**Energimyndighetens titel på projektet – svenska**

**Smart elnät i stadsmiljö i Norra Djurgårdssstaden**

**Energimyndighetens titel på projektet – engelska**

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Smart grids, smart homes, demand respons
FOREWORD

It has been a long and interesting journey. The initial talks between Fortum and ABB started already in 2008. Back then “Smart Grid” was on the agenda in all large energy utilities. The target was to create one of the most interesting and comprehensive smart grid programs in Europe and therefore we invited Ericsson and Electrolux as well.

Mission accomplished – the final consortium of Fortum, Ellevio, ABB, Ericsson, Electrolux, the Swedish Energy Agency and the Royal Institute of Technology (KTH) has created a research program that has been at the forefront of technological - and smart energy development. And as this report shows, with really interesting results.

For the first time, energy consumers have been able to see their total energy consumption: electricity, warm water and heat in real time. Comparing their energy consumption through time, but also comparing to the peers in the program. The result showed that the increased awareness changed energy behavior in a positive direction for the environment.

Affordable Smart Grid technology has been tested in grid areas where this kind of technology was not economically viable before. As a result, the Stockholm grid company Ellevio has changed their strategy for how they monitor and operate their local grids.

Cutting edge Demand/Response technology has been tested in real apartments by real families showing that the technology is ready for more volatile energy systems based on more sun and wind energy production. The best example of this is the washers and dryers that Electrolux developed for the program, that automatically started and stopped when it was best for the environment. ABB and Ericsson gained valuable experience from testing their cutting-edge energy and communication products in new areas, closer to the end customers than ever before.

When the Swedish Innovation Minister Mikael Damberg held a speech at the inauguration party he was impressed by the close co-operation between some of Sweden’s business giants – ABB, Ericsson and Electrolux, and hoped that this could be an example for the future. The results that are shown in this report suggests that this is a good idea.

For Fortum and me it has been an interesting, positive and fruitful dance with the dragons. Thank you!

Johan Ander, Program Manager – Smart Energy City
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SAMMANFATTNING


Nyckelrollen i programmet har innehafts av de 154 hushållen, som boende i nybyggda lägenheter i Norra Djurgårdssstaden. Dessa lägenheter var utrustade med smarta hemlösningar som möjliggjorde individuell energikontroll genom visualisering via en in-home display. På så sätt kunde hushållet påverka sin energiförbrukning genom att ändra belysning eller rumstemperatur, och låta tvättmaskinen bestämma den smartaste tiden att tvätta. För att motivera optimal energianvändning visualiserades hushållens förbrukning tillsammans med antingen finansiella eller miljömässiga signaler. Vidare undersökte programmet hur nätet kan bli mer effektivt och tillförlitligt genom nya krav och tekniska standarder.

Programmet visade att konsumenter reagerar både på finansiella och miljömässiga signaler, även om den finansiella signalen hade störst effekt. Förändringen i energiförbrukningen varierade mellan kundsegment, där singelhushåll och hyresgäster var mer flexibla än familjehushåll och bostadsägare. Vidare var förändringarna i energiförbrukningen under helger och helgdagar större och orsakade en positiv lastförskjutning, medan veckodagens beteendemönster verkade mindre flexibel. Sålunda är efterfrågeflexibilitet genom förändrat energibeteende möjligt och kan spela en stor roll vid framtida balansering av nätet. Hushållens flexibilitet kan dock begränsa denna förmåga, eftersom flertalet hushåll är låsta i dagliga rutiner. Att störa dessa rutiner och orsaka eventuella olägenheter kan därför kräva större/förändrade incitament.
SUMMARY

The urgent need to address climate change has created a rapid growth of renewable energy in the European power system. This development poses challenges in securing a stable electric grid, as renewable sources tend to be more volatile in nature and lack the ability to adapt to the instant power demand. Instead, a flexible demand that responds to the current power supply will be necessary to ensure an optimized power system. While technology driven demand flexibility can contribute to a more elastic electricity consumption, some flexibility can be unlocked solely with a changed energy behavior. The Smart Energy City program investigates the demand side flexibility at home, enabled by an increased reliability and availability in the smart grid. Thus, the program focuses on behavioral changes as well as the technical solutions that enable them.

The key players of the program were the 154 households, living in newly built apartments in the city district of the Stockholm Royal Seaport. These apartments were equipped with smart appliances that enabled individual energy control through visualization via an in-home tablet. In that way, tenants could impact their energy consumption by changing the lighting, modify room temperature and let the washing machine decide the smartest time to do laundry. To incentivize an optimal energy usage, the households responded to either financial or environmental signals. Furthermore, the program investigated how the grid can become more efficient and reliable through new requirements and technology standards.

The program found that consumers react both to financial and environmental signals, although the financial signal came with largest impact. The change in energy consumption varied between the customer segments, where single and rental households were more flexible than family and tenant-owned households. Furthermore, the changes in energy consumption during weekends and holidays were larger and caused positive load shift, whereas the weekday behavior seemed less flexible. Thus, demand flexibility through changed energy behavior is possible, and can play a large role in future balancing of the grid. However, the level of flexibility of a household can limit this ability as households are locked into daily routines. Interfering with these routines and causing potential inconvenience could therefore require larger/changed incentives.
1 INTRODUCTION

This chapter provides the necessary information regarding the motivations behind the Smart Energy City program. A brief description of the background, followed by a definition of the program’s purpose and a specification of the research questions will introduce the reader to the Smart Energy City program.

