned off if normal power supply fails. The feeder cables are provided in various sizes that are dimensioned to meet certain amperage and voltage ratings. The voltage rating of the cable also defines the insulation thickness and is affected by the applied line-to-line voltage, grounding and reaction time of ground fault protection system. The amperage rating defines the

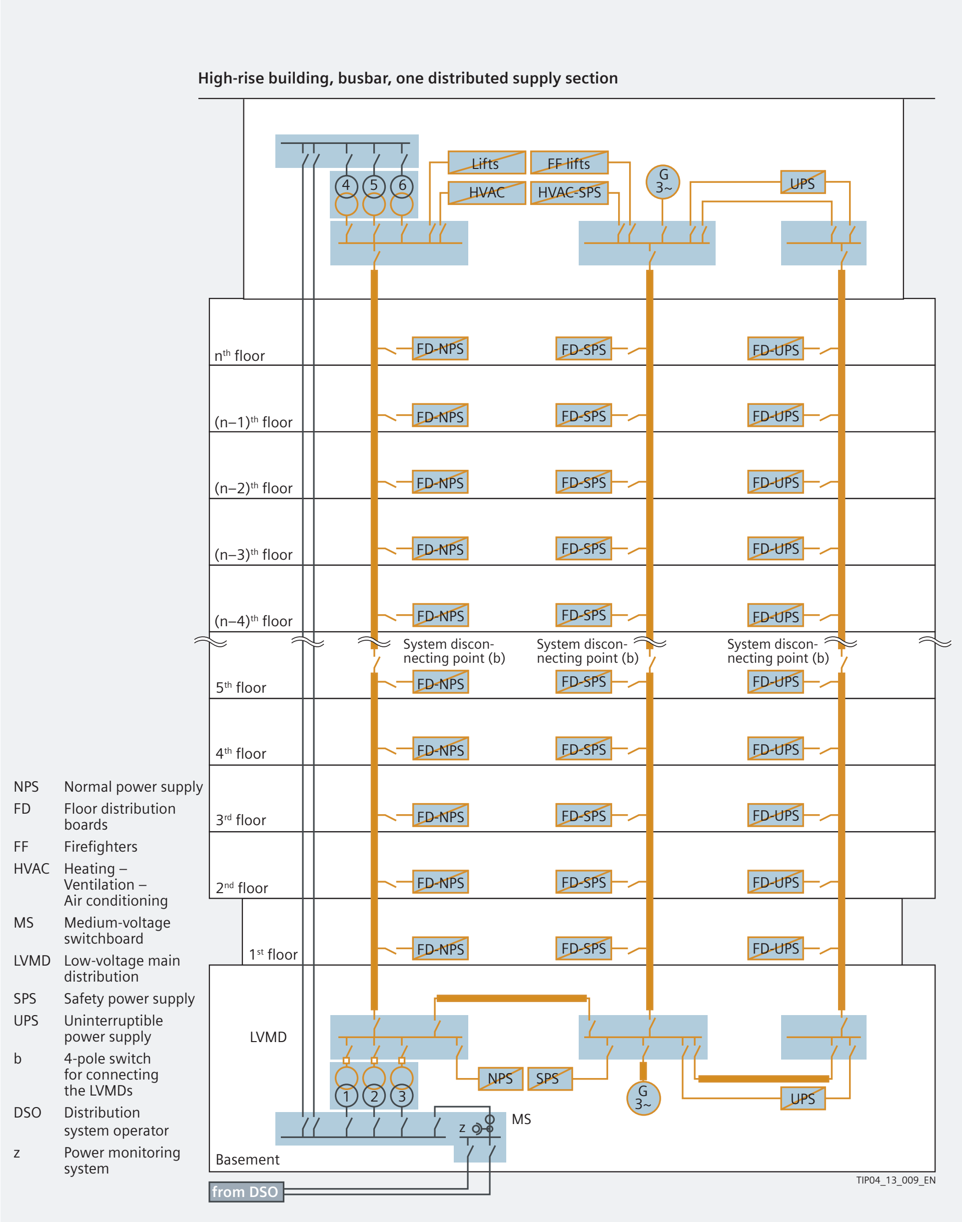


Figure 14: Illustrative example of network planning for a high-rise building [Siemens, 2015]

conductor size and is influenced by loading, thermal effects and other losses. [Naval Facilities Engineering Command, 1990]

3.2 Building and Elevator Management Systems

Building Management Systems (BMS) and Elevator Management Systems (EMS) are control systems that facility manager can use to operate the end-use systems in the facility. [Kiliccote et al., 2006] estimated in 2006 that the amount of BMS in commercial buildings was around 7%. The number has most likely significantly increased in the last decade and especially new constructions can be expected to have more sophisticated control systems. However, [Kim, 2014] stated that most of the existing control systems did not yet have the built-in capability to support Demand Response and without the built-in automation for DR, it is unlikely to be realized due to cost of manual monitoring and responding. On the other hand, [Kim, 2014] also predicted that Auto-DR capabilities might become more integrated into BMS as a result of DR being included in the LEED building credit system.

EMCS can be developed to optimize building power demand by

1. Scheduling building systems to limit total facility power demand
2. Duty cycling the operation of different subsystem units (e.g. HVAC) to avoid coincident peak demand
3. Demand limiting by defining specific demand reduction target

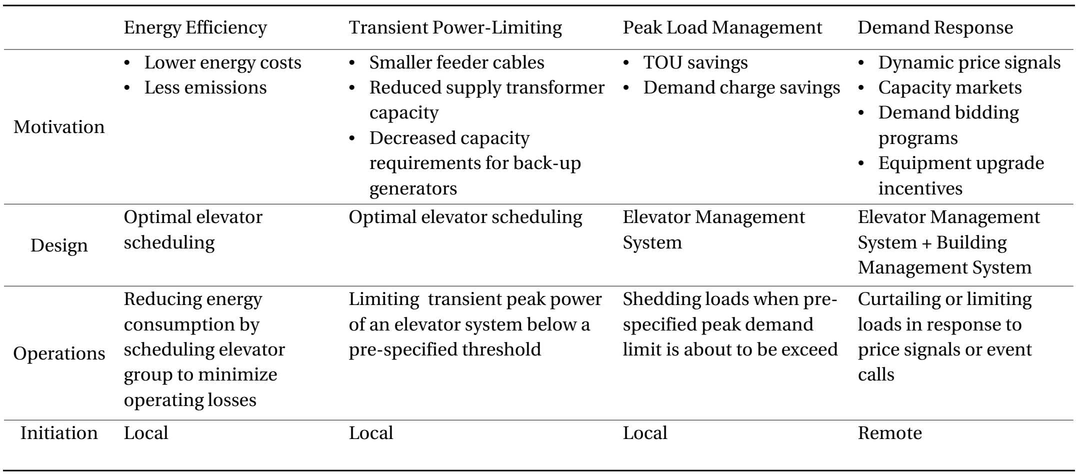
In addition to BMS and EMS, smart demand-focused control systems have been developed for the sole purpose of addressing the need for demand control. The systems function in a way that they monitor and predict facility demand, and if that forecasted demand seems to exceed kW threshold set for demand billing period, the system will reduce demand temporarily to prevent exceeding that threshold. [Smith et al., 2004] state that “These systems, with sufficient loads connected, are highly effective at achieving significant demand reductions without substantial or even noticeable changes in facility comfort”. Even adaptive systems (Neural Networks) have been developed for building automation, which at least technically should be very suitable for managing also facility demand. [Smith et al., 2004]. However, [Smith et al., 2004] also remind that load control is only secondary objective of BMS, primary goal still being management of building end use systems from central location. When developing BMS to address multiple goals, it is essential to pay attention to avoid conflicting roles between demand control and end use service goals [Smith et al., 2004].

Currently, building managers are offered elevator management systems that enable remote monitoring and controlling of elevators systems. These systems usually focus on traffic analysis and monitoring of equipment status. Demand Response functionalities have been widely excluded from these systems. Although many building appliances such as HVAC and lighting have been integrated under a centralized building management system, the elevator systems have largely remained independent of centralized BMS. However, some original equipment manufacturers have begun to introduce BMS integration to their elevator management systems [Motion Control Engineering, 2015]. These systems have pre-defined control sequences for Demand Response events that will systematically turn-off elevators in response to DR-signals.

3.3 Demand Control for Elevator Systems

Demand control activities for Demand Optimized Elevator System can be divided into four main categories: Energy Efficiency, Transient Power-Limiting, Peak Load Management and Demand Response. The motivation, design, operations and initiation for these activities have been laid out in figure 15. The framework is meant to provide a structured understanding of different demand control activities that elevator systems can be configured to carry out.

Energy Efficiency refers to the reduction in overall energy consumption by permanently lowering average demand [Motegi et al., 2007]. Energy efficiency in elevator systems is a well-studied area of research and elevator systems have already seen significant increases in energy efficiency through the implementation of regenerative systems over the past years [Sachs, 2005]. In addition to hardware upgrades, [Zhang and Zong, 2013] have proposed that energy efficient elevator scheduling will become more prevalent in the future. Although, this study will not focus on energy efficiency in elevator systems, it is still kept as a reference in the demand management framework.



	Energy Efficiency	Transient Power-Limiting	Peak Load Management	Demand Response
Motivation	• Lower energy costs • Less emissions	• Smaller feeder cables • Reduced supply transformer capacity • Decreased capacity requirements for back-up generators	• TOU savings • Demand charge savings	• Dynamic price signals • Capacity markets • Demand bidding programs • Equipment upgrade incentives
Design	Optimal elevator scheduling	Optimal elevator scheduling	Elevator Management System	Elevator Management System + Building Management System
Operations	Reducing energy consumption by scheduling elevator group to minimize operating losses	Limiting transient peak power of an elevator system below a pre-specified threshold	Shedding loads when pre-specified peak demand limit is about to be exceed	Curtailing or limiting loads in response to price signals or event calls
Initiation	Local	Local	Local	Remote

Figure 15: Demand Management Framework for Elevator Systems

Transient Power-Limiting is a demand control activity that aims to reduce the need for high surges of intermittent power supply. The transient power demand of a multi-car elevator system is highly volatile and dependent on the arbitrary coincidence between simultaneously accelerating elevator cars. These randomly occurring transient power peaks can be magnitudes higher than the average demand. The intermittent peaks do not have an impact to the electricity costs, which are determined on the basis of integrated demand metering. However, transient power peaks impose capacity requirements for the building power system assets, which will increase the capital costs for building construction. In order to mitigate these negative effects, elevator systems can be configured to limit the maximum required power supply by optimal elevator scheduling. Contrary to Peak Load Management and Demand Response, Transient Power-Limiting is a permanent configuration to the elevator group control system that will be effective at all times. Thus, it requires no participation from an operator or integration to other demand management systems.

Peak Load Management has to do with managing the long-term (minutes to hours) fluctuations in demand, which are also the basis for integrated demand metering that utilities use for billing purposes. The goal of this demand control activity would be to forecast the power demand of an elevator system and execute control sequences or discharge energy storage to shed demand if pre-defined peak demand threshold is about to be exceeded [Motegi et al., 2007]. The incentive to reduce demand would be to achieve electricity cost savings in TOU pricing and demand charges. The integrated demand of an elevator system is essentially a result of supplying power for tens or hundreds of individual elevator trips. Optimally scheduling these trips within the integrated demand window will not have impact on the measured peak demand because averaging over a long interval will even out any transient power peaks. Thus, managing peak load in elevator systems will necessarily have to have another approach than optimal elevator scheduling. One approach proposed here is utilizing a local energy storage for the purpose of controlling elevator peak loads. Other approaches could include turning of elevators sequentially or adjusting the driving parameters of the elevators. These approaches will be further studied in the chapter Analysis of Demand Optimized Elevator System.

Demand Response has nearly the same prerequisites than Peak Load Management but with one crucial difference that the control sequences are initiated in response to DR-signals. These signals can be real-time electricity price information or event calls for DR-programs. The remote initiation necessitates a bi-later communication system between the DR-program provider and the customer. Customers participating in Demand Response are provided incentives for demand reductions on € per kW basis or as an ability to optimize electricity consumption to time-varying electricity prices. The customers with DR-enabled control systems can participate in multiple DR-programs that generally offered by either the electric utility or transmission system operator. [Motegi et al., 2007] state that these DR-programs can offer a great way to achieve demand savings by incentivizing load curtailment during demand response events. Demand response event means a situation when TSO or electric utility calls for demand response participants to momentarily reduce their demand. Customers selling their demand reduction capacity will be compensated for the amount of energy reduced during the event and a fixed payment for participating. [Motegi et al., 2007]. The control sequences can be carried out in a similar way as in Peak Load Management by utilizing a local energy storage, duty-cycling elevators or adjusting driving parameters. One approach to DR in elevator systems could be to integrate elevators systems with the existing Building Management Systems that are already equipped with DR enabling controls. Under such scenario, the BMS and elevator management system would communicate with each other to determine the most cost-efficient control sequence for the elevator system.

As previously stated, the applied control sequences and economic benefits vary among different demand control activities. Also an essential difference between the different strategies is in their timescale. Peak Load Management will be dispatched during few hours each month when it seems that peak demand might exceed pre-specified limit [Kiliccote et al., 2006] and Transient Power-Limiting will be imposed permanently on the elevator system, implicit Demand Response strategies will be effective at all times when elevator system is operating and explicit Demand Response will be called-on from 5 to 100 hours per year depending on the enrolled program [Kiliccote et al., 2006]

Influence on Service Level that passengers experience is an important consideration in any of the proposed demand control activities. Since elevator systems require a real-time power supply to maintain satisfactory transportation capacity, they cannot significantly deviate from normal consumption patterns. Although, elevator scheduling provides control over transient peak power in the timeframe of few seconds, it offers no help in shedding integrated demand over longer periods. The three approaches proposed earlier for enabling Demand Response in elevator systems were: local energy storage, adjusting driving parameters and turning-off elevators sequentially. Excluding the local energy storage, the two latter approaches would have to be considered for their impact on passenger service level. Duty-cycling elevators or reducing the nominal travel speed would result in reduced transportation capacity of the elevator system. The building manager would have to consider if reduction in vertical transportation capacity would result in unacceptable decrease in service level and whether financial benefits would be great enough to offset those. [Motegi et al., 2007] point out that if a control strategy is acceptable in short term then why not implement it always? On the other hand, they also emphasize that care should be taken when considering reducing service level to gain demand savings.

The reduction in service level due to reduction in electrical demand can be overcome by sharing the burden among multiple electrical loads in the facility. In practice, the elevator system would execute control sequences among other electrical appliances such as HVAC and lighting. This way it will be less likely that the occupant satisfaction will be affected and burden will be fairly divided among all controllable building loads. [Motegi et al., 2007]. The burden sharing could also be time-dependent so that it will be best optimized to the current facility needs. For example, if elevator system needs more power to handle the morning inrush-peak, then HVAC and domestic hot water could have prepared for this by storing thermal energy in advance. Also, one approach to promote acceptance for DR could be to communicate the purpose of decreased service level to customers. For example, [Smith et al., 2004] investigated a case study in which Home Depot had participated in a demand response program. During a demand response event the stores had posted a sign explaining that the low lighting levels are because of their reduction in electrical demand for the good of community. Likewise, elevator systems could indicate to passengers whether they are operating in a low-power mode.

3.4 Demand Response

Demand Response is a voluntary reduction of electric usage by customers from their normal consumption patterns in response to price signals or other incentives intended to decrease electric usage [FERC, 2014]. The reduction of electric usage is voluntary in the sense that customer can choose to participate in demand response, but penalties might occur under some DR-programs if participant fails to respond to event call. [Motegi et al., 2007] describe demand response as “time-dependent program activities and tariffs that seek to reduce electricity use or shift usage to another time period.” and they further add that this reduction in electric demand is achieved on the expense of temporary reduction in facility service level. [Eurelectric, 2015] divide demand response into two main categories: Implicit and Explicit Demand Response. Implicit Demand Response refers to customers voluntarily shifting or lowering their demand in response to time-varying electricity prices, whereas Explicit Demand Response covers those schemes in which customers sell upfront the promise of changing their energy consumption when requested by the electric utility. Contrary to efforts in energy efficiency the goal of Demand Response is not to reduce energy consumption but to provide flexibility in the consumption. [Eurelectric, 2015]. During the time of highest system-wide demand, Demand Response can be utilized to encourage reducing or shifting demand from on-peak hours when electricity prices are high to non-peak hours with lower prices. Therefore, it also helps customers to manage their electricity costs. The aim is to minimize the negative effects on service level while achieving maximum electricity cost savings. [Motegi et al., 2007]. From the point of view of an electric utility, Demand Response is intended to address challenges in reliable power generation and price response to dynamic wholesale electricity prices [Kiliccote et al., 2006]. Benefits of Demand Response include lower requirements for installed generating capacity, avoided energy costs and long-term decrease in transmission and distribution capacity [Faruqui et al., 2010].

Especially in the United States, there is a constantly growing amount of research on Demand Response. The interest is partly due to the high peak-to-average demand ratio (PAR) of the power systems in U.S. [Hu et al., 2015]. Peak-to-average ratio refers to the ratio between peak demand and average demand of the power system. One percent of peak demand can account for 5-8% of the required generating capacity [Faruqui et al., 2010]. Most of this peak demand can be accounted for summer months due to high usage of air conditioning in buildings. In order to maintain reliable operation, the TSO has to have enough peak capacity to meet the peak demand. It used to be that TSOs acquired sufficient peak capacity only through bilateral contracts, but now the market is opening up for new players with demand side resources to bid for capacity. There are multiple Aggregators in U.S., which collect demand side resources and then bid these resources to compete against the generation suppliers on meeting the future peaks in grid electric demand. It doesn’t matter for the responsible balancing authority if the balance is maintained through increase in supply or reduction in demand. Thus, these aggregators can sell so called “negawatts” instead of generation to provide flexibility resources for the balancing authority. In US, capacity markets have been the main driver of demand response. In 2013, the US consumers participating in Demand Response received $2.2 billion dollars in revenues [SEDC, 2014].

In order to match supply and demand, the responsible balancing authorities have already been benefitting from demand response for years. [Herter et al., 2007] argues that Demand Response benefits the power system by increasing system reliability, decreasing wholesale market prices, reducing the market power of single actors and helping to maintain adequate system resources. As of now, the time-varying pricing is a relatively established rate structure in the utilities' offerings. However, as our energy systems are experiencing a revolutionary transformation towards more renewable and distributed generation, balancing the power system is becoming more challenging and additional flexibility is needed. Demand Response is fundamentally a flexibility resource, which value at any given time is determined by the market. [Eurelectric, 2015]. [US Green Building Council, 2012] also argue that commercial buildings investing in ADR enabling equipment and participating in demand response will often also lead them to new energy management procedures that can reduce both energy consumption and peak demand.

An open communication protocol has been proposed for Automated Demand Response called OpenADR, which helps to facilitate wider adaptation of Demand Response. In their study [Kim, 2014] presents a demonstration of OpenADR system. Its objective is to facilitate the price-responsive operation and demand response by exchanging XML-based information between different elements in the communication architecture. The basic system layout has been illustrated in Figure 16.

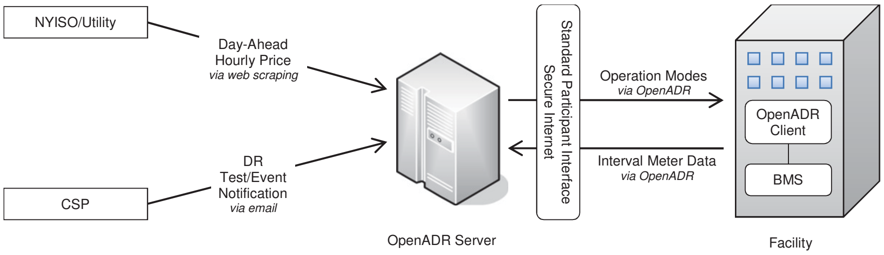


Figure 16: Basic layout of OpenADR communication infrastructure [Kim, 2014]

Curtailment Service Provider (CSP) / Aggregator signals DR events
OpenADR Server mediates DR-signals and meter data
OpenADR Client receives DR-signals at the facility
Building Management System (BMS) activates control sequences

Implementing Automated Demand Response requires careful assessment of building's present and past electricity consumptions patterns, BMS systems, operational constraints and DR capabilities. [Kim, 2014] emphasizes the importance of understanding customer goals and the impact that utility rates and demand charges will have on electricity bill when establishing DR control strategies and targets.

4 Basics of Elevator Systems

Elevators systems are essentially vertical transportation systems that provide movement between different floors in a building. [Sachs, 2005] lists elements that nearly all elevator systems have in common: control unit, cabs, guide rails, doors, lights, ventilating fans and safety devices. Elevator systems can be also divided into two main categories: hydraulic and traction elevators. In 2005, hydraulic elevators were still more common in the low-rise segment in North America, whereas traction elevators dominated the mid-rise and high-rise markets [Sachs, 2005]. Since duty cycles in low-rise building are infrequent, the total energy consumption of a hydraulic elevator is mainly determined by its standby power [Sachs et al., 2015]. The infrequent operation and low rated power constrain the potential cost-savings from demand optimization in hydraulic elevator systems.