1.1 Making the Energy City smart

With a growing share of the world’s population living in urban areas, many of the challenges and opportunities of today are at their most visible in the cities. The urbanization could put an increasing pressure on vital resources such as energy, clean air, food, and water. A failure to ensure a sustainable urban development could therefore seriously amplify social discomfort and inequality. On the other hand, the continuing trend of urbanization highlights the role of the city as an enabler of social and economic development as well as a more sustainable living. The city is a natural meeting place for personal interactions, where new ideas and opportunities provide a good platform for development and innovation. Since urban areas are key contributors to the global energy consumption as well as to carbon dioxide emissions, the city represents a natural place to turn to when aiming to tackle these issues [1].

The energy system lays the foundation for the majority of urban infrastructure and services. Without it, transportation, district heating, and water distribution as we know it today would be impossible. The European energy landscape is however in the middle of a transformation accelerated by an urgent need to address climate change. Introducing decentralized, weather dependent energy sources creates a need to redefine the historical one-way distribution to a more communicative and dynamic energy system that is better equipped to respond to this new complexity. The so-called smart grid does not only facilitate the transformation towards a more dynamic and flexible energy system but will also have benefits in terms of increased efficiency, security and reduced costs [2].

With urban areas being the natural place for creating change, the smart energy system generates more value if incorporated into a larger system: the one of the city. The smart grid is just one of many components, all interconnected to optimize the use of resources and to improve the living quality of the inhabitants. But new technology alone might not guarantee a solution to climate change and a more complex energy distribution. The consciousness of the individual must merge with the technical system to change behavior and habits to coincide with a common goal. Our energy behavior is manifested by everything we do – and don’t do, such as
when we decide to wash our clothes or what products we buy in the supermarket. It originates from knowledge, culture, attitude and social norms.

Smarter technology provides a toolkit for individuals to extend the level of impact of their own energy behavior. Therefore, a smart energy city must use smart technology to facilitate smart behavior. The questions that remain are: will the inhabitants of a smart energy city act on this opportunity? What are the requirements, the incentives and the obstacles for creating behavioral change?

1.2 The drivers behind a Smart Energy City

Thanks to a combination of information and communication technology, the future electric grid will be able to monitor and collect large amounts of data and make advanced analysis and decisions based on that information. This will make it easier to predict peak loads, locate faults and perform maintenance on time. Likewise, the changing energy landscape requires the grid to understand and manage a more elastic energy market. The goal to decarbonize the electricity market has triggered an ever-increasing share of renewable energy sources to connect to our electricity networks. As renewable sources tend to be more volatile in nature they challenge the important aspect of securing power supply. Generally, the electricity consumption in low voltage networks, seen in Figure 1, reaches its peaks in the morning and most strongly in the early evening when people come home from work to cook dinner, watch TV etc. Having these peaks can be problematic as they require a larger total installed capacity and increase costs and carbon emissions. Furthermore, when supply becomes less controllable, it will not have the technical ability to adapt to the pattern of the electricity demand.

*Figure 1. Daily electricity consumption pattern*
Flexibility of the demand side will play a key role in the balancing of the electric grid as it adapts to the availability of supply. Load shifting involves shifting energy consumption to another period, typically when supply is higher, and the price is lower. The future energy management services will allow for smart appliances to adapt to the signals of the grid and shift their use of electricity in time. When supply is low, smart appliances will automatically modify the room temperature momentarily or briefly switch off the fridge in a way that minimizes interference in consumers’ daily life. However, demand flexibility is not only limited to automated devices. As energy cost is directly connected to supply, economic incentives could also trigger consumers to make active decisions about their electricity consumption.

Optimizing the new smart energy system does therefore require new ways to incorporate flexibility into the system. Today, a large focus in research lies on storage – especially battery based – as well as automatic energy management services. While technology driven demand flexibility can contribute to a more elastic electricity consumption, some flexibility can be unlocked solely with a changed energy behavior. Empirical studies on how changes in consumer behavior can affect the energy system are however rare, adding importance to the questions that are highlighted in this report.

1.3 Program arena – Stockholm Royal Seaport

The city district Stockholm Royal Seaport is Sweden’s largest urban development program. Located in the capital of Sweden, Stockholm, it runs along the waterline of the Baltic Sea and is planned to house at least 12,000 new homes and 35,000 workplaces by its completion in the 2030s [3]. The city of Stockholm’s intention for area to be a sustainable urban district and an international model for sustainable urban planning has set high standards to achieve a minimal environmental impact and be compatible with the 2 °C climate limit [4]. By incorporating sustainability across all sectors of the city, such as energy, transportation, buildings, and waste management, the aim is to ultimately become completely climate positive. In addition, the city aims for the Stockholm Royal Seaport to safeguard the local environment by pursuing biodiversity and ecological values.

The city district forms a center for research and development of the technology behind sustainable cities and has become the arena for several research programs. Here, businesses collaborate with research institutes and the academic community to create solutions that may be integrated into the system of the smart city. One of these research programs is the Smart Energy City program.
1.4 What is the Smart Energy City program?

The Smart Energy City program is a research collaboration between Fortum, Ellevio, ABB, Ericsson, Electrolux and the Royal Institute of Technology. With financial support from the Swedish Energy Agency, it investigated the flexibility of the electricity consumers through the development and implementation of smart home services, enabled by a more efficient, resilient and secure grid. The idea is based on two concepts related to the opportunities for consumer flexibility in the 1) Active House, enabled by an increased reliability and availability in the 2) Smart Grid. In the first concept, the focus lies on the consumers’ energy behavior enabled by conscious decision making at home, whereas the second concept revolves around technical solutions and development of the technology in the smart grid.

1.5 With the program households in focus

In January 2017, 154 families moved into new apartment buildings in the city district of the Stockholm Royal Seaport. These homes had been equipped with the Internet of things (IoT) based Home Energy Management Service (HEMS), allowing the occupants to monitor and control several features of the house from a mobile application and an in-home tablet. The families could change or turn off the lighting, modify the room temperature and let the washing machine and tumble drier decide the smartest time to do the laundry. The smart home could also provide information regarding water, electricity and heat usage and compare the energy consumption related to each activity. Furthermore, the system visualized real-time energy costs or associated climate impact, expressed through a dynamic electricity tariff. The 154 households were divided into two randomly selected subgroups, responding to either the energy cost signal or the climate impact signal. Through this separation, the Smart Energy City program could investigate how financial and environmental incentive create a shift of electricity consumption from peak hours to off-peak hours and compare the responsiveness of the households in the different subgroups.

These 154 households became the most important resource in the Smart Energy City program, representing the everyday behavior of the ordinary Swedish household. Through the digital, real-time visualization of the consumption, the families were offered the opportunity for increased energy awareness and to change behaviors depending on the displayed data. As the electric grid becomes smarter, these households demonstrated how human behavior can interact with the smart energy system and change along with its implementation. Understanding how consumers behave when given the opportunity to actively impact their own climate
footprint and energy bill is one of the cornerstones to understanding future demand flexibility.

Simultaneously, the technology behind the smart grid is of equal importance, acting as an enabler for consumer flexibility. To achieve this, the Smart Energy City program focused on the development and improvement of the electric grid and investigated how to improve reliability and operation via monitoring and collection of data in the low-voltage networks. The smart grid collects real-time information from various grid components and uses it to communicate the use of capacity, power quality, faults as well as general asset health indicators. The new technology of the smart grid-enabled a reduced peak load and increased energy efficiency. Thus, the ambition of the Smart Energy City program was to research the development and interaction of smart grids, homes with HEMS and its inhabitants, to create more sustainable and efficient solutions across the entire energy system.

1.6 The program ambitions and goals

The ambition of the Smart Energy City program was to investigate the flexibility of the electricity consumers through the development and implementation of smart home services, enabled by a more efficient, resilient and secure grid. The ambitions coincide and support the target of the Swedish Government to transform the electrical energy system into becoming fossil free by 2050 with well-defined intermediate goals for 2020 and 2030 [5]. The Smart Energy City program demonstrates how an urban area can contribute to reaching these targets.

The objectives of the Smart Energy City program can be summarized in the following six goals, where (1), (2) and (3) belongs to the Active House concept and (4), (5) and (6) belongs to the Smart Grid concept.

1.6.1 Active House goals

(1) Reduce the households’ environmental impact through changed energy behavior: Decrease climate footprint by creating incentives for reduction of energy consumption.

(2) Load shifting through price and environmental signals: Verify customers’ willingness to move consumption during peak load hours to off-peak load hours based on price and environmental signals.

(3) Identify drivers for changed energy behavior of households: Investigate effects of different smart home solutions on customer behavior such as energy visualization.
1.6.2 Smart Grid goals

(4) **Reduce no-load losses in secondary substation:** Reduce transformer no-load losses without risking life expectancy and power quality.

(5) **Improved grid reliability:** Achieve improved availability in the network measured via both CAIDI (Customer Average Interruption Duration Index, the average outage duration that any concerned customer would experience because of fault repair) and SAIDI (System Average Interruption Duration Index, the average outage duration for all customers served).

(6) **Achieve reliability in forecasts for demand response:** Test how well a smart grid urban network can forecast its customers day ahead consumption by the hour in a demand response context to optimize the use of grid capacity.

Since the initial scope of the Smart Energy City program was defined in 2010 – 2011, the global trends have experienced an explosive development in digitalization, connectivity of new technologies as well as within environmental requirements and awareness. The original goals were formulated in the preparatory phase when the application to the Swedish Energy Agency was drafted and have therefore been modified to match the evolving surroundings and the learnings made during the program. The original goals can be found in Appendix 1.