In this thesis, the analysis will be limited to traction elevator systems in high-rise buildings. In traction elevator systems, the elevator cars are attached to a counterweight with wire ropes or belts that are wrapped around a pulley. The counterweight usually accounts for the weight of the cab and half of the maximum passenger load. The pulley in traction elevator is powered by either a gearless motor or through a reduction gear. Gearless motor suits best for the tallest buildings enabling fast travel speeds and geared units are used mainly for mid-rise buildings. [Sachs, 2005]. In order to guarantee smooth acceleration and deceleration, the modern traction elevators utilize permanent magnet synchronous motors that provide improved speed control and efficiency [Sachs et al., 2015]. The modern traction elevator systems can utilize regeneration where motor is also used as generator, thus allowing the energy to be conserved instead of being dissipated as heat. The recovered electricity can be fed back into the building power distribution system. Regenerative systems are estimated to yield 30% reduction in electricity consumption compared to conventional traction motor systems. [Sachs, 2005]. However, regeneration of power is not the only recent development in elevator systems. [Sachs et al., 2015] argues that the modern microprocessor-based control systems have also enabled many advances in the operation of elevator systems including adaptive elevator car scheduling and utility load control integration.

4.1 Elevator Group Control Systems

Since the first elevator systems, there have been control systems to operate the equipment. These early manually operated control systems of 1850s have through time developed into the modern computer-based control systems. Likewise, the single car control systems have advanced into group control systems capable of efficiently operating multiple interconnected elevators. [Barney and Santos, 1985]. Elevator group control system refers to a group of elevators that are physically residing close together and simultaneously scheduled by a single control unit. The control system uses an algorithm to determine which elevator cars are dispatched to serve which landing call requests. Efficiency of the elevator scheduling is an essential factor in the performance of an elevator system [Tyni and Ylinen, 2006]. The landing call allocation problem often requires sophisticated optimization techniques to achieve good results. It is an example of so-called online optimization problem where the scheduling is updated over time as more information about the system becomes available. Majority of scheduling algorithms use heuristics and thus aim not to find an exact solution. [Hiller et al., 2014]. This is because finding the exact solution can be very computationally heavy and partial solutions may already be sufficient to provide necessary service level for passengers. [Tyni and Ylinen, 2006] make a distinction between “landing call allocation” and “elevator car routing”, proposing that former should be used for methods providing only partial solutions and latter for methods providing real optimal solutions. In their study, [Tyni and Ylinen, 2006] presented “the first landing call algorithm that performs true route optimization by finding the optimal routes for each elevator in real time.”

The elevator scheduling problem has been extensively studied in literature and several optimization techniques have been proposed for elevator scheduling such as genetic algorithms, fuzzy systems, genetic network programming, artificial neural networks and DNA computing methods [Kim, 2014]. A majority of studies as well as real-world applications have focused on minimizing waiting times. Waiting time can be calculated as the time passenger has to wait between arriving in hallway to the time passenger enters elevator car. It is also one of the most basic measures of elevator performance. Besides optimizing waiting times, also multi-objective optimization has been proposed for including multiple optimization objectives in parallel. For example, [Zhang and Zong, 2014] argue that energy efficient elevator scheduling is a future trend by citing statistics, which have shown that elevators can be attributed for 3-8% of the overall energy consumption in a building. This has led to a growing interest in studying the possibility of including minimizing energy consumption as a parallel objective in elevator scheduling [Zhang and Zong, 2013]. [Zhang and Zong, 2013] suggest a balance between time performance and energy-saving elevator scheduling as an ideal execution. Similarly, [Tyni and Ylinen, 2006] propose that the goal of elevator scheduling is to provide adequate customer service with minimum energy consumption. Multiple studies have addressed this multi-objective optimization problem and results have indicated significant economic benefits [Zhang and Zong, 2013].

Similarly to minimizing energy consumption also minimizing transient peak power could be included as a parallel objective in the optimization algorithm. The optimization algorithm would aim to schedule the elevators so that coincident elevator peak demand would be minimized. This thesis will exclude the actual implementation of the multi-objective optimization algorithm and assume that a reasonable reduction in transient peak power would be possible to achieve by such algorithm. This would significantly reduce the transient peak power because of the high peak-to-average power demand ratio of high-rise elevator systems.

4.2 Power Demand

The power demand of an elevator system is primarily determined by the motor electrical power P_{me}, but also as a result of providing electrification for drives, lighting, fans and control systems. [Tyni et al., 2012] propose a method for analyzing the properties and performance of an elevator system, which is also applied in this study to model the power demand on an elevator system. Figure 17. illustrates a power demand model for an elevator system that constitutes of individual blocks for hoisting, motor and drive unit. The power transmission chain begins with the drive unit which controls the input power P_d (minus efficiency losses) for the traction motor. The mechanical power of a traction motor P_{mm} is the motor electrical power P_{me} minus internal losses in the motor. The mechanical motor power is through a hoisting transformed into conservative potential and kinetic energies P_{hc} and partially lost in friction losses P_{hl}. Figure 18. illustrates power demand of a single-car elevator system over one round-trip with empty car. Usually elevator systems are balanced so that the counterweight equals the weight of the elevator car plus half of the maximum load $m_{cwt} = m_{car} + 0,5m_{max.load}$ [Sachs, 2005]. The power needed to overcome the imbalance mass far exceeds the power losses due to friction or motor internal losses [Tyni et al., 2012]. As can also been seen in Figure 18. the power demand can take both positive and negative values, which means that consumed energy can also be partially regenerated. The peak power demand occurs right at the end of acceleration when the elevator reaches nominal travel speed.

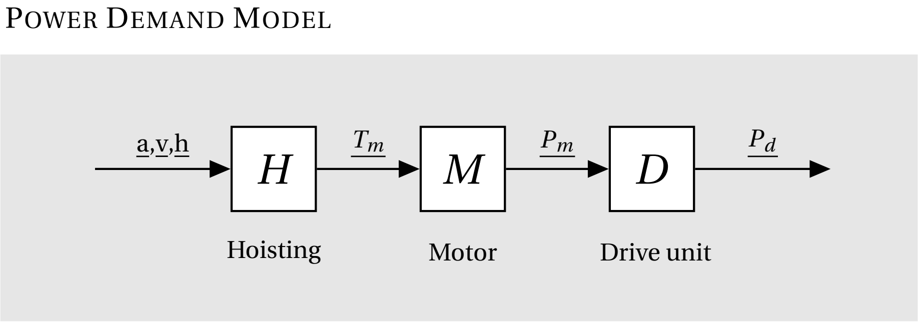

POWER DEMAND MODEL

Figure 17: Diagram of Power Demand Model for Elevator System

In the beginning the elevator starts to descend and the highest peak power occurs at [12s] when the elevator car reaches the end of acceleration. After that the system gains steadily potential energy as the heavier counterweight is lifted up. At [32s] the elevator begins to decelerate and continues to do so until it reaches the entrance floor and stops. At [48s] the elevator starts to accelerate back up and we see a momentary spike in power demand before nominal speed is reached and the regeneration of energy begins. Finally at [78s] the elevator brakes and the regeneration registers the highest peak power on the negative side. In the end, the system has returned to its initial state.

4.3 Energy Consumption

Elevator energy consumption varies based on building type, traffic patterns, elevator technology, scheduling algorithm etc. but on average elevators are estimated to contribute for roughly 3-8% of the total electricity consumption in a building [Almeida et al.,

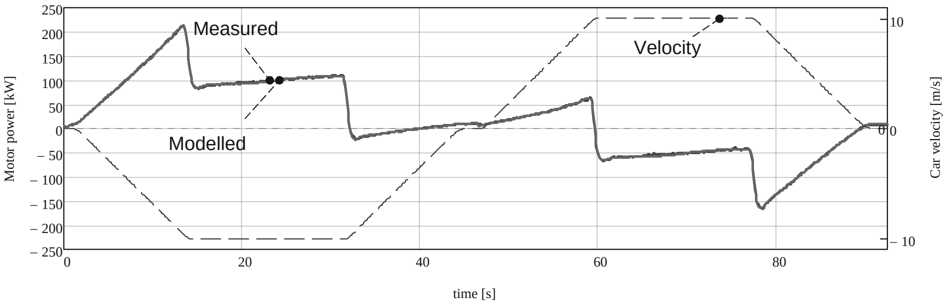


Figure 18: Modeled power demand against measurements for a single-car elevator system [Tyni et al., 2012]

2012]. Since this contribution is relatively small, elevator energy consumption hasn't been a major concern for building owners [Sachs et al., 2015]. However, the elevator energy consumption varies drastically due to the highly cyclical utilization rate of elevators. During peak times of highest utilization the elevators can contribute as much as half of a building's energy consumption. [Sachs et al., 2015]. This would seem to suggest that demand reductions hold much higher potential benefits than efforts in energy efficiency. At first the benefits would seem tenfold, if elevators can contribute 50% to the transient peak power of a building but only around 5% to the energy consumption would not also the reductions have equally proportional effect on the utility bill? However, the answer isn't this simple as we will find out when studying how demand charges are actually calculated. Nevertheless, the relative difference should be noted and its implication studied further. In addition, if for example the building uses also other energy sources, which do not account for electricity usage, this will increase the relative electricity consumption of elevators.

The choice of elevator technology and utilization frequency can have a major impact on the energy consumption. The energy consumed by an elevator system is dissipated as heat within the building. In order to account for the true energy use of elevators, this induced electricity usage to offset the temperature increase should be noted as well. [Sachs, 2005]. The standby power of elevators has decreased substantially from the past when motor-generator systems draw as much as many kW even when not utilized. Furthermore, the energy efficiency of an elevator may differ between different usage scenarios because of the relation between stand by consumption and travel consumption. Little research has been conducted on elevator energy consumption beyond national level studies, especially with a particular focus on potential energy savings [Almeida et al., 2012]. Analysis of advances in elevator energy efficiency has received some exposure in the literature but practical evaluations of cost savings and exact case studies as a result of energy efficiency and demand reductions are mostly missing.

4.4 Transient Power in Multi-car Systems

Figure 1a. illustrates a simulated transient power demand of an elevators system in a high-rise building. It is immediately evident that the infrequent intermittent power peaks are significantly higher compared to the average power demand of the elevator system. This finding is the basis for reducing transient peak power by optimal elevator scheduling. Highly infrequent power peaks are a result of unlikely events in which multiple elevator cars have been simultaneously dispatched and their coincident acceleration in so called heavy direction has resulted in a substantial transient power peak.

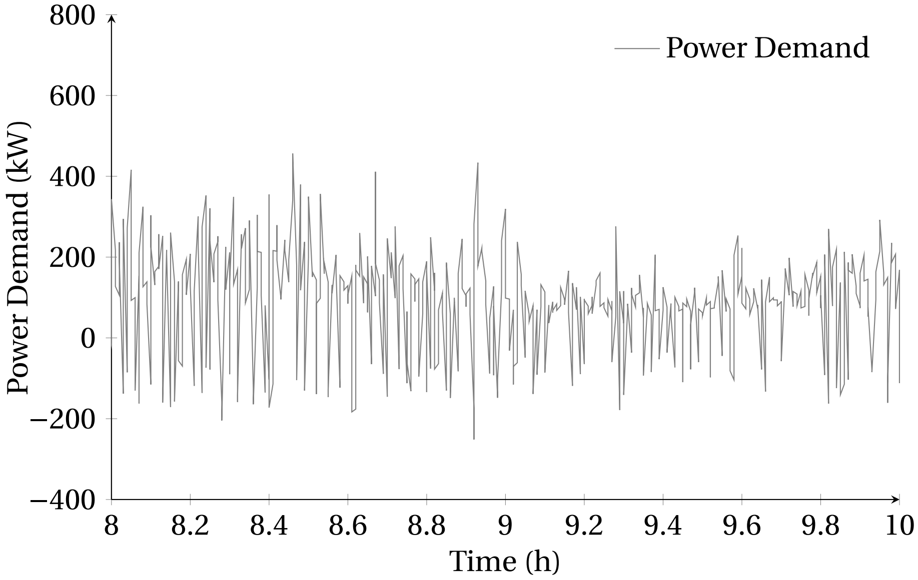


Figure 19: Simulated transient power demand of six-car elevator system in highrise office building between 8am to 10am

Elevator systems are usually stated to account for 3-8% of total electricity consumption in a building [Zhang and Zong, 2014]. However, transient peak power of an elevator system can be even as much as thirty times higher than the daily average demand of the elevator system. The extreme load volatility is especially evident in elevator systems with high nominal speeds and rated passenger load. As a result of high transient power surges, the elevator system can be the single biggest intermittent load in the building, even if their average demand is less than one tenth of all building demand. Figure 20. illustrates the relation between elevator's share of building's peak power and energy consumption for elevator systems with different rated loads and nominal speeds. The linear line in the figure represents a situation where the peak-to-average ratio of an elevator system would be reduced to one. There would be effectively no difference between peak power and average demand. Under such circumstances the elevator system would have to be coupled with an energy storage. The energy storage would act as a buffer between the integrated demand meter and the elevator system. The power would be drawn from the supply network with constant power and released from the energy storage to the use of the elevator system as desired.

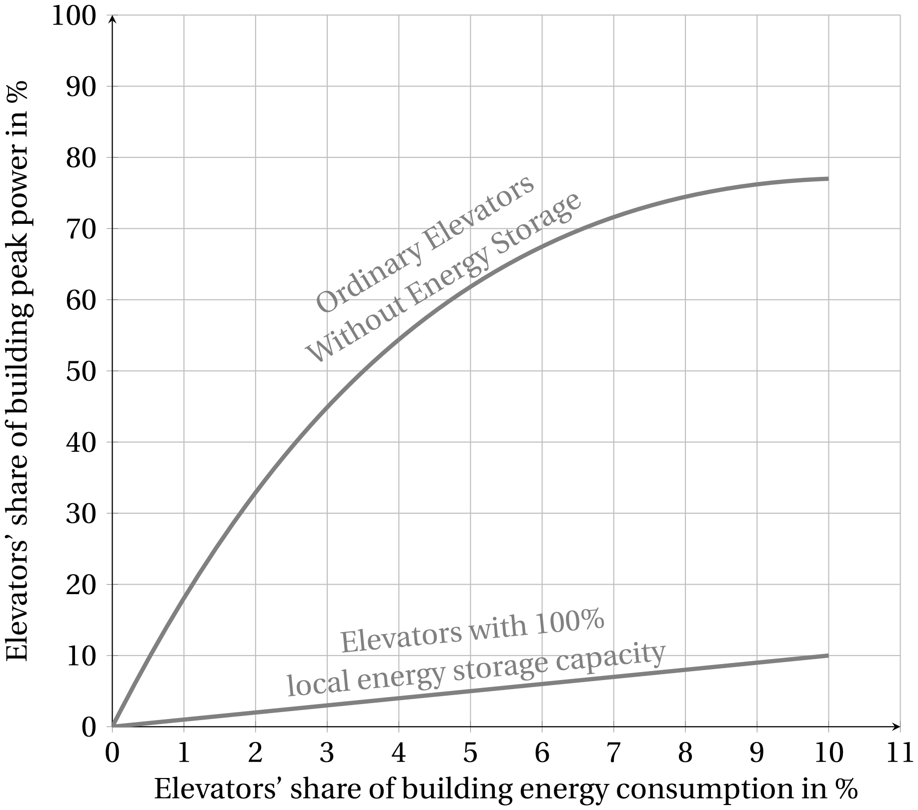


Figure 20: Illustrative example of elevators' share of building peak power and energy consumption

5 Analysis of Demand Optimized Elevator System

In order to determine the basis for Demand Optimized Elevator System, it is necessary to simulate the transient and integrated power demand of a multi-car elevator system. The simulated load profiles will serve as a baseline scenario and the demand control strategies will be compared against it. The power demand will be simulated for two multi-car elevator systems and two different traffic profiles. The analysis of Demand Optimized Elevator System will be carried out in three parts. In the first part a high-rise case building is chosen and building traffic simulations will be done with specific elevator systems. The second part consists of modeling the power demand of an elevator system and then using the earlier simulated traffic log to compute the power demand for a single day. In the third part, the daily load profile of an elevator system will be illustrated for optimal elevator scheduling and optimized to minimize electricity costs by utilizing an energy storage.

The analysis of Demand Optimized Elevator System will be based on a theoretical high-rise building, which has the same physical dimensions as Marina Bay Sands Tower 3 in Singapore (https://www.marinabaysands.com/) but is only a simplification of the elevator configuration in the actual building. The analysis will be limited to two elevator groups, which have both been dedicated to serve particular zones in the building and dimensioned to provide adequate service level for these areas. The 53 floors of the case building are divided into low-rise and high-rise zones, which means that a particular elevator group serves only pre-determined floors within the building. This is a common arrangement in high-rise buildings in which the journey times might become excessively long due to many stops on the way to the destination floor. In this building, the low-rise zone serves floors from 2 to 33 and the high-rise zone covers floors from 30 to 53 with an unserved express zone between floors 2 and 29. The both elevator groups have their main entrance on the first floor. The building traffic will be simulated under office and hotel end-use scenarios. This approach is expected to yield more generalized results than trying to estimate the traffic conditions in the actual multi-use building. The input data for building traffic simulations can be seen in the following table 2.

5.1 Building Traffic Simulations

Building traffic is fundamentally tied to the power demand of an elevator system, because the need for power supply correlates with the time-varying passenger demand in a building. Thus, estimating the building traffic is the natural first step towards understanding also the power demand of elevator systems. In their study of simulating building traffic, [Siikonen, 1997] proposes that building traffic can be divided into three traffic components that are based on statistical forecasts: incoming, outgoing and inter-floor traffic. Incoming traffic by definition is the upward traffic from the entrance floor(s) to the upper floors. Outgoing traffic refers to the downward traffic from any floor to the entrance floor(s). Inter-floor traffic is a combination of upward and downward traffic between any floors except the entrance floor(s) [Siikonen, 1997]. The traffic profile for a

Description	Specification	Value
Building Dimensions	Number of floors	53
	Floor height	3.70 m
	Total height	196.1 m
	Persons per floor (100% occupancy)	35
	Total Building population (100% occupancy)	2175
High-rise Elevators	Number of elevator cars	6
	Served floors	30-53
	Contracted capacity	1495 kg
	Nominal speed	7 m/s
	Acceleration	1 m/s^2
Low-rise Elevators	Number of elevator cars	6
	Served floors	2-33
	Contracted capacity	1495 kg
	Nominal speed	5 m/s
	Acceleration	1 m/s^2

Table 1: Input Data for Building Traffic Simulations

building is a combination of these three components with varying passenger demand rates during the day. Passenger demand rate is commonly measured as the percentage of the building population arriving in five minute interval [Barney and Santos, 1985]. Figure 21. illustrates a traffic profile forecast by KONE's Traffic Master System 9000 for 15-minute time intervals during the active hours in an office building.

Typically the most demanding traffic conditions occur during up-peak, lunch-peak and down-peak traffic. In Figure 21. we can see that the highest passenger demand rate happens during the lunch-peak when there is a lot of mixed traffic in the building. A possible explanation for such an event is that some people in the building move to other floors or exit the building to have lunch while other people at the same time are returning from their lunch break.

Up-peak traffic occurs when most of the passenger demand in the building is towards upward direction. In typical up-peak traffic conditions, passengers enter the main terminal (lobby) to be transported to their destination floors on the upper floors [Barney and Santos, 1985]. [Barney and Santos, 1985] define the up-peak arrival rate as "number of passengers who arrive at the main terminal of a building for transportation to upper floors over the worst five minute period expressed as a percentage of the total building population". Especially in office buildings the up-peak traffic often occurs during the morning inrush when employees are required to arrive at work [Barney and Santos, 1985]. Whether the employees follow a fixed working schedule or flexible working hours has an impact on the highest arrival rate during up-peak and down-peak conditions.

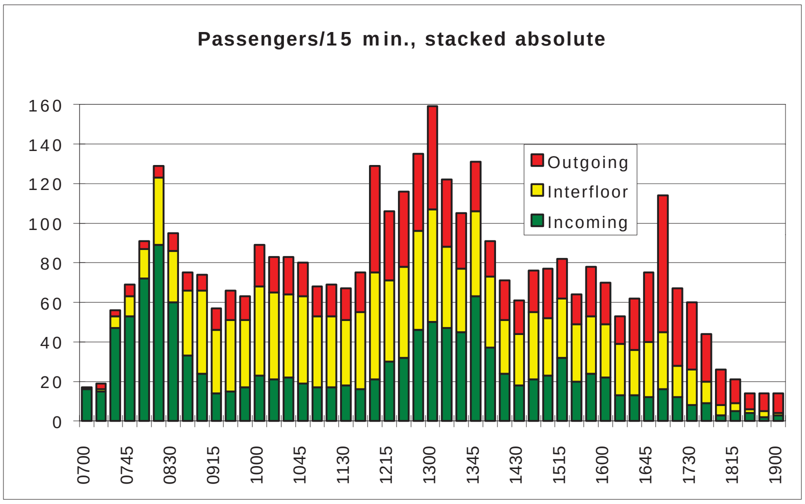
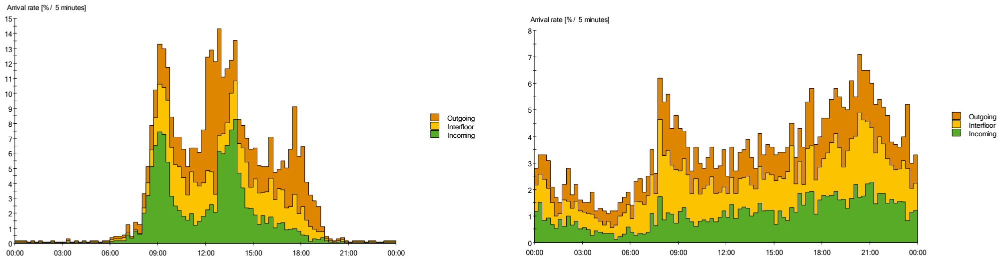


Figure 21: Traffic profile forecast for an office building in Australia. [Siikonen, 1997]

During down-peak most of the passenger demand is towards downward direction as people are travelling to the main terminal to exit the building [Barney and Santos, 1985]. [Barney and Santos, 1985] argue that down-peak traffic at the end of the workday can be considered as the opposite of up-peak traffic, but with up to 50% higher passenger demand than in the morning inrush. This can be however misleading as the relative intensity between the up-peak and down-peak traffic is heavily dependent on the particular building. Also, as mentioned earlier the working hours as well as the number of tenants can have a major impact on the distribution of passenger demand. Thus, no general rule can be drawn between the relative intensities of up-peak and down-peak traffic.