1.7 A cross-industry research collaboration

To keep up with the accelerating technological change, companies need to seek opportunities across multiple business sectors and not only focus on their own area. The ecosystem of cross-industry collaboration creates shared value outside of the company’s immediate environment, exploring new opportunities and boosting innovation. The Smart Energy City program spans several industries and forms a consortium that enables interdisciplinary research and innovation that mirrors the households’ daily life. Thanks to the collaboration of industrial partners from the electricity, automation, home appliance as well as information and communication technology industry, the solutions of this Smart Energy City program can contribute to new unique insights based on how changes in consumer behavior can enable a dynamic energy demand. The hope is that cross-industry collaboration will yield results that allow for the development of new research, commercial solutions and partnerships throughout the world. In this way, these solutions can be connected to other products, services and markets that can be used everywhere. The consortium partners and their ambitions of the Smart Energy City program is demonstrated in Table 1.
Furthermore, the construction companies NCC Boende AB (later Bonava AB, condominiums), HEBA Fastighets AB (rentals) and Byggnadsfirman Erik Wallin AB (condominiums) were key stakeholders and enablers of the program. They participated in the program through the construction of new apartment buildings in the Stockholm Royal Seaport and the installation of The Active House smart home equipment. In addition, they provided the program with data from the tenants such as hot tap water usage etc.

2 IMPLEMENTATION

2.1 Solutions

This chapter presents the system solution and the execution of the program. It will give an overview of the general system solution and dig deeper to describe the Smart Grid and Active House solutions respectively.
2.1.1 System solution

The 154 program apartments in the Smart Energy City program were completed in 2016 and consisted of 82 tenant-owned condominiums and 72 rental apartments. To validate outcomes and results from the program, data from 123 households living in comparable condominiums built a few years earlier – also in the Stockholm Royal Seaport location – were used as a reference. The Smart Energy City program was built on two concepts, the Active House and the Smart Grid, integrated into one larger system, as illustrated in Figure 2.

![Figure 2. Solutions Diagram of the Smart Energy City](image)

Each apartment in the Smart Energy City program is equipped with an in-home tablet and a mobile application that are connected via the home gateway to smart meters, smart devices and smart appliances within the apartment. Smart Grid sensors and Fault indicators are installed in the secondary substations and connected to a Smart Grid gateway that sends obtained data to the Smart Grid lab and partially directly to the control system SCADA (Supervisory Control and Data Acquisition). Lastly, the Active House and Smart Grid equipment sends data for research analytics to the Royal Institute of Technology concerning the utilization and behavior surrounding the in-home tablet and its features, the utilization of smart devices and the data collection in the substations and verification of goals. To generate accurate feedback to the tenants, hourly day-a-head spot prices are collected from Nord Pool power exchange and calculated to combined hourly based tariff including both the energy supply price and grid tariff for the next day into a
price signal. This price signal is used in the Demand Response algorithm, delivered by ABB and Ericsson, to schedule washing machines, dryers and electric vehicle charging. Furthermore, this data in combination with weather data and other data (such as load data) is used to do the forecasting, delivered by ABB.

2.1.2 Solutions of the Active House

The Active House is enabled by digital technology and smart equipment integrated into one smart home system, used to create awareness and ultimately behavioral change for a more comfortable and sustainable way of life.

2.1.2.1 Smart Home features

The IoT revolution has accelerated the launch of wireless devices that, connected to high-speed internet, enable the technology behind smart home systems. New energy efficient wireless protocols can be connected to smaller battery powered devices. This means cheaper and lighter products have become available to the market. Simultaneously, new ways of storing data allow for easier real-time energy analysis, which is a pre-requisite for a successful smart home system with energy visualization as a basic feature. Since today’s homes are equipped with powerful wireless technology that can facilitate connected devices, combined with falling technology costs and new ways to store data, more and more devices and home appliances can come online.

Home appliances connected to smart plugs allow for monitoring of real-time electricity consumption down to appliance-level. Smart lighting allows households to remotely turn lights on and off and to dim or brighten them when desired. Likewise, smart thermostats can be controlled remotely from both the in-home tablet and the mobile application and make it possible to increase or reduce the temperature in specific rooms. The smart washing machines and tumble dryers provide the possibility for users to delay the laundry to a point in time with lower cost or environmental impact, while still meeting requirements on desired completion time and result. Before initiating a cycle, the appliances communicate with the smart home application to gather information regarding the current cost or climate impact associated with the expected electricity consumption of the cycle. Based on this information, the consumer can delay the cycle to a time with lower cost or carbon footprint by using the in-home tablet.

The buildings in the Smart Energy City program have solar panels installed on the roofs and the electricity production can be observed on the display. In addition, EV charging poles are installed in the garage of the buildings for electrical vehicles. In the same way as for the washing machine and dryer, the charging poles are
connected to the in-home tablet and can be operated directly from the apartment. Thus, the system can help the EV owners to minimize cost or climate impact when charging their car, while causing no inconveniences and ensuring a full battery when desired.

2.1.2.2 Energy visualization
To allow households to interact and control the smart home technology, Fortum has developed a smart home solution specifically for the Smart Energy City program, providing the user interface to the smart home system. With the help of this smart home solution, households can control the home through several types of monitoring options and features through the in-home tablet and mobile application. The functionalities of the in-home displays are illustrated in Figure 3.