The distribution of passenger demand and the relative intensities of incoming, outgoing and inter-floor traffic differ between different building types. Some of the most commonly used building types in traffic simulations include: single-tenant office, multi-tenant office, hotel and residential building. All of these have their uniquely characteristic traffic profiles that impose different requirements for the elevator configuration. In order to provide sufficiently high transportation capacity, the elevator system has to be dimensioned so that waiting and journey times are not excessively long. For this purpose, the up-peak percentage arrival rate is commonly used to determine the number of elevators, their passenger capacity and travelling speeds [Siikonen, 2000]. However, the passenger demand rate has another far less studied implication. It has an effect on the power demand of an elevator system. Highly volatile passenger demand will also indicate high peaks in the power demand of an elevator system. Thus, buildings with similar building populations can have widely different load profiles for elevator systems based on different traffic conditions in the buildings. In this thesis, the building traffic simulations are used for computing the correlation between time-varying passenger demand and power demand of an elevator system. The building traffic simulations were run with office and hotel traffic profiles, which can be seen illustrated in figure 22. These are both generic traffic profiles for the building end-use scenarios that are based on measurements done at real locations. The purpose of comparing two different traffic profiles is to see how the varying passenger demand influences the power demand of an elevator group.



(a) Multi-tenant office

(b) Hotel

Figure 22: Traffic profiles for different building end-use scenarios

In the building traffic simulations the effective floor population was based on the allocated service area for the particular elevator group and does not necessarily reflect the actual population on the floor if multiple elevators serve the same area. Thus, only those people whom are allocated for that elevator group are considered when dimensioning the elevator configuration. In addition, absence rate was used to take into account that not all of the building population is usually present at the same time. The total building population and floor populations were used to calculate the arrival rate probabilities for building traffic simulations. At first, the building dimensions and end-use scenarios were considered in order to determine reasonable floor populations for the building. The second step was to dimension the elevator configuration so that it would correspond to a sufficient elevator performance under both end-use scenarios and with estimated floor populations. The floor populations were defined so that the elevator configuration would perform on a satisfactory or better service level according to the common traffic planning guidelines in the elevator industry.

It should be noted that the BTS comes with a collection of traffic profiles, which have a discrepancy between incoming and outgoing traffic. On the assumption that every passenger travelling upwards will later also take an elevator to travel downwards should result in a balance between incoming and outgoing traffic. The amount of people entering minus the people exiting the building should roughly equal to zero over one day. The traffic measurements most likely had some slight inherent error, which accumulates when simulations are run for extensive time periods. Consequently, the traffic profiles used in this thesis have been balanced so that the incoming and outgoing traffic cancel each other out when summed over the entire day. This corrective measure will not have a dramatic effect on the power demand of an elevator system but it will slightly improve the accuracy of the simulation results.

5.2 Power Demand Model for Elevator System

In this thesis, the power demand of an elevator system is derived from the simulated traffic data. At first, the daily passenger demand data is obtained from the simulated building traffic log (incl. starttime, stoptime,startfloor, stopfloor and passenger load), and then the power demand over each logged elevator trip is simulated by utilizing a dedicated power demand model. In their study of energy-efficient elevators, [Hakala et al., 2001] propose a similar method of using elevator load and travel distributions to calculate the energy consumption of an elevator system. The proposed simulation method includes models for both mechanical and electrical parameters of the elevator system. In this study, the utilized power demand model generates a motion profile and power demand for each simulated elevator trip. The model consists of shaft, motor, drive and electrification models that aim to simulate the operating conditions of real elevator systems. The elevator load and travel distribution are obtained from the building traffic log for one day. These time-stamped events are then used as parameters in the power demand model to simulate the daily transient power profile.

POWER DEMAND SIMULATION MODEL

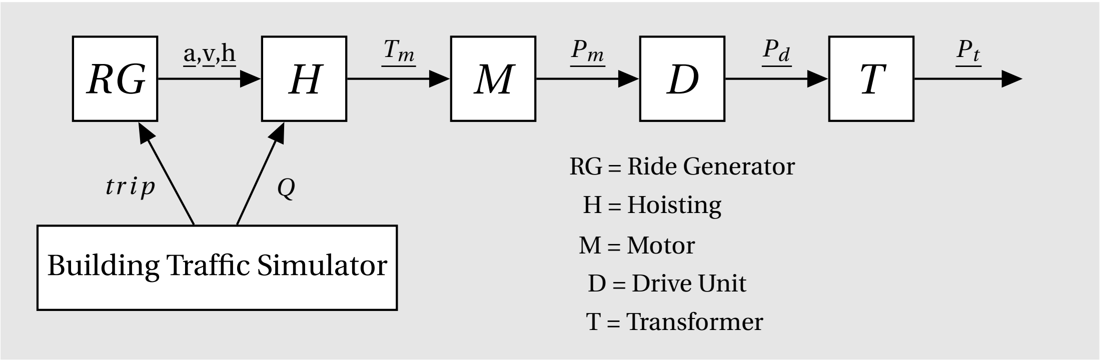


Figure 23: Diagram for simulating power demand in elevator systems

Power demand of a regenerative vertical transportation system can have both positive and negative values depending on the travel direction and whether applied torque is positive or negative. When the power demand is negative the regenerated power will be dissipated in resistors or fed back to the building power distribution system. The elevator drive can operate in four modes that are illustrated in a figure 24. In the ride generator model, the ideal elevator kinematics are considered under three scenarios similarly as proposed by [D., 1998] in his study of vertical transportation in buildings. These three conditions are an elevator run, in which the elevator reaches nominal speed; elevator reaches nominal acceleration but not nominal speed; and neither nominal acceleration nor nominal speed is reached [D., 1998].

The simulation results for transient peak power in high-rise elevator systems can be seen in Figures 25b. and 25a. The initial dataset has 86400 samples for every second during the day. The transient power peaks illustrated in the figures represent the highest value that power demand reached within the one second time window. In this study,

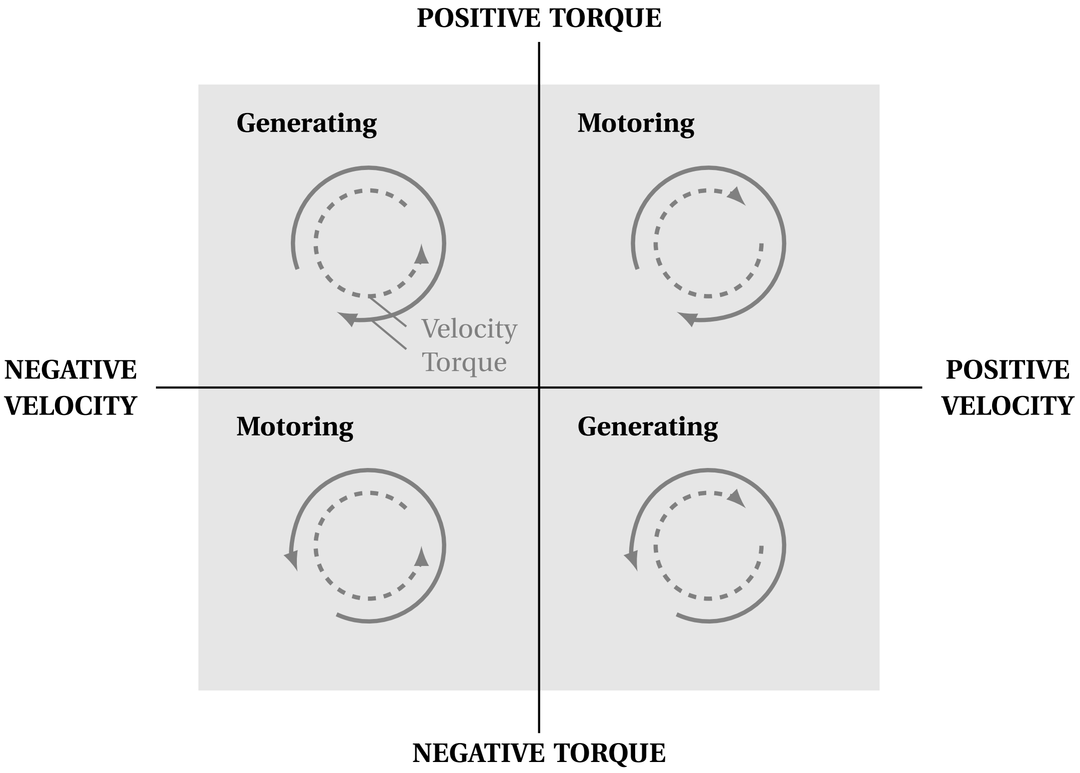
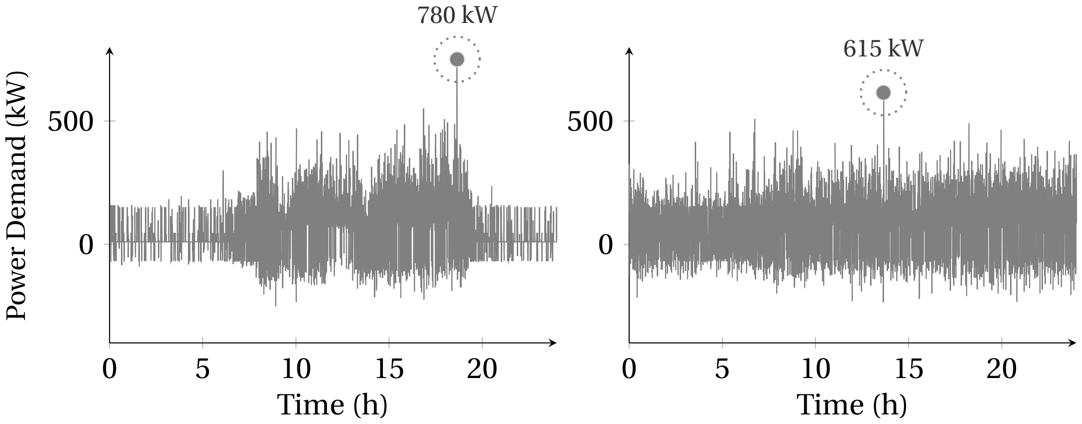


Figure 24: The four modes of elevator drive. Based on [D., 1998]

.

one-second intervals were considered to be precise enough to illustrate even the highest intermittent power peaks. As it can be seen from the figures, the power demand under both end-use scenarios is extremely volatile. The highest transient power peaks reach roughly 600-800 kW while the peak-to-average demand ratio is around 20. As described earlier, the transient peak power occurs when the peak power demand of multiple elevators coincides with each other. Thus, we can expect that it is more likely for the transient peak power to occur during the highest passenger demand when many elevators are in constant transit. However, there is no certainty of this due to the randomness in the scheduling process.

Reducing transient peak power by optimal elevator scheduling is more likely to achieve significant reductions in peak power if the intermittent peaks are very rare. Figure 26. illustrates the cumulative distribution of power demand for the simulated elevator load profile under hotel end-use scenario. The cumulative distribution of power demand will show how much of the time power demand will fall below the level given on the x-axis. In this study, a reasonable reduction from demand optimization by elevator scheduling is expected to be 3% of the highest and lowest values in the load profile. This would reduce the transient power peaks from 780kW down to 210kW for the simulated load profile of high-rise elevator system in a office building and from 615kW down to 225kW in case of a hotel building. In the absolute worst case scenario all of the six elevators in the group would reach maximum power demand simultaneously. However, the building



(a) Office

(b) Hotel

Figure 25: Transient peak power of a six-car elevator group serving high-rise zone under two building end-use scenarios.

power distribution systems are not dimensioned for the absolute worst case scenario but instead apply so called diversity or simultaneity factor which takes into account the unlikeliness of coincident peak power between multiple elevators.

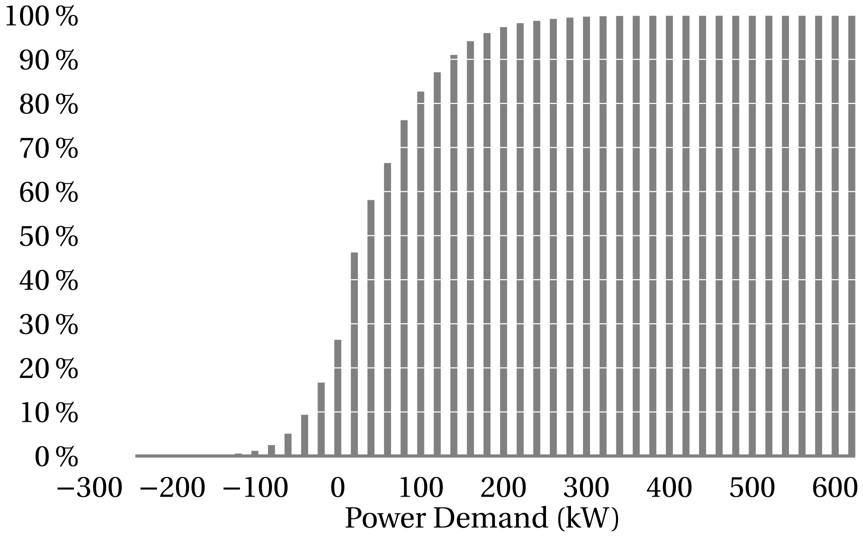
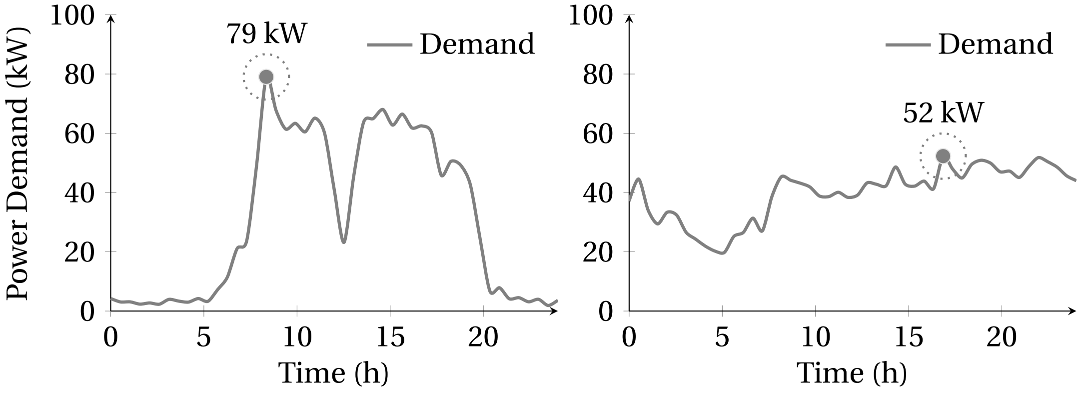
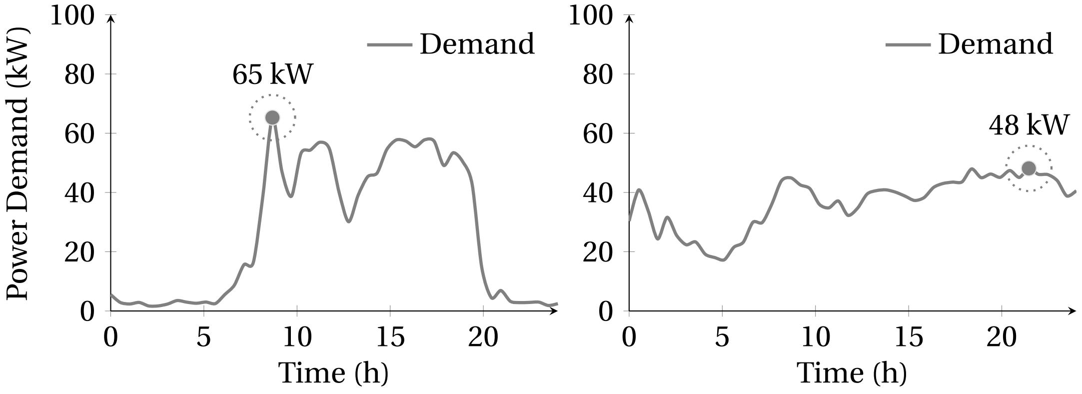


Figure 26: Cumulative distribution of power demand for a highrise elevator group in a hotel

Since utilities are less concerned with transient power demand and more interested in average demand over longer time intervals, we will compute secondary load profile, which represents the integrated demand for the elevator system. In this case, 30-min integrated demand is considered, which can be obtained by taking a moving average with a time window of 30-min over the entire dataset. In this thesis, the integrated demand results were additionally calculated with elevator trip -based computation method, which helped to verify the results. Figure 27. illustrates the integrated demand profiles for high-rise and low-rise elevator groups under both end-use scenarios. The integrated demand profiles reveal the correlation between passenger demand and power demand of the elevator system much more clearly than the transient power profile. In an office building the highest measured demand occurs around 8.30am during the morning inrush whereas in a hotel building the highest demand occurs in the evening. As expected the load profiles between elevator groups serving low-rise and high-rise zones are very similar with the exception that high-rise group can reach higher peak demand. Also, although the elevator systems in both building end-use scenarios are the same, still the integrated peak demand of a high-rise elevator group is roughly 50% more in an office building than in a hotel building. This is because in an office building the traffic is heavily concentrated to certain time periods during the working hours. As a result, it can be expected that demand optimization would yield greater benefits in an office building due to its relatively high morning up-peak.



(a) High-rise Office (b) High-rise Hotel



(c) Low-rise Office (d) Low-rise Hotel

Figure 27: Integrated demand profiles for high-rise and low-rise elevator groups under both building end-use scenarios

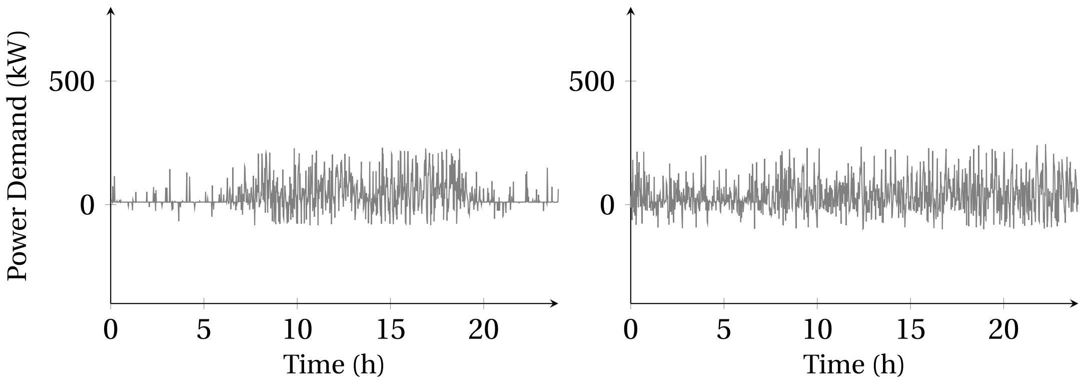
5.3 Demand Control Strategies

In this study, demand optimization is based on two demand control strategies that are reducing transient peak power by optimal elevator scheduling and adjusting integrated demand by utilizing an energy storage. Anticipated impact of the former demand control strategy has been only demonstrated in this thesis and actual control algorithm has not been developed for the purpose of this study. In order to determine the economic performance of such control strategy, reasonable assumptions have been taken to evaluate the impact of demand optimizing elevator scheduling algorithm. In practice, the optimal elevator scheduling algorithm should limit transient peak power below a predetermined threshold that cannot be surpassed even if the optimization procedure cannot find a satisfactory solution. Under such circumstances, the group control system has also a supervisory role in determining when elevators can be dispatched without violating the predefined power-limit. The reduction in transient peak power by optimal elevator scheduling is a permanent configuration and thus it cannot be really called as a demand response activity, which would imply responsiveness to outside signals.

However, adjusting demand by utilizing an energy storage can be referred as demand response activity because it implies adaptation to time-varying electricity prices or other remote signals. For this control strategy, a simulation environment was developed to test the optimal operating of an energy storage system. An optimization algorithm was formulated that would aim to reduce energy and demand costs by optimizing the charging and discharging behavior of the energy storage. The simulation environment was developed to have a time resolution of 30-min, which corresponded with the utilities rate structures in both market areas. The rate structures and load profiles were inputs for the applied multi-objective genetic algorithm that utilized evolutionary computation to find optimal load profiles for the elevator system. The algorithm also required prespecifying the maximum storage capacity, which was then held as a constraint in the optimization. It should be also noted that the optimization algorithm was configured to have a perfect forecast of future power demand, which is expected to yield slightly too optimistic results compared to real world circumstances.