![Figure 3. Energy visualization functionalities](image)

The home screen of the in-home tablet, seen in Figure 4 and Figure 5, shows an overview of the electricity, hot tap water and heating consumption. The electricity consumption is visualized in real-time, while the tap water is an aggregated value spanning the past 24 hours. The heating consumption displayed is a calculated value. The measured energy used for heating of the whole building is divided by the building’s total square meter living space. The heating energy is then distributed
and displayed according to each apartment’s specific square meter living space. The electricity, hot tap water, and heating consumption can be compared to historical consumption, both daily and monthly, to show how each household’s energy usage evolve over time. The data can also be compared to peers, highlighted as a red, green or yellow curve in each of the three meters.

![Energy visualization home display](image)

*Figure 4. Energy visualization home display*

When leaving the apartment, the Away or Eco Away mode can be activated to switch off unused energy consuming activities and thereby reduce the household’s environmental impact and increase energy efficiency. When activating the Away mode, the ceiling lights turns off as well as the devices connected to the smart plugs, whereas the Eco Away mode in addition also reduces the set temperature on the thermostats by three degrees.
Thus, the energy visualization tool provides several ways to quantify energy usage. By displaying the real-time hourly electricity cost, or the relative environmental impact, the application can support users in making active choices regarding their consumption of electricity.

2.1.2.3 Incentives for demand response

To help short-term balancing when supply flexibility is limited, demand response seeks to adjust the demand to match the supply. Two types of demand response functionalities were tested via the Active House. First, the households were provided with several tools for behavioral change through the smart home features, such as scheduling functions for whitegoods and EV charging as well as the Eco Away mode, described in chapter 2.3.1 and 2.3.2. Second, the program aimed to create awareness by visualizing financial and environmental signals incentivizing reduced or shifted energy consumption.

All participating households were randomly divided into one of two groups with different incentives, either financial or environmental. By using two types of incentive, the Smart Energy City program could explore how the users react to both a financial and an environmental signal. The first group responded to a price tariff developed by the program, consisting of an hourly varying spot market price and a time of use distribution tariff, as the buildings were collectively measured with sub-metering per household. The relationship between the time and price is shown in Figure 6 and is at its largest of 1.6 SEK/kWh during peak hours and 0.6 SEK/kWh
during off-peak hours, a move of load valued at 1 SEK/kWh. These price levels were selected to ensure the participants in this group never had to pay more in total compared to what they would have paid if they were not part of the program (i.e. having the conventional electricity tariff). The participants in this group could keep the cost savings obtained when shifting consumption to times with relatively low prices. To investigate how the households would reduce or shift their electricity consumption during peak hours, the Smart Energy City program introduced a differentiated electricity tariff to stimulate behavioral change. The tariff in the program Smart Energy City was dynamic and consisted of a retail price as well as the grid tariff, excluding any fixed costs. In the program, the peak periods were defined between 06:00 – 09:00 and 17:00 – 21:00 for every day.

The second group responded to environmental incentives and did not get to keep any cost savings. Instead, the Smart Energy City program purchased carbon emission rights for the theoretical savings obtained by the households change in electricity consumption. The amount of carbon emission was communicated to the participants. The price and environmental impact histograms only differ in units,
where the financial signal is measured in SEK/kWh and the environmental signal is measured in “high” and “low” impact. They each display a straight stepping curve with values stretching over 24 hours with the existing time and value indicated by a large bright dot together with a text illustrating the value for that point.

2.1.3 Solutions of the Smart Grid
The Smart Grid solutions focus on the development and improvement of the electric grid, aiming to reduce losses as well as improve reliability and operation via monitoring and collection of data in the medium and low voltage networks. Therefore, the smart grid solutions are one of the most important enablers for introducing renewables to the grid.

2.1.3.1 Reduce load losses
No-load losses (P₀) are the constant losses in a transformer that is independent of the connected load, hence the name no-load losses. The losses are caused by the magnetizing current that powers the core of the transformer. These losses can be minimized in several ways. However, during the Smart Energy City program the European Union’s Ecodesign Directive and the succeeding standard SS-EN 50588-1 came into place introducing maximum load (P_k) and no-load losses as well as sound power levels (LWA) that governed the technical solution chosen. Three different approaches were investigated.

The first idea was to disconnect one out of two transformers during off-peak load periods to reduce the transformers’ no-load losses. Today, secondary substations in Stockholm often consist of two transformers. If disconnecting one transformer during off-peak load periods, the no-load losses of that transformer would be eliminated. The plan was to perform this by continuous measurement of power and local automation of the transformers’ circuit breakers. One drawback with this idea was the limited lifetime of the circuit breakers due to many operations as well as the high noise level when operating the breakers.

The second idea was to use a dry-type transformer with the amorphous metal core. Using amorphous metal core has the advantage that P₀ is low but the disadvantage is the high sound noise level – 82dB_A compared to maximum 67dB_A that Ellevio has as a requirement in its frame agreements.

The third and final idea that was also used in the Smart Energy City program was to put requirements of maximum values for P₀, P_k and LWA on the transformers delivered by ABB to the program. [6]
2.1.3.2 Automatic switch-over at power loss

Reliability in power supply is an important factor in power quality measurements. KPI’s such as SAIDI and SAIFI (System Average Interruption Frequency Index) specifically target duration and frequency of interruptions in power supply. As a tool to improve reliability in supply in urban areas, ABB implemented an automatic switch over solution between two stations as part of the Smart Energy City program. This made it possible to monitor the power supply to each station continuously. In the event of a supply interruption in one of the stations (A), the system would verify that the combined load of both stations could be handled by the other station (B). In those cases, the system was switched so that station B fed all end users of both stations. Simultaneously, the system continuously monitored the load levels during the supply interruption. Should the load level become too high the system would shed the load from customers connected to station A, minimizing the power supply interruption.

2.1.3.3 Improved grid reliability

The aim was to use big-data analytics from the Smart Grid lab with intelligent scheduling techniques to improve distribution-grid reliability index, SAIDI and CAIDI via predictive and conditional maintenance. Hence, to increase the reliability, avoid fatal errors, lower maintenance cost and to improve efficiency in local maintenance. To investigate this, monitoring and wireless communication equipment were installed in five of Ellevio’s secondary substations (transformation between medium and low voltage) together with ABB and Ericsson. Information was then remotely collected by sensors mounted in the secondary substation and sent via wireless communication to the network operation center. A schematic view of the secondary substation can be seen in Figure 7.
Generally, the secondary substations around Stockholm are locally operated and the monitoring is limited to a very basic remote communication, setting the “Basic monitoring level” seen in Table 2. Even though different sensors exist in the secondary substations, the only connected alarm that is possible to monitor remotely consist of a few unique alarms triggered by e.g. the fault indicators, used to detect short circuit and earth faults. When any of these alarms go off, it triggers a “sum alarm” just indicating that there is an alarm, lacking specific descriptions of the issue occurred. Furthermore, the sum alarm goes through signal cables to the primary substation (transformation between high and medium voltage) and from there to the SCADA system in the network operations center. Thus, the alarm sent to the network operations center only shows at which primary substation the alarm was triggered, that in turn is connected to several secondary substations.

Figure 7. Schematic view of the monitoring system of a secondary substation
Table 2. Functional Levels for monitoring

<table>
<thead>
<tr>
<th>OPERATING MODES</th>
<th>BASIC MONITORING LEVEL</th>
<th>LOW MONITORING LEVEL</th>
<th>MEDIUM MONITORING LEVEL</th>
<th>HIGH MONITORING LEVEL</th>
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<tr>
<td>Circuit-breakers</td>
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<td>Switch disconnectors</td>
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<th>MEASUREMENTS</th>
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<tbody>
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<td>LV</td>
<td>LV, temperatures</td>
<td>LV, temperatures, MV*,</td>
<td>LV, LV feeders*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FAULT INDICATORS</th>
<th>Short circuit and earth faults</th>
<th>Short circuit and earth faults</th>
<th>Short circuit and earth faults</th>
<th>Short circuit and earth faults</th>
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<tr>
<th>ALARM TYPE</th>
<th>Sum alarms</th>
<th>Alarms and events</th>
<th>Alarms and events</th>
<th>Alarms and events</th>
</tr>
</thead>
</table>

*Optional

For the Smart Energy City program, the functional level implemented in the secondary substations were either medium or high monitoring level. The high-level monitoring, also seen in Table 2, describes a situation where alarms, events, faults, operating modes, and various kinds of measurements are sent directly to the SCADA system, the distribution management system and the Smart Grid lab. This means that both the exact location and type of alarm will be specified, providing faster and more reliable detection of outages, location isolation of the faulted circuit as well as shortened restoration and repair time. Furthermore, the data collection can improve predictive maintenance as several types of data are collected and can be used to analyze the asset health of the substations’ components.

Two different systems for monitoring were installed in the five secondary substations: Ericsson provided the system for two substations (8410 and 8371) and ABB provided the system for three substations (8593, 8594 and 8343). Among these, two of the systems were installed in newly built secondary substations and three installed in already operating secondary substations. The systems provided by ABB had a high monitoring level, but the number of measurements varied between the systems. Ericsson’s system had a medium monitoring level. Table 3 shows an overview of the functionalities for each installation.

The ABB solution is designed to provide information on power data in high granularity. Measurements gathered in the substations is forwarded to the SCADA and Smart grid lab receiving points without restrictions. This big data approach
provides the operators with the opportunity to visualize consumption patterns, deviations in harmonics or any other from a vast range of KPIs. The historical database and Smart grid lab serve as tools for trend reports providing short and long-term data trends which can be used for fault detection and optimization of power quality.

In central Stockholm, the medium voltage network is designed as a double cable network, seen in Figure 8. In a secondary substation connected to the double cable network, the medium voltage switchgear has four cable bays connected to both cable systems with an automatic switch-over functionality. In station 8343, the automatic switch-over was installed already when the secondary substation was built. In both station 8593 and 8594 the medium voltage switchgear had two cable bays, and each station was connected to a separate cable system. The low voltage switchgear in both stations was interconnected with three low voltage feeders. This allowed for some degree of redundancy although not complete. Consequently, in stations 8593 and 8594 delivered by ABB, an automatic switch-over functionality had been implemented for the LV side. [6]
2.1.3.4 Increase use of grid capacity via demand response

Demand response can ensure that the installed grid capacity is utilized more efficiently. This means that the overall grid capacity can be reduced to fulfill the same energy demand over time. As the context and demand changes for a local grid when new houses are built that needs power supply, new services like Photo Voltaic (PV) generation and EV charging are connected to the grid, the grid will also be more resilient and need fewer investments in capacity upgrades if the existing capacity can be better utilized and optimized. Energy losses will also be lower if load balancing in the grid is better optimized.