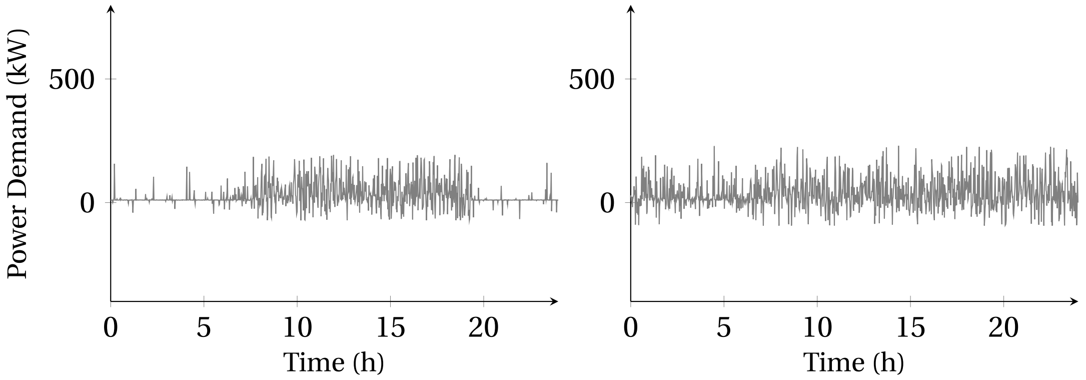
5.4 Results of Demand Control Simulations

The results of demand control strategies were studied for reducing transient peak power in elevator systems by optimal elevator scheduling and adjusting integrated demand by utilizing an energy storage. The reduction in transient peak power is based on conservative assumption about realistic performance of an optimal elevator scheduling algorithm, whereas the decrease in integrated demand is based on actual simulations with time-varying prices and different storage sizes. In figure 28. the effect of reducing transient peak power by optimal elevator scheduling is illustrated for high-rise and low-rise elevator groups under both building end-use scenarios. However, the plotted power demand does not represent actual simulation result but only aims to illustrate the impact of functioning optimization algorithm. The optimized demand profiles were created in a way that approximately 3% of the highest and lowest transient power peaks were “shaved-off” and redistributed among the load profile to produce the impact of power-limiting. As it can be seen in the figures, the 3% -peak shaving produces substantial reduction in the peak power. Without optimization the transient peak power was 780kW (high-rise office), 615kW (high-rise hotel), 478kW (low-rise office) and 509kW (low-rise hotel). After optimization the transient peak power was reduced below 225kW in all four scenarios. This result has a significant impact on the capacity requirements that transient peak power imposes on the building power distribution system. The benefits of this are explored more deeply in the next chapters.



(a) High-rise Office

(b) High-rise Hotel



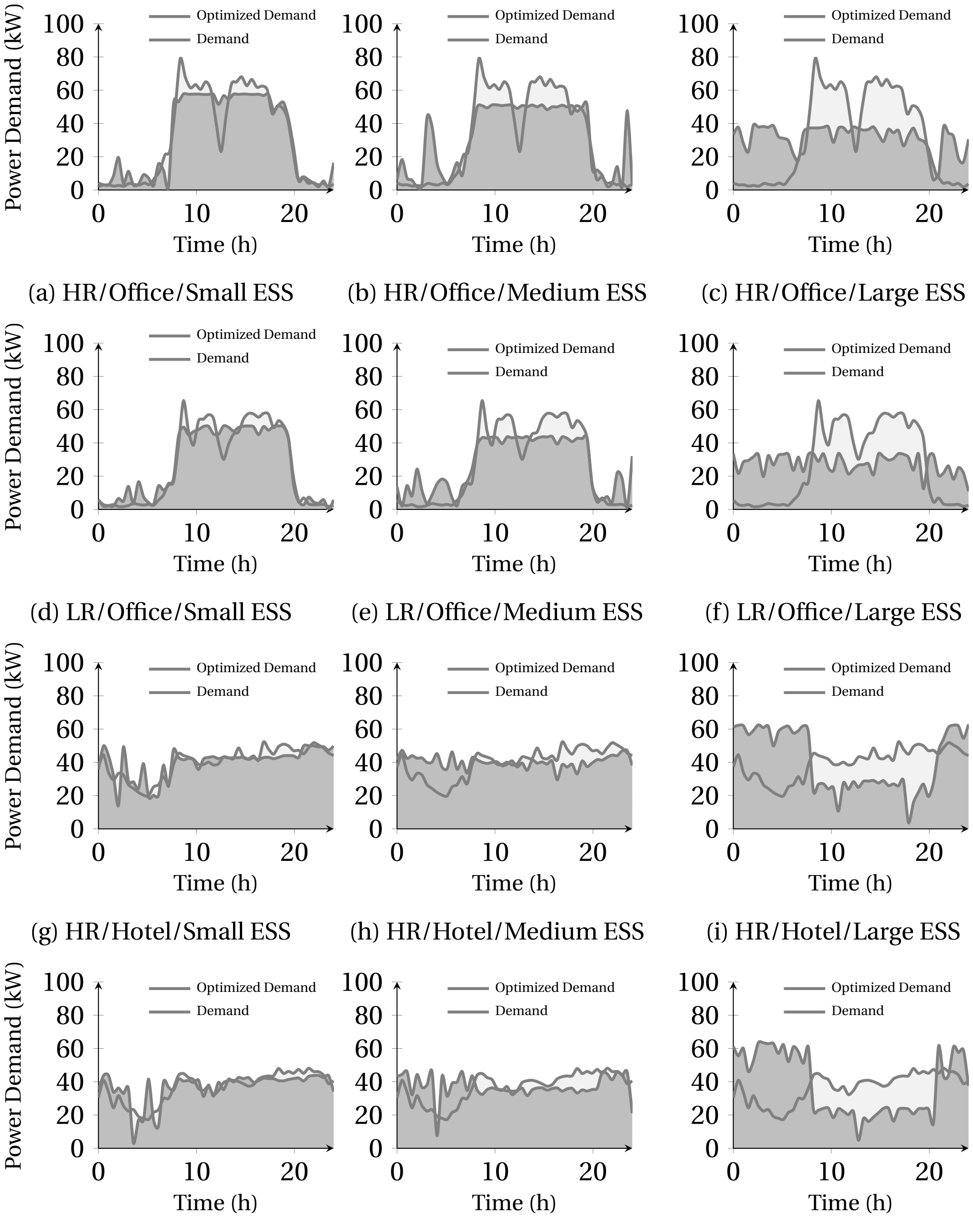
(c) Low-rise Office

(d) Low-rise Hotel

Figure 28: Illustration of optimized transient peak power of a six-car elevator groups serving high-rise and low-rise zone under two building end-use scenarios. Note: not based on actual simulations.

The second approach to demand optimization in elevator systems considers utilizing an energy storage. The purpose of an energy storage is partly to shave-off any extreme volatility on the transient power level but also to decrease electricity costs by affecting the integrated demand profile of the elevator system. The results of optimizing integrated demand in relation to time-varying electricity prices have to be calculated separately for different rate structures and energy storage sizes. Ultimately twenty four different simulations were carried out to compute the optimized load profiles under different market areas, building end-use scenarios, elevator groups and storage capacities. The results illustrated in figures 30. and 29. for London and NYC demonstrate well how the varying rate structures in different market areas can have a major impact on the optimal load profile. In general, electricity is cheapest during the night when demand is lowest and most expensive in the early evening when demand is highest in the electric grid. Consequently, it is evident from the figures that under both market areas the large-sized energy storage aims to shift consumption to night time. However, the greatest difference between rate structures in London and NYC is in the demand charges. In NYC, peak demand is charged substantially more than in London, which results in a widely different optimized load profiles for the two market areas. In London, the triad-system imposes heavy charges on peak demand only based on customer's peak demand during the three hours that the system wide demand is the highest in a year. It can be seen from Figure 30. that in London the demand optimization aims to reduce consumption during the time period of 4-6pm when wholesale prices are the highest and also there's a risk of triad-pricing becoming in effect. In NYC, the demand optimization will reduce peak demand consistently in order to avoid high demand charges.

Figure 29. illustrates how under the office end-use scenario already a small-sized energy storage can yield noteworthy decrease in peak demand of the elevator system by discharging the energy storage during morning up-peak. The optimization algorithm aims to find solutions, which utilize the energy storage system so that power demand is distributed more evenly. In NYC, the case building is served under a rate structure, which has time-of-use based demand charges that are mainly effective between 6am and 8pm. These demand charges can be seen penalizing integrated demand peaks and thus encouraging demand reduction during on-peak hours. Under hotel end-use scenarios, due to relatively even baseline load profiles, there is not as much potential for decreasing peak demand as in office buildings. Under such circumstances in contrast to demand shedding, the energy storage system can been to execute demand shifting by moving consumption to time periods with lower electricity prices. The key notion to pick up from the simulation results is that the small-sized energy storage yields the highest reduction in peak demand relative to storage capacity.



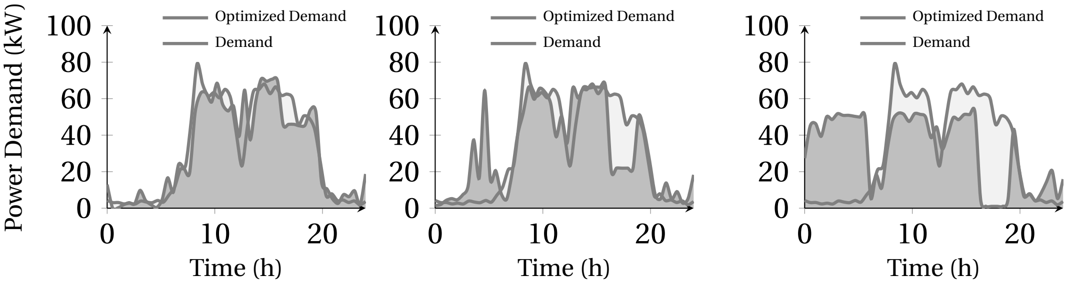
(a) HR/Office/Small ESS (b) HR/Office/Medium ESS (c) HR/Office/Large ESS

(d) LR/Office/Small ESS (e) LR/Office/Medium ESS (f) LR/Office/Large ESS

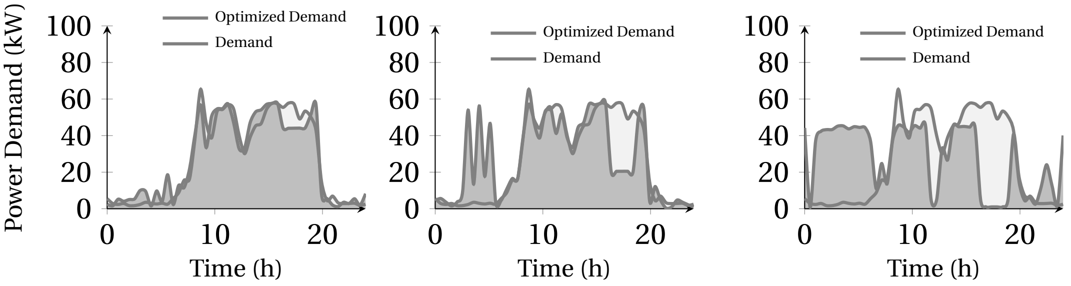
(g) HR/Hotel/Small ESS (h) HR/Hotel/Medium ESS (i) HR/Hotel/Large ESS

(j) LR/Hotel/Small ESS (k) LR/Hotel/Medium ESS (l) LR/Hotel/Large ESS

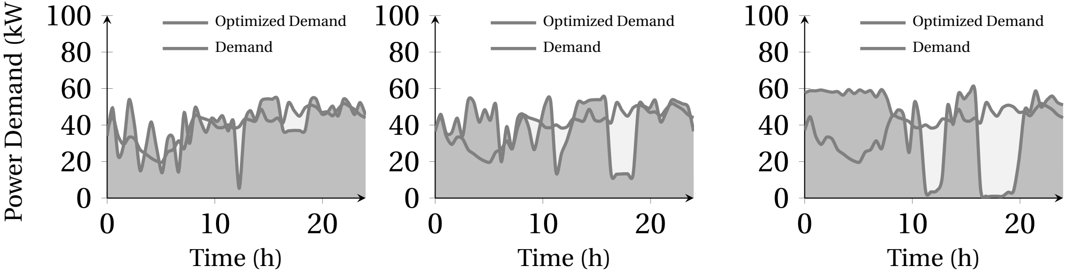
Figure 29: Optimized demand profiles in NY for high-rise and low-rise elevator groups under both building end-use scenarios and with small, medium and large-sized energy storage



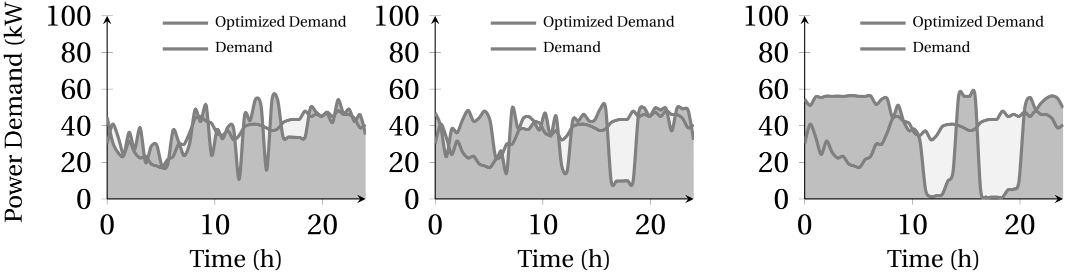
(a) HR/Office/Small ESS (b) HR/Office/Medium ESS (c) HR/Office/Large ESS



(d) LR/Office/Small ESS (e) LR/Office/Medium ESS (f) LR/Office/Large ESS



(g) HR/Hotel/Small ESS (h) HR/Hotel/Medium ESS (i) HR/Hotel/Large ESS

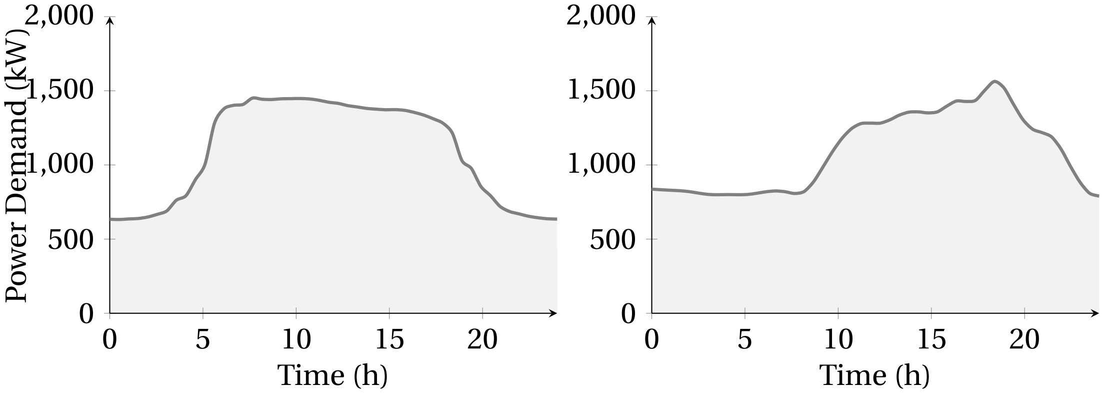


(j) LR/Hotel/Small ESS (k) LR/Hotel/Medium ESS (l) LR/Hotel/Large ESS

Figure 30: Optimized demand profiles in UK for high-rise and low-rise elevator groups under both building end-use scenarios and with small, medium and large-sized energy storage

6 Value of Demand Optimized Elevator System

In this chapter the previous simulation results for demand optimization in elevator systems are evaluated in the context of capital and operating cost savings. The benefits of demand optimization will be compared against a baseline scenario, which is based on initial building load profiles in Figure 31. and capacity requirements for the building power system assets. At first, the cost of relevant power system assets is estimated for building construction and also electricity costs are calculated for the case building. Next, the capital cost savings in power system assets and operating cost savings in electricity costs are evaluated separately. The cost-benefit assessment in this chapter acts as a basis for the later investment analysis.



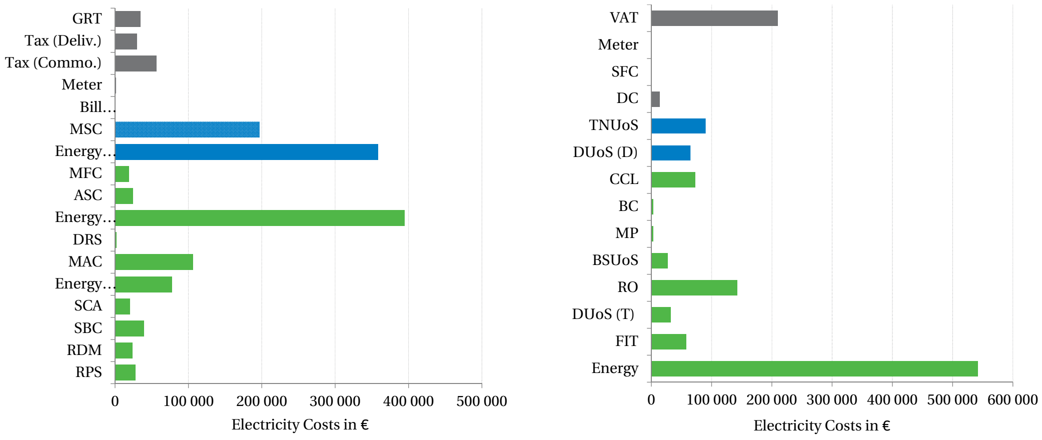
(a) Office (b) Hotel

Figure 31: The initial building load profiles (without elevators) for electricity cost calculations. Based on typical load profiles for building end-use scenarios.

6.1 Electricity Costs

The building electricity costs will be first calculated for a baseline situation, which includes elevator systems as they are now without any kind of demand control. Load profiles for high-rise and low-rise elevator groups were previously simulated for each building type. The baseline load profile for other building loads is formulated from generic daily average load profiles for office and hotel buildings. Electricity is expected to be purchased under real-time pricing tariff and no tax benefits are taken into consideration. Electricity costs are decomposed into individual components as they might occur on consumer's electricity bill. It should be noted that these components are not necessarily comparable between different electric utility companies and policy areas. In order to make the electricity bill components comparable, the cost components are also categorized whether they are energy based (calculated per kWh), demand based (calculated per kW) or fixed costs. The division between energy and demand based costs is important for estimating the benefits of demand optimization on electricity bill.

Decomposing the electricity bill shows that under both market areas the energy based



(a) NYC

(b) UK

Figure 32: Electricity cost breakdown for an office building

pricing components (green) are much more common than demand based ones (blue). However, the weight of demand based components in NYC is significantly higher than in London. The high demand charges in NYC create a strong incentive for demand optimization. In London, the opportunities for demand savings are much smaller and most of the charges are energy based. However, a triad – pricing methodology has been implemented in UK, which charges customers based on their average demand during the three highest half-hour periods of demand in the UK electric transmission system between November and February. Large commercial customers can optimize their electricity costs by reducing demand during these triad periods.

The total building electricity costs in NYC reach approximately 1,40m€ for office and 1,44m€ for hotel building, whereas in London the electricity costs are slightly less with 1,25m€ for office and 1,29m€ for hotel building. The impact of demand charges is evident in NYC where demand based costs account for 39% of the total electricity costs, whereas in London the share of demand charges is only 12%. Based on these results, demand optimization can be expected to yield more cost savings in New York than in London.

The share of annual building electricity costs for the two elevator groups in New York would total in 94k€ for office and 90k€ for hotel building. In London the costs would be 71k€ for office and 82k€ for hotel. Also proportionally elevators are slightly more expensive to run in New York than in London due to higher demand charges. In New York, elevators account for 6,5% of total building electricity costs as in London the share is 6%. This indicated that the elevators' share of total building electricity costs is less than the earliest hypotheses would have suggested. This is mainly due to the integrated demand metering, which bills building demand in intervals of 30-min. Thus the transient peaks in building load caused by elevators do not contribute to the electricity bill nearly as much as they affect the building peak power. In case that utilities would shorter their

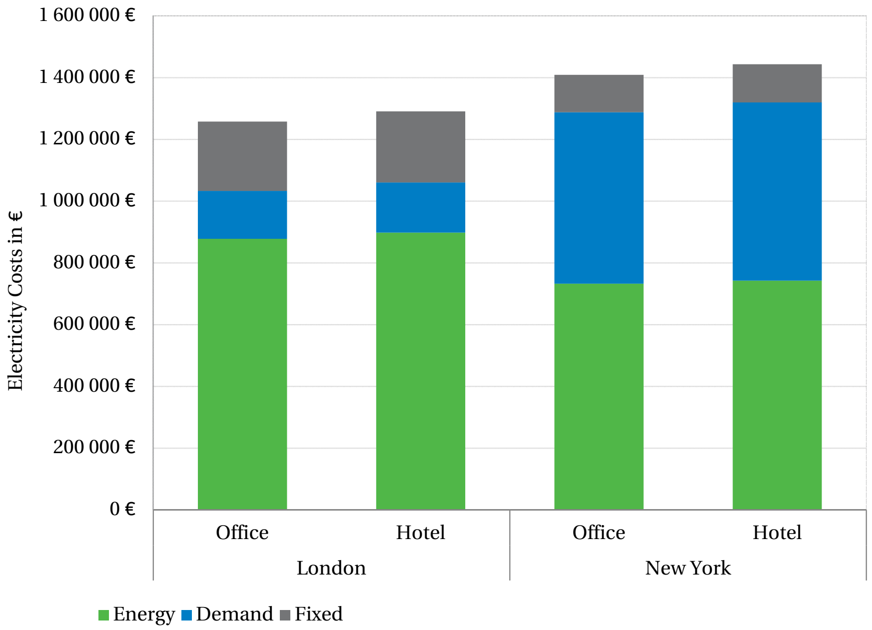


Figure 33: Annual electricity costs for office and hotel buildings under both market areas (inc. elevator system)

integrated demand metering period, it would also mean that the elevator's share of total building electricity costs would increase.

6.2 Capital Costs in Building Power System

In this chapter, the demand optimized elevator system is evaluated for its impact on the cost of building power system assets. Analysis has been limited to the building systems and excludes benefits that might arise beyond the point at which building power distribution system connects to the supply network. The costs involved in establishing a new connection to the building are only included if the extension assets can be considered to be part of the building power distribution system. These assets include building transformers located at the premises but exclude high-voltage cables that connect them to the supply network. It is assumed that the impact of demand optimized elevator system on the high-voltage network is so insignificant that it can be disregarded in this study.