In a demand response context as in Smart Energy City, where a Time of Use distribution tariff combined with a variable hourly tariff from the retailer is used, it will impact how the load is distributed, which is why the load forecasting was updated based on the new load patterns to take that into account. From a power grid operational point of view, the Smart Energy City program has investigated two specific event-driven demand response use cases, using the application of DRMS the Scheduled calculation and the Manual triggered by an unforeseen event. The Scheduled calculation is done one day ahead daily, using the updated load forecasting algorithm. In a scenario where the load forecast indicates that any load will exceed any load thresholds, an event will be sent to impact the scheduling of...
Electrical Vehicle (EV) charging as well as runs of washing machines and dryers. The manual triggered by unforeseen events reacts based on events that have not been considered in the forecast (e.g. failure in the grid). When such an event occurs, the DSO – Ellevio, can create a manual event that triggers a change in the scheduling of EV chargers and not yet started runs of washing machines and dryers.

Due to regulatory uncertainty of DSOs right to intervene in the demand response Smart Energy City program based on HEMS as well as the Smart Energy City program not wanting to interfere and give households conflicting demand response messages, these event-driven demand response use cases were not implemented in the scheduling used in the HEMS. The use cases were built on data collected from the Smart Energy City program and effects have been estimated by simulation.
2.1.4 Implementation history

The Smart Energy City program timeline is shown in Figure 9 and presents the key events and activities, kicking off with the partner contract in December 2013 to the completion of the final report in August 2018. Not shown in Figure 9 is the preparatory work before the official start of the program, such as the pre-study, establishment of agreement and application to the Swedish Energy Agency. The timeline is divided into one internal track demonstrating the partner activities and one external track presenting the events of the builders and other stakeholders.

Figure 9. Timeline of the Smart Energy City program

2.1.5 Market concept

In today’s Swedish electricity market, demand is inelastic as most residential consumers are charged flat grid tariffs and have their consumption metered monthly. Also, the price of electricity is often fixed by contract for a certain period, and even if it is variable it varies only from month to month. As investigated in the Smart Energy City program, consumers can change their energy consumption in response to dynamic tariffs or financial incentives when smart metering with hourly measurements are available. The aggregate load shift or load reduction provides flexibilities to the system and consequently brings notable benefits through the improvement of economic efficiency and reliability. The foreseeable increasing
price sensitivity of power demand together with larger price volatility due to more intermittent renewable energy sources brings challenges to retailers of both load forecast and planning. This can result in larger deviations between the purchased volume on the day-ahead market and the real-time consumption, jeopardizing grid balancing. Thus, a well-developed strategy for short-term bidding would be important as more demand response applications emerge in the future. Two studies were carried out as part of the Smart Energy City program to develop the short-term planning tools to set bids on the day ahead market with flexible demand [7] [8].

The study “Purchase bidding strategy for a retailer with flexible demands in the day-ahead electricity market,” proposes a framework for price-taker retailers to forecast the demand under dynamic tariffs and construct bidding curves for day-ahead trading. A bottom-up load model was developed to forecast the aggregate power demand of a residential customer group with dynamic tariffs, considering the flexibilities of a smart washing machine, tumble dryer, dishwasher, and EV charging. The model was then utilized in the day-ahead planning with stochastic programming to manage the uncertainties of spot price, regulating price, consumption behaviors, and responsiveness to dynamic tariffs and Conditional Value-at-Risk (CVaR) to consider the low-profit risk. An application of the stochastic planning is demonstrated in a case study based on data from Sweden, showing that a real-time selling price can affect the aggregate load of a residential consumer group and lead to load shift toward low-price periods. The optimal bidding curves for specific trading periods can be generated. By comparing the bidding strategies under different risk factors, the case study shows that a risk-averse retailer tends to adopt the strategies with larger imbalances. The benefit lies in the reduction of low-profit risk. However, the aversion to risk can only be kept to a certain level. A larger imbalance may lead to a quick reduction of profit in all scenarios [7] [8].

The second study, “Price-maker bidding in day-ahead electricity market for a retailer with flexible demands”, focuses on the short-term planning problem of price-maker retailers whose bids could influence the market price. The study proposes a stochastic optimization framework for price-maker retailers to determine their bids on day-ahead market. The method concerns the price and load uncertainties in day-ahead trading and imbalance settlement. Moreover, both CVaR and volume deviation risk are considered. After optimization, a piecewise bidding curve with multiple segments could be determined for each hour of the next day. Based on the proposed framework, a numerical study using the data from the Nordic electricity market is performed to investigate the influence of risk factors on the
retailer’s profit, risk levels, average spot price, and total consumption. Three types of price elasticity are compared to show that the retailer can benefit from the flexibility in demand side in some cases. The flexibility also leads to lower spot prices so that the customers in real-time price-based demand response can face a lower electricity price per unit power consumption [7] [8].