Network operator charges costs that incur due to establishing a new connection from an existing electric grid to a building. These charges are calculated by local DSO and divided into costs that are fully paid by customer, apportioned between customer and DSO, and fully paid by DSO. The extension assets to establish connection to the distri-

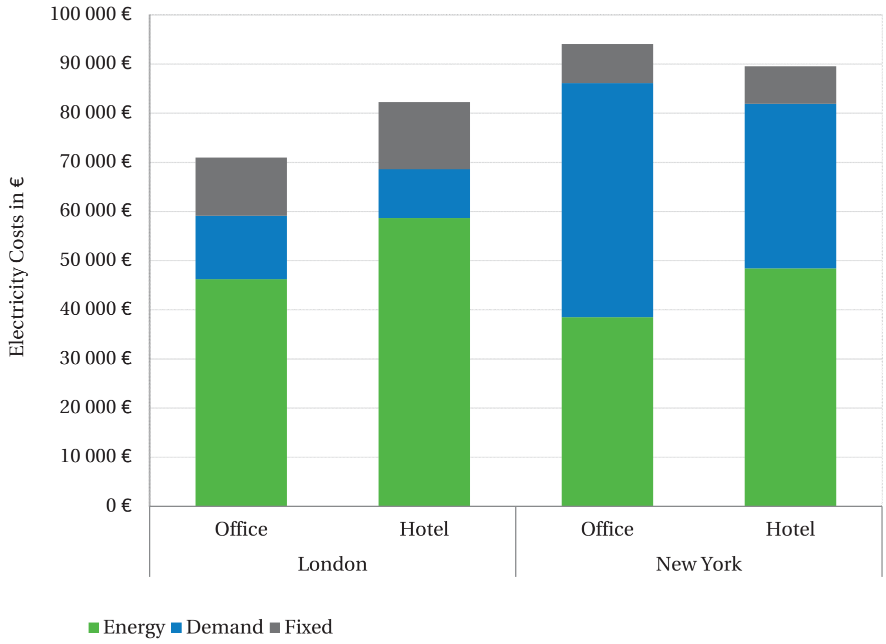


Figure 34: Annual electricity costs for elevator system of 12 cars in office and hotel buildings under both market areas

bution network are fully charged from customer while required reinforcements that add capacity to the network are shared among customer and DSO. [UK Power Networks, 2012]. [UK Power Networks, 2012] provides a breakdown of connection costs, which at minimum include cost for labor, cables, substations, required reinforcements and securing land rights.

In addition to capital cost savings in building transformers, demand optimized elevator system will reduce the required size for the feeder cables that provide main supply for the elevators. In the electrical dimensioning of an elevator system, the peak power demand will influence the required capacity for feeder cables, transformers and circuit breakers. Additionally, space requirements for the power system assets will also decrease when capacity requirements are lowered. Large-sized transformers can require many square meters of expensive surface area in high-rise buildings. Furthermore, the often undersized building back-up generators can during loss of primary power supply, keep providing sufficient power for an entire elevator group instead of forcing the shut down of most of the elevators as currently is required. The increased utilization level under back-up generation would also benefit the operating of elevators in building construction phase and evacuation during which power supply capacity is often a scarcity.

In the case building, the power distribution system has 22kV transformer at floor 55 serving the high-rise elevator group and another 22kV transformer at floor 22 supplying the low-rise elevator group. The cable length from transformers to elevator machine room is fifty meters. Under the initial setting, both transformers are estimated to be rated for 1500kVA.

Power Supply Cables The electric supply for the six-car elevator groups is divided half so that three elevator cars are grouped together and supplied with four $240mm^2 XLPE/PVC$ cables. Thus, each elevator group requires four hundred meters of cable in total. Our hypothesis suggests that cable sizes can be significantly reduced with optimal elevator scheduling and even further reduced by utilizing an energy storage. Under the initial setting, high-rise and low-rise groups are dimensioned to be supplied with maximum amperage of 2x718A, which roughly corresponds with 1MW of peak power. Under optimal elevator scheduling, the transient power demand is expected to be limited to a considerably lower level and as a result the required maximum amperage of feeder cables will also decrease. Considering a modest 3% reduction on both positive and negative side of cumulative power demand, transient peak power could be limited below 225kW in all cases. As a result, feeder cables supplying the elevator group could be dimensioned to meet only maximum amperage of 330A. Two $240mm^2 XLPE/PVC$ cables per elevator group would be easily sufficient to meet this requirement. When elevator system is coupled with energy storage, the feeder cables can be dimensioned to an even lower size. The simulations suggest that energy storage could bring the peak power of the elevator group below 80kW in all cases. This would correspond with maximum amperage of 118A and required supply cable sizing of single $95mm^2 XLPE/PVC$ cable. The $240mm^2 XLPE/PVC$ cable costs approximately 39€ per meter and $95mm^2 XLPE/PVC$ cable approximately 16€ per meter [Nexans Olex, 2013].

$$\textbf{Feeder Cables (Initial)} = 2\cdot 2\cdot 4\cdot 50m = 1\ 800\text{m}$$

$$\textbf{Feeder Cables (Elevator Scheduling)} = 2\cdot 2\cdot 50m = 200\text{m}$$

$$\textbf{Feeder Cables (Energy Storage)} = 2\cdot 50m = 100\text{m}$$

Transformers Under the initial setting, each elevator group is supplied with a 22kV transformer that is rated to handle elevator and other building loads within its supplied portion of the power distribution system. Similarly to cables, transformers are also dimensioned to handle transient power peaks and thus lowering transient peak power of an elevator system can yield capacity reductions in building transformers. As earlier stated, under the initial setting each elevator group is rated for a maximum 1MW of peak power. Optimal elevator scheduling would bring peak power below 225kW and utilizing energy storage below 80kW. It should be noted that large transformer sizes are available in rather great incremental steps so small decreases in peak power will not necessarily achieve transformer capacity reductions. However, the calculations will be done on cost per kVA basis. 22kV transformer rated for 1500kVA costs roughly 70 000€, 1000kVA transformer costs 54 000€ and 500kVA transformer costs 40 000€ [Endeavour Energy, 2015]. Since we have no knowledge of the actual power rating for building transformers we will assume a current rating of 1500kVA and that costs will decrease on average 30€ per kVA of reduced capacity.

$$\textbf{Building Transformers (Initial)} = 2 \cdot 1500\text{kVA} = 3000\text{kVA}$$
$$\textbf{Building Transformers (Elevator Scheduling)} = 2 \cdot 725\text{kVA} = 1450\text{kVA}$$
$$\textbf{Building Transformers (Energy Storage)} = 2 \cdot 580\text{kVA} = 1160\text{kVA}$$

Back-up Generators In case of power supply failure, it is common for large commercial buildings to have back-up generators installed to provide SPS for power outages. These generators can be very high in cost, [Caphert, 2014] estimates the capital costs for internal combustion engine based back-up generator system to range from 270€ to 730€ per kVA. As a result, back-up generators are often undersized to handle all the normal building loads and thus in order to avoid overloading, it is common to take most of the elevators out of service during blackouts. Of course, this is a subpar procedure, which will negatively impact occupant satisfaction due to lowered service level. Under such circumstances, demand optimization would allow all of the elevators to remain in service. Peak power reduction would lower back-up generators' rated capacity by 2x775kVA in case of optimal elevator scheduling and 2x920kVA with energy storage. Calculating generator costs on cost per kVA basis can be misleading since back-up generators are not necessarily dimensioned to meet all building loads. Another approach to assess costs would be to estimate the lost man-hours and decreased customer satisfaction due to lowered elevator traffic capacity. However for our purposes, we will assume that the case building is currently equipped with two 2000kVA rated back-up generators that have enough capacity to supply all the normal building loads and also keep all the elevators operational. The cost for a single diesel generator with rated capacity of 2000kVA is roughly 345 000€, with rated capacity of 1280kVA it is around 230 000€ and with rated capacity of 1000kVA it is 164 000€. Thus, we estimate per kW price for a diesel generator to be around 220€.

$$\textbf{Back-up Generators (Initial)} = 2 \cdot 2000\text{kVA} = 4000\text{kVA}$$
$$\textbf{Back-up Generators (Elevator Scheduling)} = 2 \cdot 1225\text{kVA} = 2450\text{kVA}$$
$$\textbf{Back-up Generators (Energy Storage)} = 2 \cdot 1080\text{kVA} = 2160\text{kVA}$$

6.3 Electricity Cost Savings

Electricity cost savings are calculated for all twelve scenarios, which include two market areas (NYC and London), two building types (Office and Hotel) and three energy storage sizes (30kWh, 100kWh and 300kWh). The baseline scenarios for office and hotel building loads were formulated on the basis of average load profiles for the building type and simulated elevator system loads without demand optimization. Demand optimized load

Description	Demand Control Strategy	Cost
Feeder Cables	Initial	31 200 €
	Elevator Scheduling	7 800 €
	Energy Storage	1 600 €
Transformers	Initial	140 000 €
	Elevator Scheduling	93 500 €
	Energy Storage	84 800 €
Back-up Generators	Initial	880 000 €
	Elevator Scheduling	539 000 €
	Energy Storage	475 000 €

Table 2: The cost of power system assets under different demand control strategies

profiles were then simulated for each scenario while varying the market area, building type and storage capacity. The demand optimization was configured to minimize total electricity costs in every scenario. The resulting annual cost savings can be seen in figure 35.

The savings are also divided into energy, demand and fixed components so that it becomes evident whether cost savings have been achieved in energy costs or in demand charges. As expected, the results indicate that demand savings would yield the greatest cost savings in NYC, which was earlier noted for its high demand charges. The total cost savings are also greatest in NYC for every scenario. It is also clear that cost savings will not increase linearly in relation to storage capacity. The smallest storage size yields the greatest benefits in terms of savings per kWh. On average, the total electricity cost savings for both elevator groups with the smallest energy storages account for 6000€ (or 200€/kWh), medium energy storage size account for 11 500€ (or 115€/kWh) and the largest energy storage size accounts for 21 000€ (or 70€/kWh).

In figure 36. cost savings are illustrated as a percentage of the initial elevator systems' electricity costs in order to place them into a better context. On average the largest energy storage can reduce roughly 24% of the elevators' electricity costs, the medium-sized 13% and the small one 7%. Also, office buildings seem to be more suitable for demand optimization than hotels, which seems to be especially true in New York. Since the electricity costs are relative to the coincidence between load profile and time-varying prices, the building type can have a significant impact on electricity costs. In general, office buildings have a period of high demand during the morning in-rush, which can cause demand charges to surge. Furthermore, in NYC the applied ConEdison tariff has a time-of-use rate structure that aggressively penalizes consumption between 8am and 6pm.

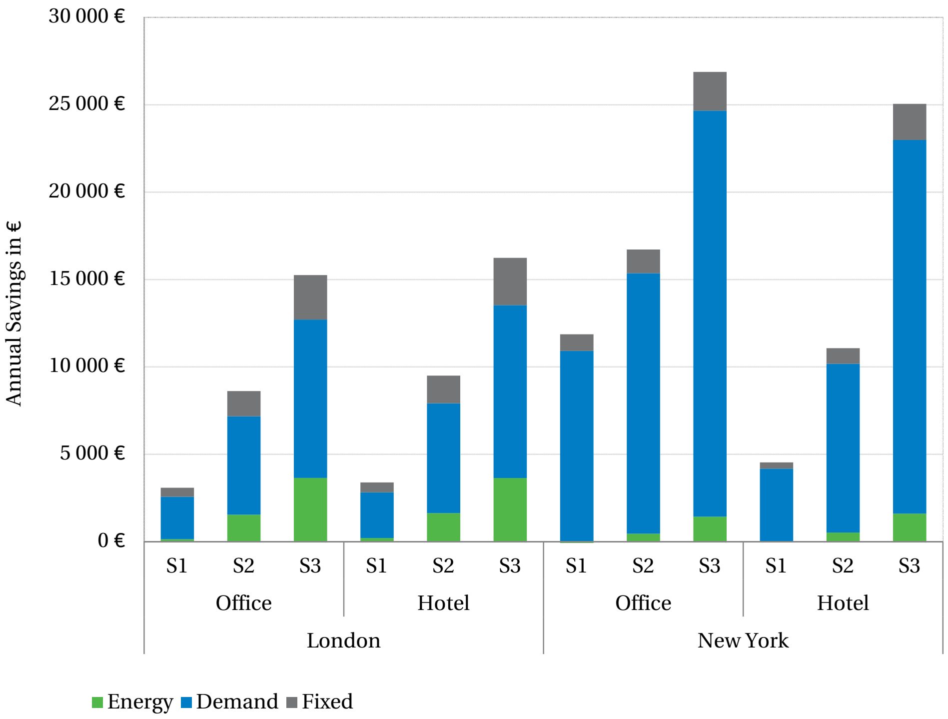


Figure 35: Annual electricity cost savings from Demand Optimized Elevator System

6.4 Capital Cost Savings in Building Power System

Capital cost savings are assessed for the building power system assets under two scenarios. The first scenario deals with reducing transient peak power through optimal elevator scheduling and the second scenario considers adjusting integrated demand by utilizing an energy storage. The transient peak power in the building power distribution system is estimated to decrease in relation to the reduced peak power in the elevator system. Based on earlier simulations, the building peak power is estimated to drop 1,55MW and 1,84MW under the two scenarios, respectively. Three primary sources of capital cost savings are identified: cables, transformers and back-up generators. Demand optimization will also slightly affect other electrical equipment that make up the building power distribution system but these effects are estimated to be so negligible that they are left out of the scope. In addition, capital cost savings are not evaluated separately under different market areas due to a lack of country-specific cost information. Contrary to electricity costs, the primary benefiter from capital cost savings is not the building owner but the building constructor or developer. Capital cost savings through demand optimization will reduce building construction costs, which will directly benefit the responsible stakeholder.

In figure 37. the capital cost savings are illustrated for the case building. Reduced capac-

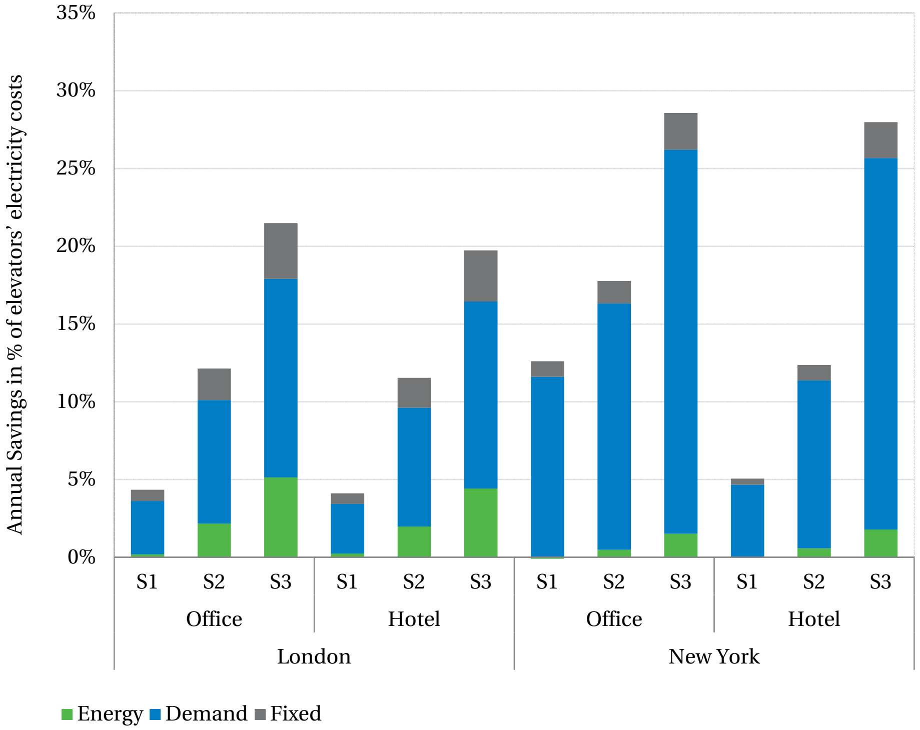


Figure 36: Annual electricity cost savings (as a percentage of initial electricity costs) from Demand Optimized Elevator System

ity requirements for SPS have the greatest impact on cost savings. This is because the cost per kVA is significantly higher for back-up generators than for building transformers and feeder cables, which also explains why many commercial buildings would opt to undersize their back-up generators. Smaller transformers contribute to the capital cost savings nearly twice as much as the smaller feeder cables. It should be noted though that the cable costs are heavily affected by the distance between elevator machine room and building transformers. In the case building, transformers were located at relatively close distance from the machine room (50m). This significantly reduces the investment cost in feeder cables because the required amount and size of the feeder cables on medium-voltage side are much less than on low-voltage side.

The overall difference in capital cost savings between the two demand control strategies is approximately 80 000€. The investment in energy storage will thus increase the capital cost savings by 19% to 490 000€. In addition to this, the energy storage investment will also bring electricity cost savings that should be taken into account when making the investment decision. A more detailed investment cost analysis will be carried out in next the chapter.

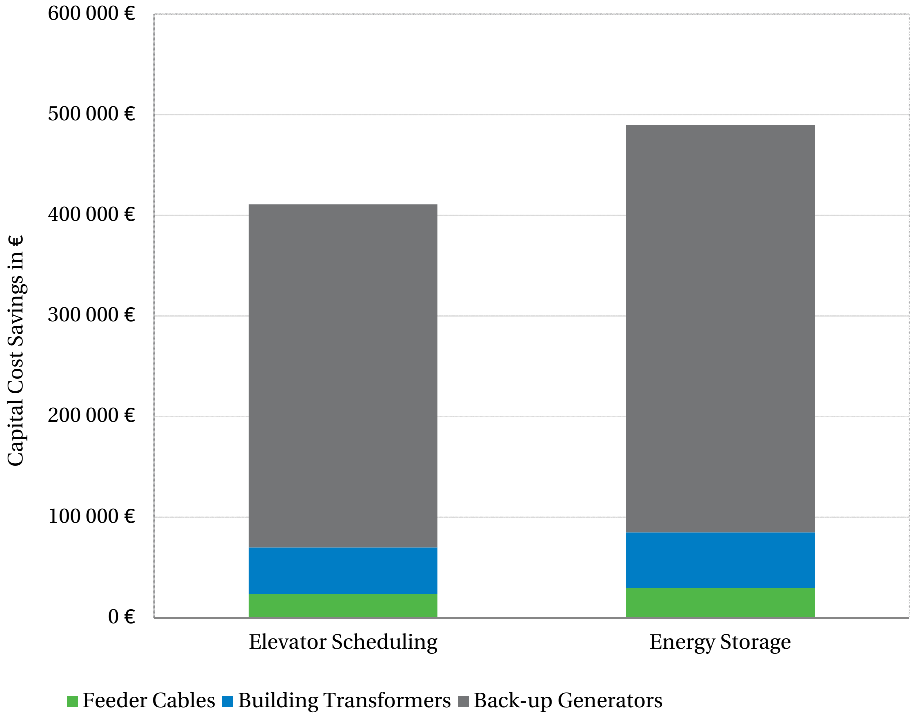


Figure 37: Capital cost savings in building power distribution system under two demand control strategies

7 Investment Analysis of Demand Optimized Elevator System

In this chapter, the previously calculated cost savings in different demand optimization scenarios are analyzed in the light of investment profitability. At first, the initial investment costs are determined in terms of capital costs for the energy storage. The Net Present Values -analysis will be limited to demand optimization by utilizing and energy storage because optimal elevator scheduling is considered to not have any initial investment or maintenance costs. The possible investment incentives are explained briefly but they are not included in the investment calculations due to uncertainties in eligibility. A typical Net Present Value -analysis will be carried out for the energy storage investments, which computes future cash flows into present values. In addition, profitability index and payback period have been computed for each investment scenario. The investment analysis is carried out for 25 years of expected elevator lifetime.

7.1 Investment Cost Breakdown

The chosen technology for energy storage was battery storage. Based on the review of current battery technologies, the most promising battery technology for a battery-coupled elevator system was estimate to be Lithium Titanate Battery (LTO). It has the benefit of long lifetime (potentially as high as 20 000 cycles), high charging and discharging power and ability to withstand deep discharge cycles. In the year 2014, the price for lithium titanate batteries ranged from \$800/kWh to \$2000/kWh. This is significantly higher than price for the cheapest lithium-ion batteries, which reach as low as \$250/kWh. [Jaffe, 2014]. However, over the past few years, the battery costs have been declining steadily. Rapidly falling battery costs can have a significant impact on the profitability of the energy storage investment. [Nykvist and Nilsson, 2015] analyzed multiple sources to determine, how the cost of Li-ion battery packs in electric vehicles have fallen recently. The average of all estimates placed Lithium-ion battery costs at around 300US\$ in 2015. However, at present the difference between market leaders and other industry manufacturers is great, but expected to become narrower in the future. [Nykvist and Nilsson, 2015] In order to determine how battery costs will develop over the lifecycle of an elevator system, we need to estimate certain price points for the future when batteries are being replaced. The price point estimates based on the above mentioned study are as follows: 2016: 100%, 2026: 75% and 2036: 50%. Furthermore the battery-coupled elevator system requires not only an energy storage but also DC-AC inverters, which regulate the current from mains supply and to the elevators. The inverters can be implemented in different setups, of which two are illustrated in figure 38. The basic difference between the setups is how well the systems is safeguarded against individual inverter malfunction. Two inverters on the load side can be considered a minimum to provide enough back-up in case that either of the inverters fail. The inverters are estimated to last for the entire lifecycle of elevator system (25 years).

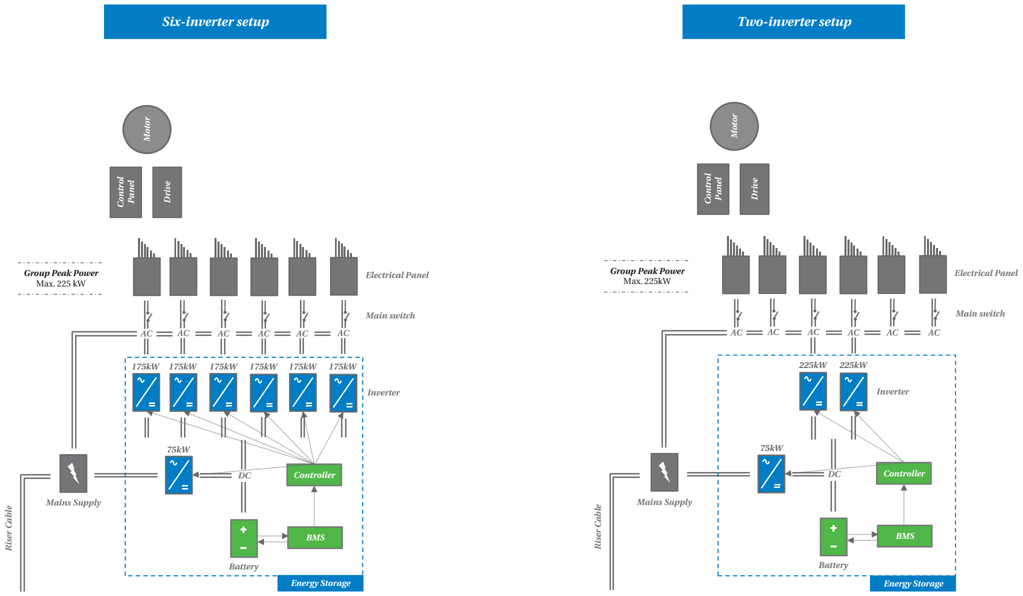


Figure 38: Two alternative inverter configurations for six-car elevator system coupled with ESS

7.2 Investment Incentives

United States is one of the countries that is aggressively pushing energy storage adaptation. Recently, the regulatory mandates and subsidies for energy storage have seen a great increase in US. Both in New York and California utilities are offering programs, which encourage behind-the-meter energy storage installations. [Neubauer and Simpson, 2015]. For example, the incentive rates for energy storage from PG&E and ConEdison are $1300 and $2100 per kW respectively [Pacific Gas and Electricity Company, 2016, Consolidated Edison Company of New York, Inc., 2016a]. This can amount for a substantial savings in investment costs, which can offset the relatively high cost of current storage technologies. However, the incentive programs are often limited to a certain percentage of total investment costs and thus for the investment to be profitable, the customer should also have other benefits from the storage investment [Neubauer and Simpson, 2015]. These benefits can be savings in electricity costs, reduced transformer sizing, smaller cable dimensioning, improved emergency operation etc. In UK, similar incentives for energy storage as in US are not yet provided. The country is running few government subsidized pilot projects in energy storage but no significant incentives exist to support companies to install energy storage. [Stone,].

Building certification systems are also an important driver of investment in more energy efficient and effective building systems. A building certification system - LEED has piloted Demand Response –credit, which promotes the implementation of demand response technologies. The credit is aimed for buildings that seek to enroll in currently existing demand response programs or plan to take part in future demand response programs. Obtaining the credit mandates that the project must have a full capability to participate in automatic demand response, contract to enroll in DR-program for a minimum of one year and comprehensive plan for carrying out demand reduction. In case that currently no DR-program exists in which the project could participate in, then the proof of ability to participate is sufficient for the credit. The project team is still required to provide necessary infrastructure and comprehensive plan to participate in demand response. In this case, the required amount of demand to be shed during demand response event should be at least 10% or 20kW of building demand, depending which is greater. No particular technology is mandated for implementation but a level of automation is required. The demand response measures on-site should be pre-programmed and either manually or automatically initiated. [US Green Building Council, 2012]. Currently, the other large building certification system - BREEAM (Building Research Establishment Environmental Assessment Methodology) does not offer specific DR-credits. It should be also recognized that demand optimized elevator system does no only contribute to cost savings but also to resource efficiency be requiring less materials for building power system assets.

7.3 NPV and Payback Period

In order to assess the profitability of investing in energy storage based demand optimization, it is necessary to first determine all of the positive and negative cash flows for the investment lifetime. A discount rate of 7% is expected for these cash flows to take into account the time value of money. Net Present Value –method is used to discount future cash flows into present values and Profitability Index (Net Present Value / Initial Investment Cost) is used to compare the attractiveness of different investment scenarios. Energy storage investment profitability is evaluated for all twelve scenarios, which include two market areas, two building types and three energy storage sizes. The capital cost savings are only taken into account for the portion that can be directly allocated to be gained by energy storage and couldn't have been achieved with only group control based optimization. The additional capital cost savings are then added to the achieved savings in electricity costs under each scenario. Finally the benefits are evaluated against varying investment costs for different energy storage sizes. The calculations are done for a typical elevator lifetime of 25 years. Energy storage lifetime is estimated at 10 years after which the battery cells have to be replaced. Annual degradation factor is assumed to be 2% so that batteries will have 80% of their initial capacity left when being replaced. No residual value for the battery cells is taken into account. Neither any storage investment incentives are taken into account. Operating and maintenance costs are estimated at 800€ per year regardless of storage size. The cost per kWh of storage capacity is estimated at 659€ in 2016, which includes all the capital costs for implementing an energy storage. The cost for battery cells is estimated to decrease so that in 2026 it is 333€ per kWh and in 2036 only 258€ per kWh. The other relevant information used in the investment calculations can be found in the appendices.

In figure 39. the Net Present Values for different investment scenarios are illustrated. Half of the investment scenarios have a positive Net Present Values after 25 years. The small-

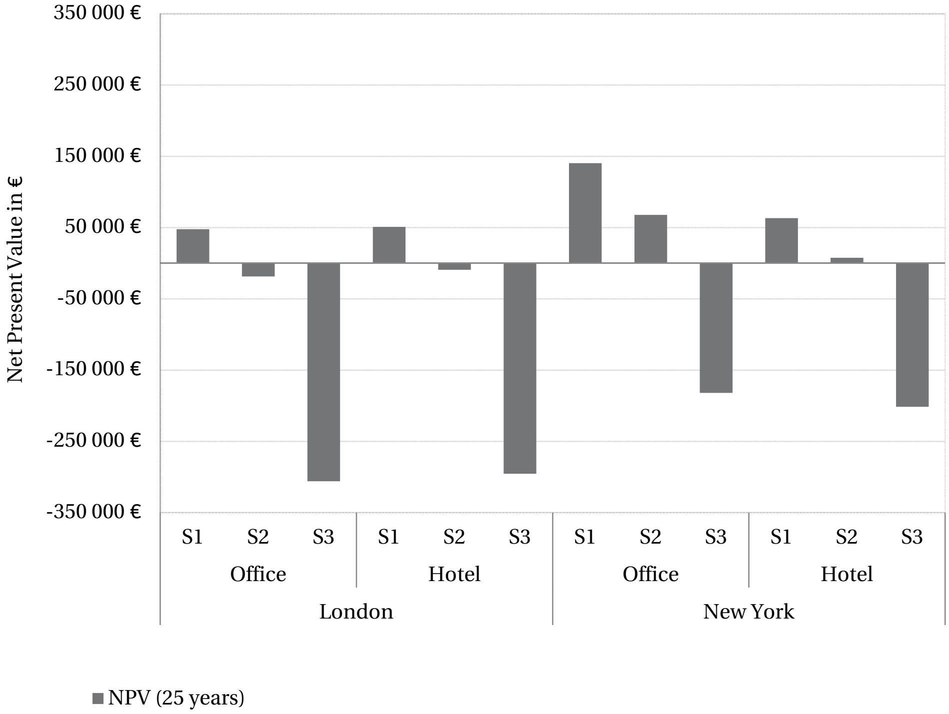


Figure 39: Net Present Value for energy storage investment under different scenarios

est energy storage size has the highest average Net Present Value of 76 000€, medium-sized energy storage has an average NPV of 12 000€ and large storage has an average NPV of -246 000€. The small energy storage seems to have the right combination of cost savings and low enough initial investment costs to be profitable. Another interesting aspect is the difference between investment profitability in London and NYC. The small-sized energy storage can yield more than two times better NPV in NYC than in London. The difference can be assumed to derive from the high demand charges in NYC, which can already be significantly reduced by even a small energy storage.

The profitability Index will show the Net Present Values in relation to the initial investment costs. Smaller initial investment costs require less capital and also indicate smaller risk. Investment can be considered profitable if its Profitability index is greater than 1. The profitability threshold is marked with a dashed line on Figure 40. The results indicate that five of the twelve scenarios can be regarded as profitable. Small-sized energy storage has on average Profitability Index of 2,75, medium-sized has 1,08 and large-sized has 0,38. The high Profitability Index is also evidence of short payback period for the investment. The small-sized energy storage scenarios can already pay back the initial investment costs in the capital cost savings that they generate, thus payback period is effectively 0. Medium-sized storage in NYC would pay itself back in the period of 4 years in office building and in the period of 15 years in hotel building. All other

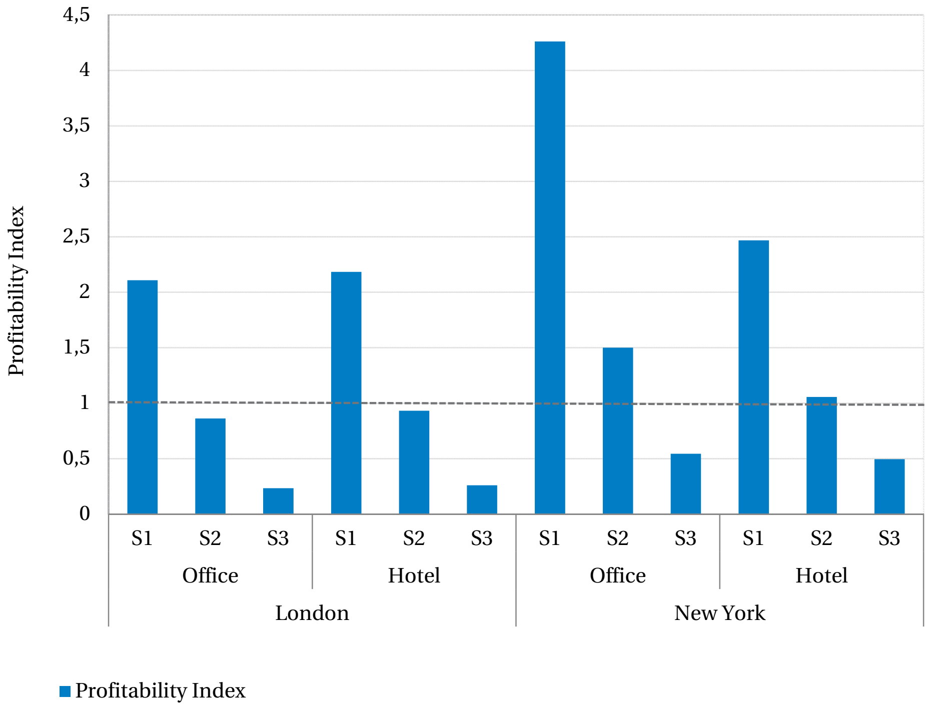


Figure 40: Profitability Index for energy storage investment under different scenarios

scenarios have a payback period of higher than 25 years and cannot be recovered within the elevator system's lifetime.

7.4 Financial Summary

The profitability of investing in Demand Optimized Elevator System can be considered excellent under the elevator scheduling based demand optimization, which yields very high cost savings with minimal investment costs. On the other hand, in the case of energy storage based demand optimization, the additional cost savings are sufficient enough to offset the increased investment costs only under half of the studied investment scenarios. The results indicate that the investment in small-sized energy storage can be profitable under every scenario, but already with medium-sized energy storage the investment is only borderline profitable. Large energy storage isn't profitable under any scenario due to its high initial investment costs and inability to gain enough cost savings to offset the sunk costs. In general, energy storage can be considered to be a better investment in NYC than in London because of the electricity rate structures in NYC that favor demand reduction.

Demand optimization by optimal elevator scheduling has the advantage of not requiring any additional investment in hardware and thus has a favorable position over energy storage. The energy storage systems have also an additional risk due to uncertainties in system lifetime, which can greatly influence the investment profitability. However, with the declining cost of battery storage, energy storage is becoming increasingly attractive choice for optimizing power demand in elevator systems. The return of investment for optimal elevator scheduling was expected to be in the range of 350 000€, whereas the energy storage scenarios were able to yield capital cost savings of 400 000€ and average annual electricity cost savings from 6000€ to 21 000€. These results indicate that capital cost savings are the primary source of value while electricity cost savings can be considered a secondary benefit of demand optimized elevator system.

8 Conclusion and Recommendations

The results of this study have shown that Demand Optimized Elevator System can be an economically viable concept under particular implementation. Reducing transient peak power through optimal elevator scheduling has the greatest benefit to cost ratio because it requires only upgrading the group control unit and has just marginal hardware costs. Energy storage based demand optimization can also be a profitable investment but mainly in the case of small-sized energy storage. In the studied case building, a relatively small-sized energy storage (30kWh) yielded roughly 80 000€ in additional capital cost savings compared to elevator scheduling, and on average 6000€ in annual electricity cost savings. Thus, it is fair to say that the primary functionality of the energy storage system would be to act as a buffer between the elevator system and building power distribution system. The capacity reductions in building power system assets can be considered more valuable than possible electricity cost savings.

Optimizing transient power by elevator scheduling does not have any preference for either market area because building power system assets can be expected to have only marginal differences in regional prices. However, the results indicate that optimizing transient power would have the greatest benefits in high-rise elevator systems with high nominal speeds and high rated passenger loads. Also, in office buildings, the achievable decrease in transient peak power can be expected to be greater than in hotel buildings due to more volatile transient power. It should be noted though that currently the electrical dimensioning for elevator systems is based on empirical value (diversity factor) for coincidence between transient peak power of multiple elevators, and it does not take into account e.g. building traffic conditions. In reality, the traffic conditions will have an impact on the likelihood of simultaneous transient peak power between multiple elevators. In addition, the achievable capital cost savings in building power system assets also depend on how much safe margin (diversity factor) has been currently applied in the electrical dimensioning of the power system assets that supply power to the elevator system. This kind of uncertainty could be avoided in Demand Optimized Elevator System, because transient peak power of an elevator system could be defined explicitly. The buildings with high requirements for SPS are also an especially good choice for Demand Optimized Elevator System due to achievable reduction in power output requirements for back-up generators. As a result, the normal transportation capacity of the elevator system could be maintained even during loss of normal power supply.

Analysis showed that coincidence between power demand and time-varying electricity costs can have a significant impact on the energy storage investment. The different rate structures and tariff plans in NYC and London influence the potential savings from optimizing integrated demand by utilizing an energy storage. The electricity rate structures in NYC are clearly more favorable towards optimizing integrated demand than those in London. The building end-use scenario (office, hotel etc.) has also a noticeable impact on achievable savings in electricity costs because volatility in the integrated demand of elevator system can be expected to be much higher in offices than in hotels. The volatile integrated demand will contribute to demand costs for building owner if the building is served under a tariff plan that has demand based charges. Based on this, it can be argued that demand optimization by utilizing an energy storage should be primarily aimed at office buildings.

In addition, the coincidence between building power demand and demand profile of the elevator system will have a significant impact on achievable electricity cost savings from utilizing an energy storage. This is because demand metering for billing purposes will be nevertheless carried out on building level. In this study, the demand profiles were expected to coincide so that the highest peaks in building power demand were assumed to originate from the power demand of elevator systems. Under circumstances in which the integrated demand of elevator system would not coincide with building peak demand would also the potential for demand optimization be reduced. Small-sized energy storage was estimated to provide the greatest value per kWh, because investment costs increase in direct relation to storage capacity while cost savings do not. However, a more precise evaluation of optimal sizing for energy storage should be assessed on its own. In addition, more precise studies are needed in order to determine the exact capital costs, eligibility for incentives and battery lifetime of the energy storage system. Energy storage can also yield other benefits that haven't been included in the investment calculations. For example, the lack of sufficient emergency power supply capacity is becoming a problem if elevators are to be used more and more in building evacuation. Energy storage could further improve the reliability of the elevator system under emergency operation by providing power supply during outage or even when the building power distribution network has been damaged. Another additional benefit of energy storage could be the increased adaptability of renewable energy generation on-site.

The two demand control strategies, elevator scheduling and coupling elevator system with energy storage, can be both argued to provide profitable investment scenarios. The results indicated that elevator scheduling would yield significant benefits for building constructor/developer in reduced cost for building power system assets and increased transportation capacity during outage. On the other hand, coupling elevator system with energy storage could also bring additional benefits in electricity costs by optimizing the integrated demand of elevator system. The choice between these control strategies should be based on the evaluation of additional benefits against increased investment risk under energy storage -based control strategy. Additionally, the customer's building end-use scenario and applied electricity tariff should be taken into account when making the decision.

In this study, electricity markets and pricing were studied under two market areas (NYC and London) in the context of Demand Optimized Elevator System. Demand optimization was further elaborated in an overview of demand control strategies and demand response in buildings. Basics of elevator and building power systems were explained in a general summary, which explained the technical basis for optimizing power demand in elevator systems. Additionally, a framework was developed to analyze demand optimization in elevator systems and simulations were carried out to study the performance of Demand Optimized Elevator System. The analysis and simulation results were used to determine the value of two different demand control strategies, elevator scheduling and coupling elevator system with energy storage. Finally, the investment profitability of Demand Optimized Elevator System was evaluated for both demand control strategies.

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A Appendices

Energy (KWh)									Demand (kW)					Fixed				
			Delivery				Commodity		Delivery			Commodity				Commodity	Delivery	
RPS	RDM	SBC	SCA	EDL	MAC	DRS	ASC	MFC	Energy Demand			MSC		Bill	Meter	Tax		GRT
Mon-Sun	Mon-Sun	Mon-Sun	Mon-Sun	Mon-Sun	Mon-Sun	Mon-Sun	Mon-Sun	Mon-Sun	Mon-Fri 8am-6pm	Mon-Fri 8am-10pm	Mon-Sun	Mon-Fri 8am-6pm	Mon-Fri 8am-10pm					
€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kW	€/kW	€/kW	€/kW	€/kW	€/bill	€/bill	/bill	/bill	/bill
0,003	0,003	0,004	0,002	0,007	0,013	0,000	0,002	0,002	0,000	7,013	4,583	0,000	7,919	1,072	92,058	8,880 %	4,500 %	2,490 %
0,003	0,003	0,004	0,002	0,007	0,012	0,000	0,002	0,002	0,000	7,013	4,583	0,000	7,919	1,072	92,058	8,880 %	4,500 %	2,490 %
0,003	0,003	0,004	0,002	0,007	0,009	0,000	0,002	0,002	0,000	7,013	4,583	0,000	7,919	1,072	92,058	8,880 %	4,500 %	2,490 %
0,003	0,003	0,004	0,002	0,007	0,014	0,000	0,002	0,002	0,000	7,013	4,583	0,000	7,919	1,072	92,058	8,880 %	4,500 %	2,490 %
0,003	0,003	0,004	0,002	0,007	0,007	0,000	0,002	0,002	0,000	7,013	4,583	0,000	11,391	1,072	92,058	8,880 %	4,500 %	2,490 %
0,003	0,003	0,004	0,002	0,007	0,008	0,000	0,003	0,001	5,086	9,508	14,286	11,391	0,000	1,072	92,058	8,880 %	4,500 %	2,490 %
0,003	0,003	0,004	0,001	0,007	0,005	0,000	0,003	0,002	5,086	9,508	14,286	11,391	0,000	1,072	92,058	8,880 %	4,500 %	2,490 %
0,003	0,001	0,004	0,001	0,007	0,007	0,000	0,002	0,002	5,086	9,508	14,286	11,391	0,000	1,072	92,058	8,880%	4,500 %	2,490 %
0,003	0,001	0,004	0,001	0,007	0,008	0,000	0,002	0,002	5,086	9,508	14,286	11,391	0,000	1,072	92,058	8,880 %	4,500 %	2,490 %
0,002	0,001	0,004	0,001	0,007	0,005	0,000	0,002	0,002	0,000	7,013	4,583	0,000	11,391	1,072	92,058	8,880 %	4,500 %	2,490 %
0,002	0,001	0,004	0,001	0,007	0,012	0,000	0,002	0,002	0,000	7,013	4,583	0,000	7,160	1,072	92,058	8,880 %	4,500 %	2,490%
0,002	0,001	0,004	0,001	0,007	0,016	0,000	0,003	0,002	0,000	7,013	4,583	0,000	7,160	1,072	92,058	8,880 %	4,500 %	2,490 %

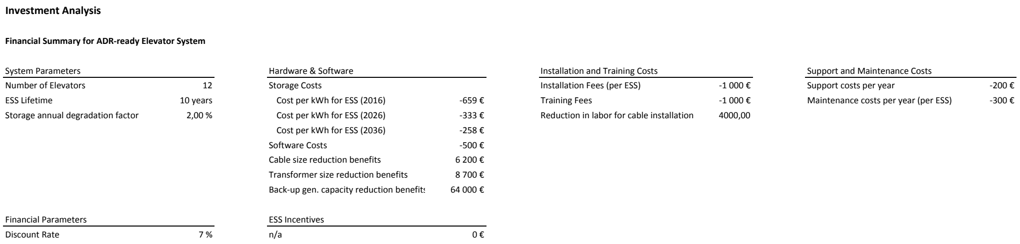
[1] Table does not include NYISO Day-ahead Market prices

Table A1: Electricity tariff breakdown for a large customer in NYC

Energy (kWh)												Demand (kW)		Fixed			
FIT	DUoS (T)						RO	BSUoS	MP	BC	CCL	DUoS (D)	TNUoS	DC	SFC	Meter	VAT
Mon-Sun all hours	Mon-Fri 11pm-7am	Mon-Fri 7am-11am	Mon-Fri 11am-2pm	Mon-Fri 2pm-4pm	Mon-Fri 4pm-7pm	Mon-Fri 7pm-11pm	Mon-Sun all hours	Mon-Sun all hours	Mon-Sun all hours	Mon-Sun all hours	Mon-Sun all hours	Mon-Sun all hours	Triad all hours				
€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kWh	€/kw/day	€/kW/month	€/month	€/day	€/MPAN/month	%
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255
0,005	0,000	0,000	0,013	0,000	0,013	0,000	0,013	0,003	0,000	0,000	0,007	0,107	4,905	1112,233	2,049	34,851	0,255

[1] Table does not include APX Half-hour Day-ahead Market prices

Table A2: Electricity tariff breakdown for a large customer in London



Investment Analysis

Financial Summary for ADR-ready Elevator System

System Parameters	
Number of Elevators	12
ESS Lifetime	10 years
Storage annual degradation factor	2,00 %

Hardware & Software	
Storage Costs	
Cost per kWh for ESS (2016)	-659 €
Cost per kWh for ESS (2026)	-333 €
Cost per kWh for ESS (2036)	-258 €
Software Costs	-500 €
Cable size reduction benefits	6 200 €
Transformer size reduction benefits	8 700 €
Back-up gen. capacity reduction benefit	64 000 €

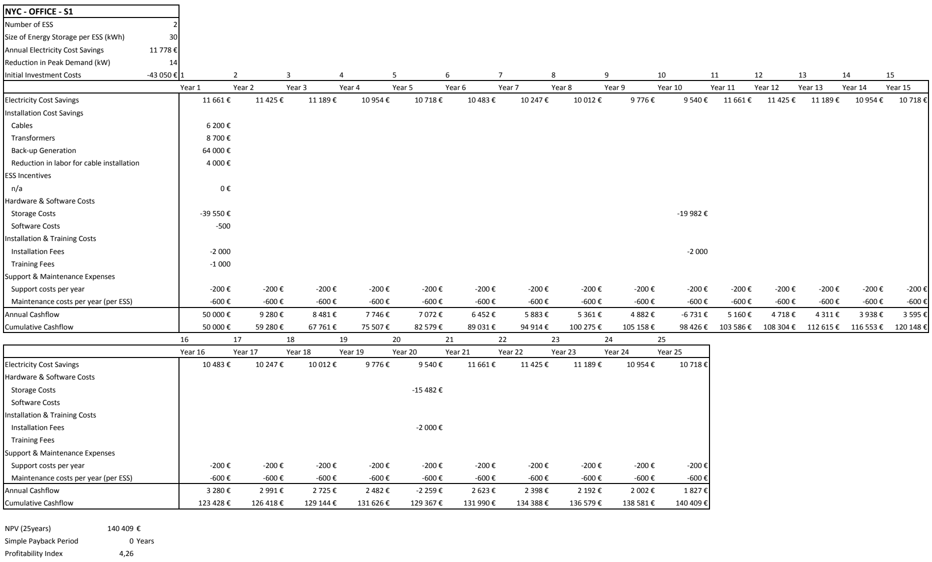
Installation and Training Costs	
Installation Fees (per ESS)	-1 000 €
Training Fees	-1 000 €
Reduction in labor for cable installation	4000,00

Support and Maintenance Costs	
Support costs per year	-200 €
Maintenance costs per year (per ESS)	-300 €

Financial Parameters	
Discount Rate	7 %

ESS Incentives	
n/a	0 €

Figure A1: Input variables for investment analysis



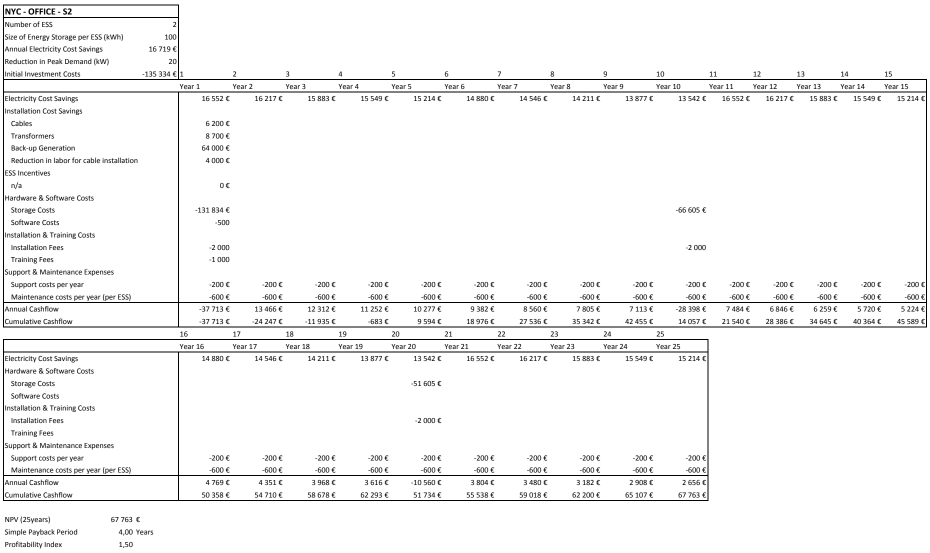
NYC - OFFICE - S1	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	30
Annual Electricity Cost Savings	11 778 €
Reduction in Peak Demand (kW)	14
Initial Investment Costs	-43 050 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	11 661 €	11 425 €	11 189 €	10 954 €	10 718 €	10 483 €	10 247 €	10 012 €	9 776 €	9 540 €	11 661 €	11 425 €	11 189 €	10 954 €	10 718 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-39 550 €									-19 982 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	50 000 €	9 280 €	8 481 €	7 746 €	7 072 €	6 452 €	5 883 €	5 361 €	4 882 €	-6 731 €	5 160 €	4 718 €	4 311 €	3 938 €	3 595 €
Cumulative Cashflow	50 000 €	59 280 €	67 761 €	75 507 €	82 579 €	89 031 €	94 914 €	100 275 €	105 158 €	98 426 €	103 586 €	108 304 €	112 615 €	116 553 €	120 148 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	10 483 €	10 247 €	10 012 €	9 776 €	9 540 €	11 661 €	11 425 €	11 189 €	10 954 €	10 718 €
Hardware & Software Costs										
Storage Costs					-15 482 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	3 280 €	2 991 €	2 725 €	2 482 €	-2 259 €	2 623 €	2 398 €	2 192 €	2 002 €	1 827 €
Cumulative Cashflow	123 428 €	126 418 €	129 144 €	131 626 €	129 367 €	131 990 €	134 388 €	136 579 €	138 581 €	140 409 €

NPV (25years)	140 409	€
Simple Payback Period	0	Years
Profitability Index	4,26	

Figure A2: Results of investment analysis for small-sized ESS/Office/NYC



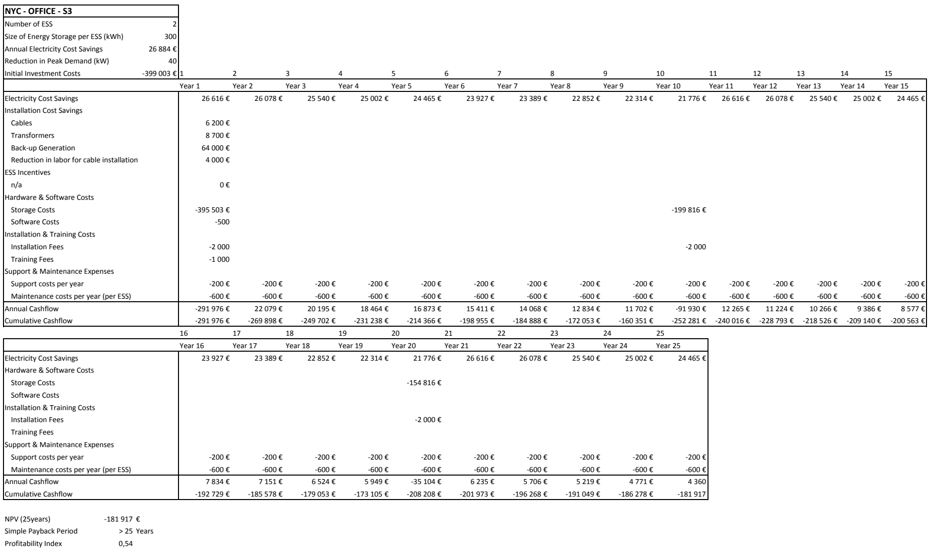
NYC - OFFICE - S2	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	100
Annual Electricity Cost Savings	16 719 €
Reduction in Peak Demand (kW)	20
Initial Investment Costs	-135 334 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	16 552 €	16 217 €	15 883 €	15 549 €	15 214 €	14 880 €	14 546 €	14 211 €	13 877 €	13 542 €	16 552 €	16 217 €	15 883 €	15 549 €	15 214 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-131 834 €									-66 605 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	-37 713 €	13 466 €	12 312 €	11 252 €	10 277 €	9 382 €	8 560 €	7 805 €	7 113 €	-28 398 €	7 484 €	6 846 €	6 259 €	5 720 €	5 224 €
Cumulative Cashflow	-37 713 €	-24 247 €	-11 935 €	-683 €	9 594 €	18 976 €	27 536 €	35 342 €	42 455 €	14 057 €	21 540 €	28 386 €	34 645 €	40 364 €	45 589 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	14 880 €	14 546 €	14 211 €	13 877 €	13 542 €	16 552 €	16 217 €	15 883 €	15 549 €	15 214 €
Hardware & Software Costs										
Storage Costs					-51 605 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	4 769 €	4 351 €	3 968 €	3 616 €	-10 560 €	3 804 €	3 480 €	3 182 €	2 908 €	2 656 €
Cumulative Cashflow	50 358 €	54 710 €	58 678 €	62 293 €	51 734 €	55 538 €	59 018 €	62 200 €	65 107 €	67 763 €

NPV (25years)	67 763	€
Simple Payback Period	4,00	Years
Profitability Index	1,50	

Figure A3: Results of investment analysis for medium-sized ESS/Office/NYC



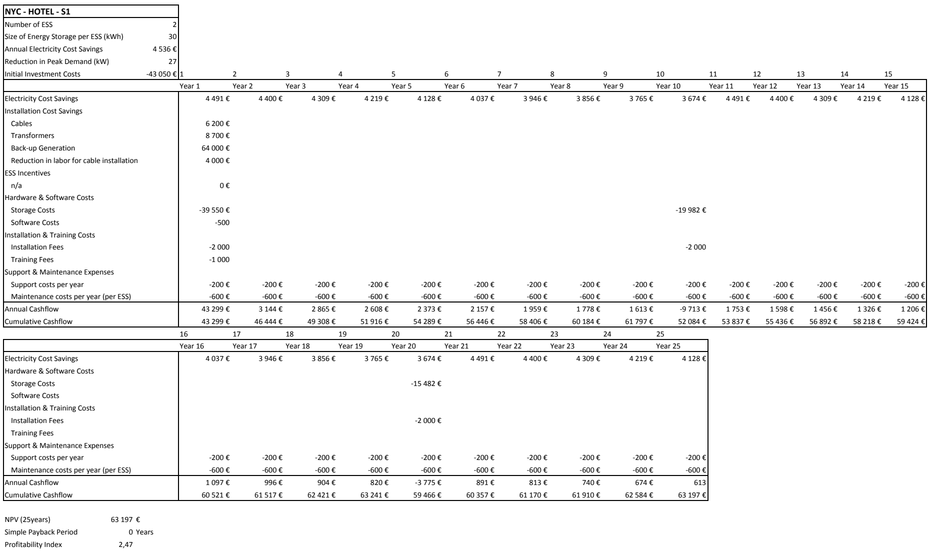
NYC - OFFICE - S3	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	300
Annual Electricity Cost Savings	26 884 €
Reduction in Peak Demand (kW)	40
Initial Investment Costs	-399 003 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	26 616 €	26 078 €	25 540 €	25 002 €	24 465 €	23 927 €	23 389 €	22 852 €	22 314 €	21 776 €	26 616 €	26 078 €	25 540 €	25 002 €	24 465 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-395 503 €									-199 816 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	-291 976 €	22 079 €	20 195 €	18 464 €	16 873 €	15 411 €	14 068 €	12 834 €	11 702 €	-91 930 €	12 265 €	11 224 €	10 266 €	9 386 €	8 577 €
Cumulative Cashflow	-291 976 €	-269 898 €	-249 702 €	-231 238 €	-214 366 €	-198 955 €	-184 888 €	-172 053 €	-160 351 €	-252 281 €	-240 016 €	-228 793 €	-218 526 €	-209 140 €	-200 563 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	23 927 €	23 389 €	22 852 €	22 314 €	21 776 €	26 616 €	26 078 €	25 540 €	25 002 €	24 465 €
Hardware & Software Costs										
Storage Costs					-154 816 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	7 834 €	7 151 €	6 524 €	5 949 €	-35 104 €	6 235 €	5 706 €	5 219 €	4 771 €	4 360
Cumulative Cashflow	-192 729 €	-185 578 €	-179 053 €	-173 105 €	-208 208 €	-201 973 €	-196 268 €	-191 049 €	-186 278 €	-181 917

NPV (25years)	-181 917	€
Simple Payback Period	> 25	Years
Profitability Index	0,54	

Figure A4: Results of investment analysis for largel-sized ESS/Office/NYC



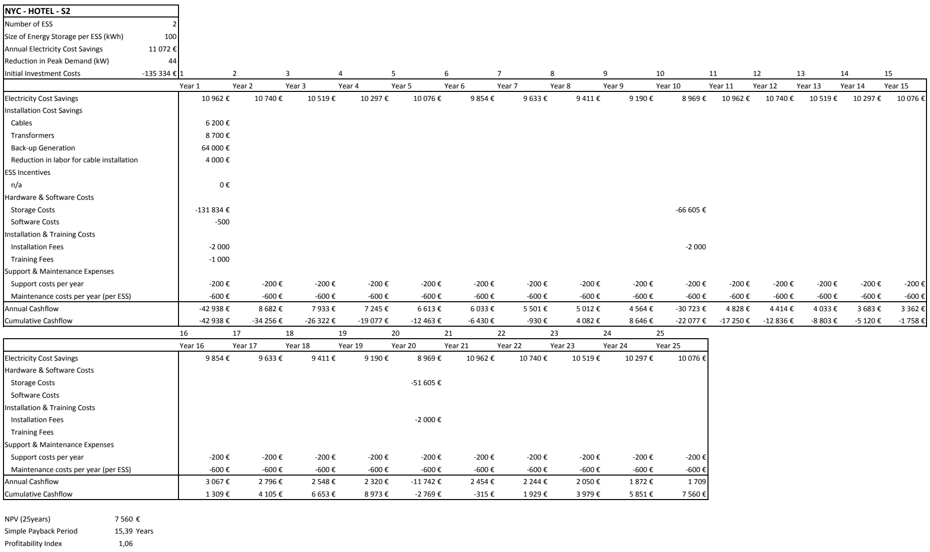
NYC - HOTEL - S1	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	30
Annual Electricity Cost Savings	4 536 €
Reduction in Peak Demand (kW)	27
Initial Investment Costs	-43 050 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	4 491 €	4 400 €	4 309 €	4 219 €	4 128 €	4 037 €	3 946 €	3 856 €	3 765 €	3 674 €	4 491 €	4 400 €	4 309 €	4 219 €	4 128 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-39 550 €									-19 982 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	43 299 €	3 144 €	2 865 €	2 608 €	2 373 €	2 157 €	1 959 €	1 778 €	1 613 €	-9 713 €	1 753 €	1 598 €	1 456 €	1 326 €	1 206 €
Cumulative Cashflow	43 299 €	46 444 €	49 308 €	51 916 €	54 289 €	56 446 €	58 406 €	60 184 €	61 797 €	52 084 €	53 837 €	55 436 €	56 892 €	58 218 €	59 424 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	4 037 €	3 946 €	3 856 €	3 765 €	3 674 €	4 491 €	4 400 €	4 309 €	4 219 €	4 128 €
Hardware & Software Costs										
Storage Costs					-15 482 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	1 097 €	996 €	904 €	820 €	-3 775 €	891 €	813 €	740 €	674 €	613
Cumulative Cashflow	60 521 €	61 517 €	62 421 €	63 241 €	59 466 €	60 357 €	61 170 €	61 910 €	62 584 €	63 197 €

NPV (25years)	63 197	€
Simple Payback Period	0	Years
Profitability Index	2,47	

Figure A5: Results of investment analysis for small-sized ESS/Hotel/NYC



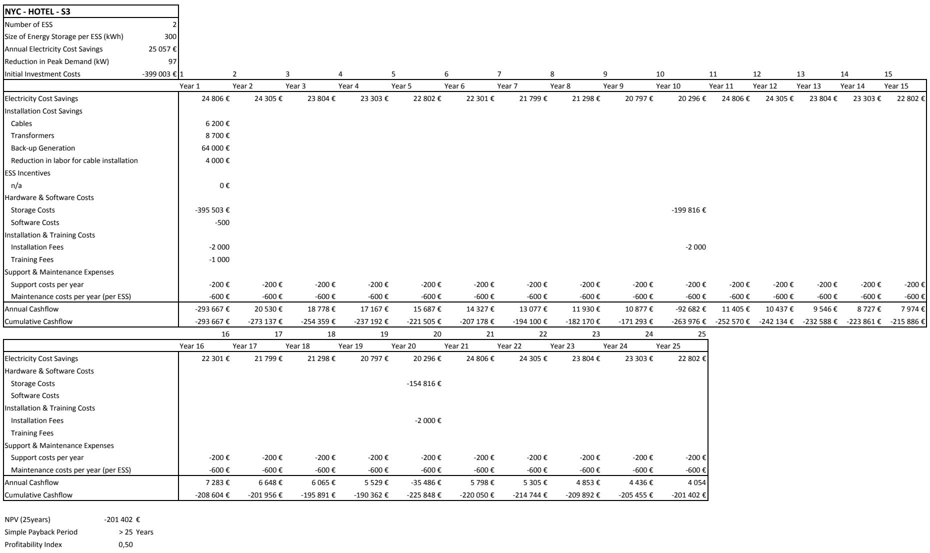
NYC - HOTEL - S2	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	100
Annual Electricity Cost Savings	11 072 €
Reduction in Peak Demand (kW)	44
Initial Investment Costs	-135 334 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	10 962 €	10 740 €	10 519 €	10 297 €	10 076 €	9 854 €	9 633 €	9 411 €	9 190 €	8 969 €	10 962 €	10 740 €	10 519 €	10 297 €	10 076 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-131 834 €									-66 605 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	-42 938 €	8 682 €	7 933 €	7 245 €	6 613 €	6 033 €	5 501 €	5 012 €	4 564 €	-30 723 €	4 828 €	4 414 €	4 033 €	3 683 €	3 362 €
Cumulative Cashflow	-42 938 €	-34 256 €	-26 322 €	-19 077 €	-12 463 €	-6 430 €	-930 €	4 082 €	8 646 €	-22 077 €	-17 250 €	-12 836 €	-8 803 €	-5 120 €	-1 758 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	9 854 €	9 633 €	9 411 €	9 190 €	8 969 €	10 962 €	10 740 €	10 519 €	10 297 €	10 076 €
Hardware & Software Costs										
Storage Costs					-51 605 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	3 067 €	2 796 €	2 548 €	2 320 €	-11 742 €	2 454 €	2 244 €	2 050 €	1 872 €	1 709
Cumulative Cashflow	1 309 €	4 105 €	6 653 €	8 973 €	-2 769 €	-315 €	1 929 €	3 979 €	5 851 €	7 560 €

NPV (25years)	7 560	€
Simple Payback Period	15,39	Years
Profitability Index	1,06	

Figure A6: Results of investment analysis for medium-sized ESS/Hotel/NYC



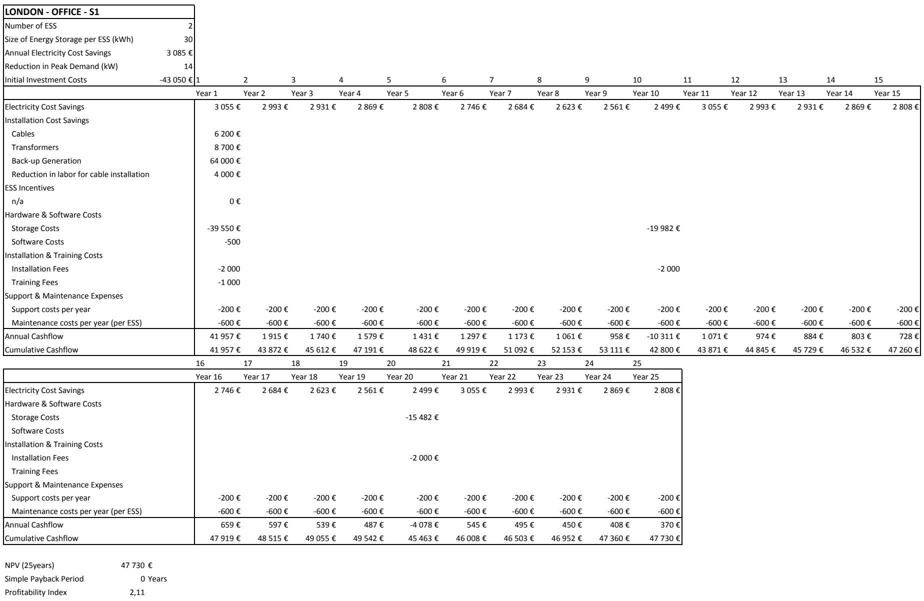
NYC - HOTEL - S3	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	300
Annual Electricity Cost Savings	25 057 €
Reduction in Peak Demand (kW)	97
Initial Investment Costs	-399 003 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	24 806 €	24 305 €	23 804 €	23 303 €	22 802 €	22 301 €	21 799 €	21 298 €	20 797 €	20 296 €	24 806 €	24 305 €	23 804 €	23 303 €	22 802 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-395 503 €									-199 816 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	-293 667 €	20 530 €	18 778 €	17 167 €	15 687 €	14 327 €	13 077 €	11 930 €	10 877 €	-92 682 €	11 405 €	10 437 €	9 546 €	8 727 €	7 974 €
Cumulative Cashflow	-293 667 €	-273 137 €	-254 359 €	-237 192 €	-221 505 €	-207 178 €	-194 100 €	-182 170 €	-171 293 €	-263 976 €	-252 570 €	-242 134 €	-232 588 €	-223 861 €	-215 886 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	22 301 €	21 799 €	21 298 €	20 797 €	20 296 €	24 806 €	24 305 €	23 804 €	23 303 €	22 802 €
Hardware & Software Costs										
Storage Costs					-154 816 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	7 283 €	6 648 €	6 065 €	5 529 €	-35 486 €	5 798 €	5 305 €	4 853 €	4 436 €	4 054
Cumulative Cashflow	-208 604 €	-201 956 €	-195 891 €	-190 362 €	-225 848 €	-220 050 €	-214 744 €	-209 892 €	-205 455 €	-201 402 €

NPV (25years)	-201 402	€
Simple Payback Period	> 25	Years
Profitability Index	0,50	

Figure A7: Results of investment analysis for large-sized ESS/Hotel/NYC



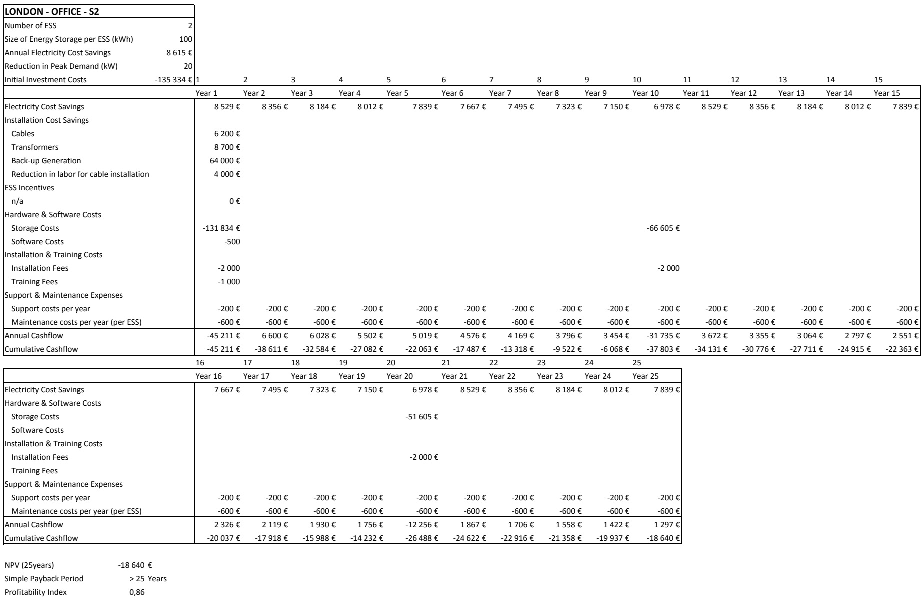
LONDON - OFFICE - S1	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	30
Annual Electricity Cost Savings	3 085 €
Reduction in Peak Demand (kW)	14
Initial Investment Costs	-43 050 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	3 055 €	2 993 €	2 931 €	2 869 €	2 808 €	2 746 €	2 684 €	2 623 €	2 561 €	2 499 €	3 055 €	2 993 €	2 931 €	2 869 €	2 808 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-39 550 €									-19 982 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	41 957 €	1 915 €	1 740 €	1 579 €	1 431 €	1 297 €	1 173 €	1 061 €	958 €	-10 311 €	1 071 €	974 €	884 €	803 €	728 €
Cumulative Cashflow	41 957 €	43 872 €	45 612 €	47 191 €	48 622 €	49 919 €	51 092 €	52 153 €	53 111 €	42 800 €	43 871 €	44 845 €	45 729 €	46 532 €	47 260 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	2 746 €	2 684 €	2 623 €	2 561 €	2 499 €	3 055 €	2 993 €	2 931 €	2 869 €	2 808 €
Hardware & Software Costs										
Storage Costs					-15 482 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	659 €	597 €	539 €	487 €	-4 078 €	545 €	495 €	450 €	408 €	370 €
Cumulative Cashflow	47 919 €	48 515 €	49 055 €	49 542 €	45 463 €	46 008 €	46 503 €	46 952 €	47 360 €	47 730 €

NPV (25years)	47 730 €
Simple Payback Period	0 Years
Profitability Index	2,11

Figure A8: Results of investment analysis for small-sized ESS/Office/London



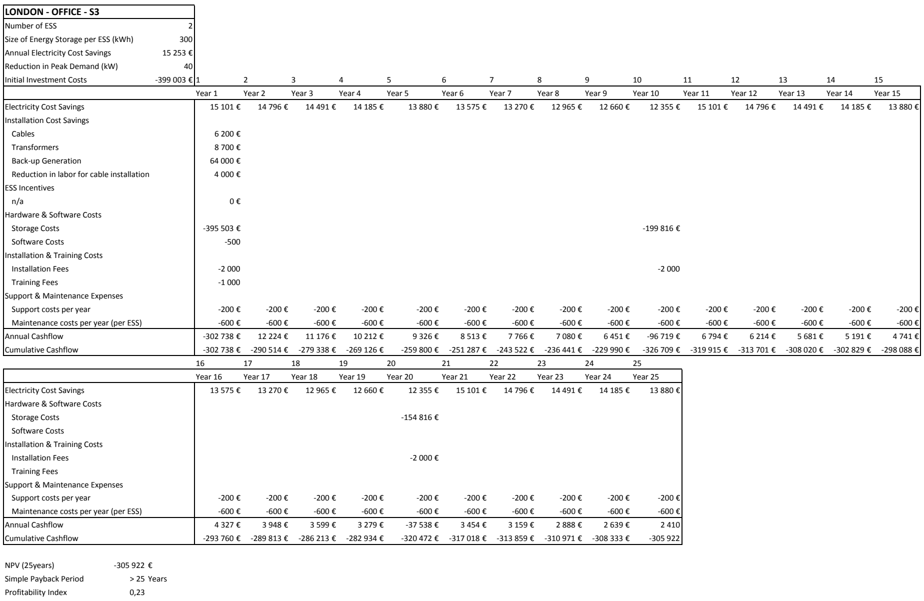
LONDON - OFFICE - S2	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	100
Annual Electricity Cost Savings	8 615 €
Reduction in Peak Demand (kW)	20
Initial Investment Costs	-135 334 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	8 529 €	8 356 €	8 184 €	8 012 €	7 839 €	7 667 €	7 495 €	7 323 €	7 150 €	6 978 €	8 529 €	8 356 €	8 184 €	8 012 €	7 839 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-131 834 €									-66 605 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	-45 211 €	6 600 €	6 028 €	5 502 €	5 019 €	4 576 €	4 169 €	3 796 €	3 454 €	-31 735 €	3 672 €	3 355 €	3 064 €	2 797 €	2 551 €
Cumulative Cashflow	-45 211 €	-38 611 €	-32 584 €	-27 082 €	-22 063 €	-17 487 €	-13 318 €	-9 522 €	-6 068 €	-37 803 €	-34 131 €	-30 776 €	-27 711 €	-24 915 €	-22 363 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	7 667 €	7 495 €	7 323 €	7 150 €	6 978 €	8 529 €	8 356 €	8 184 €	8 012 €	7 839 €
Hardware & Software Costs										
Storage Costs					-51 605 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	2 326 €	2 119 €	1 930 €	1 756 €	-12 256 €	1 867 €	1 706 €	1 558 €	1 422 €	1 297 €
Cumulative Cashflow	-20 037 €	-17 918 €	-15 988 €	-14 232 €	-26 488 €	-24 622 €	-22 916 €	-21 358 €	-19 937 €	-18 640 €

NPV (25years)	-18 640 €
Simple Payback Period	> 25 Years
Profitability Index	0,86

Figure A9: Results of investment analysis for medium-sized ESS/Office/London



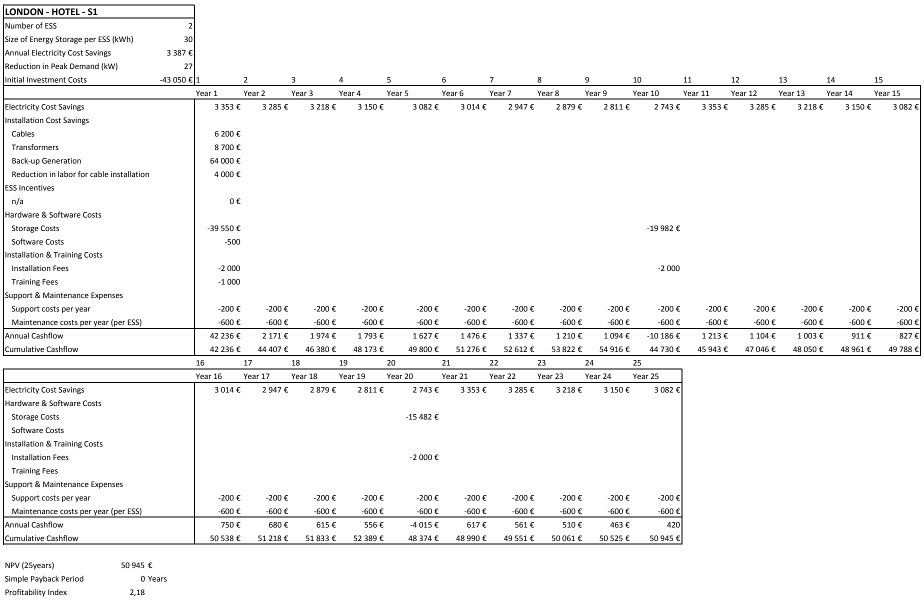
LONDON - OFFICE - S3	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	300
Annual Electricity Cost Savings	15 253 €
Reduction in Peak Demand (kW)	40
Initial Investment Costs	-399 003 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	15 101 €	14 796 €	14 491 €	14 185 €	13 880 €	13 575 €	13 270 €	12 965 €	12 660 €	12 355 €	15 101 €	14 796 €	14 491 €	14 185 €	13 880 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-395 503 €									-199 816 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	-302 738 €	12 224 €	11 176 €	10 212 €	9 326 €	8 513 €	7 766 €	7 080 €	6 451 €	-96 719 €	6 794 €	6 214 €	5 681 €	5 191 €	4 741 €
Cumulative Cashflow	-302 738 €	-290 514 €	-279 338 €	-269 126 €	-259 800 €	-251 287 €	-243 522 €	-236 441 €	-229 990 €	-326 709 €	-319 915 €	-313 701 €	-308 020 €	-302 829 €	-298 088 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	13 575 €	13 270 €	12 965 €	12 660 €	12 355 €	15 101 €	14 796 €	14 491 €	14 185 €	13 880 €
Hardware & Software Costs										
Storage Costs					-154 816 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	4 327 €	3 948 €	3 599 €	3 279 €	-37 538 €	3 454 €	3 159 €	2 888 €	2 639 €	2 410
Cumulative Cashflow	-293 760 €	-289 813 €	-286 213 €	-282 934 €	-320 472 €	-317 018 €	-313 859 €	-310 971 €	-308 333 €	-305 922

NPV (25years)	-305 922 €
Simple Payback Period	> 25 Years
Profitability Index	0,23

Figure A10: Results of investment analysis for largel-sized ESS/Office/London



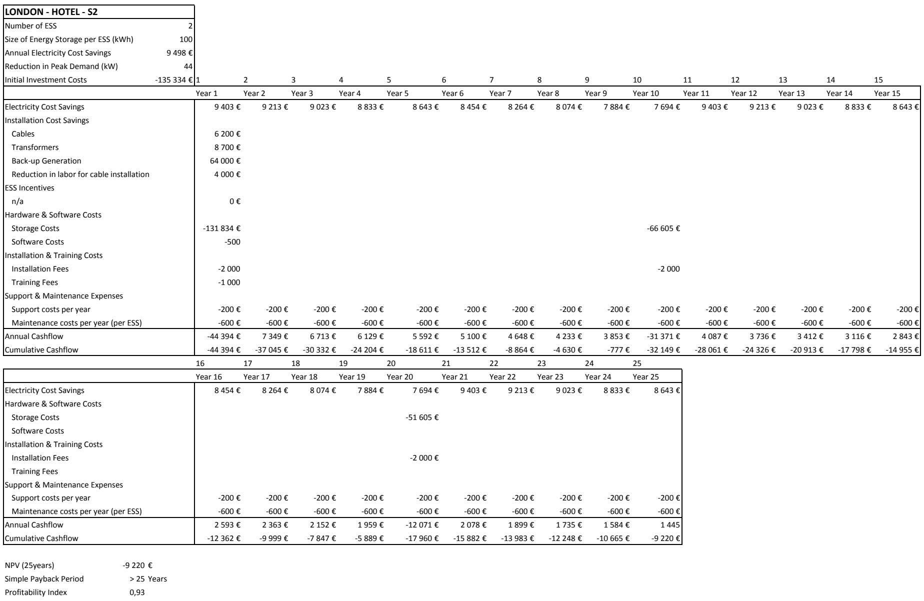
LONDON - HOTEL - S1	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	30
Annual Electricity Cost Savings	3 387 €
Reduction in Peak Demand (kW)	27
Initial Investment Costs	-43 050 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	3 353 €	3 285 €	3 218 €	3 150 €	3 082 €	3 014 €	2 947 €	2 879 €	2 811 €	2 743 €	3 353 €	3 285 €	3 218 €	3 150 €	3 082 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-39 550 €									-19 982 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	42 236 €	2 171 €	1 974 €	1 793 €	1 627 €	1 476 €	1 337 €	1 210 €	1 094 €	-10 186 €	1 213 €	1 104 €	1 003 €	911 €	827 €
Cumulative Cashflow	42 236 €	44 407 €	46 380 €	48 173 €	49 800 €	51 276 €	52 612 €	53 822 €	54 916 €	44 730 €	45 943 €	47 046 €	48 050 €	48 961 €	49 788 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	3 014 €	2 947 €	2 879 €	2 811 €	2 743 €	3 353 €	3 285 €	3 218 €	3 150 €	3 082 €
Hardware & Software Costs										
Storage Costs					-15 482 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	750 €	680 €	615 €	556 €	-4 015 €	617 €	561 €	510 €	463 €	420
Cumulative Cashflow	50 538 €	51 218 €	51 833 €	52 389 €	48 374 €	48 990 €	49 551 €	50 061 €	50 525 €	50 945 €

NPV (25years)	50 945 €
Simple Payback Period	0 Years
Profitability Index	2,18

Figure A11: Results of investment analysis for small-sized ESS/Hotel/London



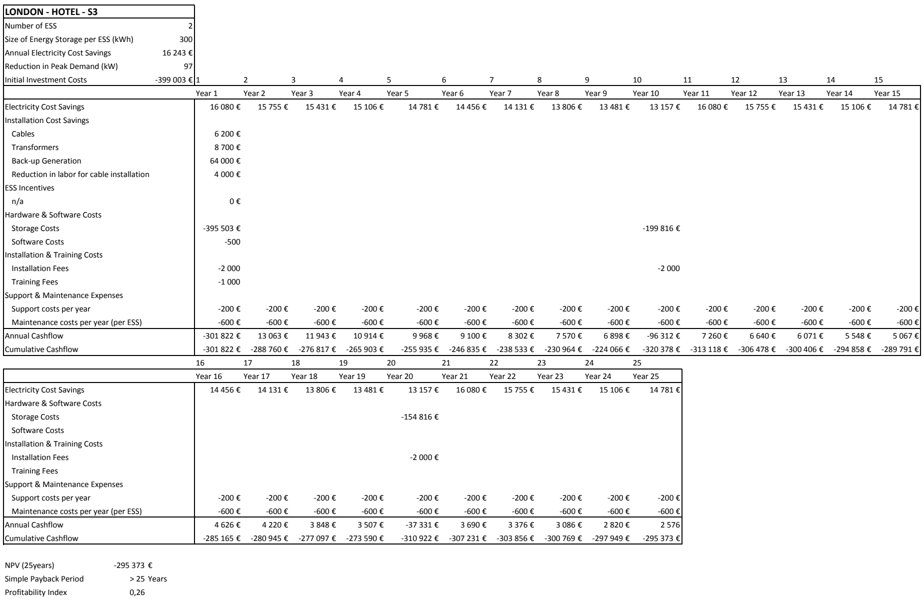
LONDON - HOTEL - S2	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	100
Annual Electricity Cost Savings	9 498 €
Reduction in Peak Demand (kW)	44
Initial Investment Costs	-135 334 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	9 403 €	9 213 €	9 023 €	8 833 €	8 643 €	8 454 €	8 264 €	8 074 €	7 884 €	7 694 €	9 403 €	9 213 €	9 023 €	8 833 €	8 643 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-131 834 €									-66 605 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	-44 394 €	7 349 €	6 713 €	6 129 €	5 592 €	5 100 €	4 648 €	4 233 €	3 853 €	-31 371 €	4 087 €	3 736 €	3 412 €	3 116 €	2 843 €
Cumulative Cashflow	-44 394 €	-37 045 €	-30 332 €	-24 204 €	-18 611 €	-13 512 €	-8 864 €	-4 630 €	-777 €	-32 149 €	-28 061 €	-24 326 €	-20 913 €	-17 798 €	-14 955 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	8 454 €	8 264 €	8 074 €	7 884 €	7 694 €	9 403 €	9 213 €	9 023 €	8 833 €	8 643 €
Hardware & Software Costs										
Storage Costs					-51 605 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	2 593 €	2 363 €	2 152 €	1 959 €	-12 071 €	2 078 €	1 899 €	1 735 €	1 584 €	1 445
Cumulative Cashflow	-12 362 €	-9 999 €	-7 847 €	-5 889 €	-17 960 €	-15 882 €	-13 983 €	-12 248 €	-10 665 €	-9 220 €

NPV (25years)	-9 220 €
Simple Payback Period	> 25 Years
Profitability Index	0,93

Figure A12: Results of investment analysis for medium-sized ESS/Hotel/London



LONDON - HOTEL - S3	
Number of ESS	2
Size of Energy Storage per ESS (kWh)	300
Annual Electricity Cost Savings	16 243 €
Reduction in Peak Demand (kW)	97
Initial Investment Costs	-399 003 €

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity Cost Savings	16 080 €	15 755 €	15 431 €	15 106 €	14 781 €	14 456 €	14 131 €	13 806 €	13 481 €	13 157 €	16 080 €	15 755 €	15 431 €	15 106 €	14 781 €
Installation Cost Savings															
Cables	6 200 €														
Transformers	8 700 €														
Back-up Generation	64 000 €														
Reduction in labor for cable installation	4 000 €														
ESS Incentives															
n/a	0 €														
Hardware & Software Costs															
Storage Costs	-395 503 €									-199 816 €					
Software Costs	-500														
Installation & Training Costs															
Installation Fees	-2 000									-2 000					
Training Fees	-1 000														
Support & Maintenance Expenses															
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	-301 822 €	13 063 €	11 943 €	10 914 €	9 968 €	9 100 €	8 302 €	7 570 €	6 898 €	-96 312 €	7 260 €	6 640 €	6 071 €	5 548 €	5 067 €
Cumulative Cashflow	-301 822 €	-288 760 €	-276 817 €	-265 903 €	-255 935 €	-246 835 €	-238 533 €	-230 964 €	-224 066 €	-320 378 €	-313 118 €	-306 478 €	-300 406 €	-294 858 €	-289 791 €

	16	17	18	19	20	21	22	23	24	25
	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25
Electricity Cost Savings	14 456 €	14 131 €	13 806 €	13 481 €	13 157 €	16 080 €	15 755 €	15 431 €	15 106 €	14 781 €
Hardware & Software Costs										
Storage Costs					-154 816 €					
Software Costs										
Installation & Training Costs										
Installation Fees					-2 000 €					
Training Fees										
Support & Maintenance Expenses										
Support costs per year	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €	-200 €
Maintenance costs per year (per ESS)	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €	-600 €
Annual Cashflow	4 626 €	4 220 €	3 848 €	3 507 €	-37 331 €	3 690 €	3 376 €	3 086 €	2 820 €	2 576
Cumulative Cashflow	-285 165 €	-280 945 €	-277 097 €	-273 590 €	-310 922 €	-307 231 €	-303 856 €	-300 769 €	-297 949 €	-295 373 €

NPV (25years)	-295 373 €
Simple Payback Period	> 25 Years
Profitability Index	0,26

Figure A13: Results of investment analysis for large-sized ESS/Hotel/London