3 RESULTS

This chapter will provide the results that were obtained from this program. The first sections describes the findings related to the flexibility in the Active House and the second section describes the findings of the Smart Grid.

3.1 Results of the Active House

The Active House has investigated the consumers’ energy behavior to understand what triggers or facilitates reductions or shifts in energy consumption.

3.1.1 Electricity reduction is larger during winter

The electricity consumption of the 154 households can be seen in Figure 10 and illustrates an average annual reduction of 10% compared to the reference households. The decrease in consumption varies widely throughout the year and reaches its maximum during the colder months averaging -14% compared to -5% during the summer months. During the data collections, the largest reductions occurred during off-peak hours as opposed to peak hours, with a reduction of 12% and 4% respectively [9].
3.1.2 Tenants react positively to both environmental and financial signals, but the results differ

Figure 11 illustrates the annual mean relative changes in electricity consumption for households with price and environmental signals, respectively, in 2017. It illustrates that the mean reduction in overall electricity consumption among households with the price signal amounts to around -13%, whilst the corresponding figure for the households with the environmental signal was -7%. Furthermore, the reductions were much larger during off-peak hours compared to peak hours. For example, the mean relative change in electricity consumption during peak hours of households with the environmental signal was 0.1%, indicating no change in consumption. However, changes in the distribution of consumption varied considerably between individual households, where the coefficients of variation reveal that the normalized standard deviation in several cases amounts to more than one hundred percent [9].
3.1.3 Single and rental households are more flexible

During the data collection period, the mean electricity consumption was 2.0 MWh, 2.3 MWh and 2.9 MWh for single, couples and family households respectively, illustrated in Figure 12. Between these different households, the most prominent reductions were found among single households, with a mean electricity reduction of 17% for households with a financial signal and 16% for households with an environmental signal. In contrast, the reduction in family households were modest, ranging from -4% for households with a financial signal to -7% for households with an environmental signal. For couple households the difference between electricity reduction amongst households with a financial versus an environmental signal differed the most with a range from -17% to -6% respectively [10].
The electricity reduction among the households was further dependent on the type of apartment. The rental apartments showed greater reduction with an average of -15% compared to tenant-owned households with a reduction of electricity of 5%. Also, in these cases, the reduction was larger among households using the financial incentives and less for households with the environmental incentive, as seen in Figure 13 [10].
3.1.4 Load shifting shows weekend and holiday patterns

The load shift for each day during the data collection is plotted in Figure 14. Positive load shift shows in 110 days i.e. 41% of the total days. Among those days, the largest shift was 8.1% and the average shift was 3.3%. On the other hand, a negative load shift appears in 161 days i.e. 59% of the total days. Among those days, the largest shift was -8.5% and the average shift was -2.9%. The average load shift in the whole period was -0.4%.
The daily load shift shows apparent weekly and holiday patterns. For each week, the negative shift happened from Monday to Friday, whereas the positive shift happened on Saturday and Sunday. Figure 15 shows a comparison between the load of the program apartments and the reference load in a week. Generally, the peak load in the Smart Energy City program apartments is higher than the reference peak load on weekdays, explaining why the load shift appears to be negative on those days. On the other hand, the morning peak during the weekend is postponed which leads to a positive shift. Besides weekends, a positive shift occurs more frequently during holidays e.g. the Easter holidays, Midsummer, the summer vacation, the sports holidays, Christmas and New Year holidays [11].

![Figure 15. Example of a weekly load shift between 2018-8-21 and 2017-10-15](image)

3.1.5 Positive load shift although low utilization of smart washing machines and tumble dryers

During the data collection period, the total amount of washing cycles was recorded to 5270 for all the 154 program apartments. The household with the maximum utilization used their washing machine 229 times, while the average utilization was 37.4 cycles per household. Of the 5270 washes, 212 were delayed using the delay function, corresponding to 4% of the total washing cycles. In total 41 households used the scheduling delay function to postpone their laundry at least once. Among them, the most active household delayed their laundry 28 times, while the average utilization of the scheduled delay function was 5.1 times per household. Over the period of one week, the delay function was used primarily during weekdays than
during weekends. Figure 16 illustrates the length of delay for those cycles. The longest delay was 18 hours, while the average delay time was 5.5 hours.

![Figure 16. Length of delay](image)

The electricity consumption of the households that used the delay function for washing machines was between 1.8-24.2 kWh/day. Assuming the energy consumption is 1.35 kWh for a standard washing cycle (excluding tumble drying), the laundry can contribute to 5.6%-74.6% of daily consumption. Thus, 5.6%-74.6% of the daily consumption could be shifted if the scheduled delay function is well utilized. As shown in Figure 17, most laundry happens during the days and in the evenings. Comparing with the reference condition, laundry done between 6:00-9:00 and between 19:00-24:00 have been delayed the most, often to off-peak periods [11].
3.1.6 Variations in hot tap water consumption

The 154 program apartments and the 123 reference apartments are all individually measured for hot tap water consumption. The mean change in consumption can be seen in Figure 18. The average reduction for the program apartments was 7%. However, the data contained large variations between individual households across all parameters of analysis. The largest reduction was measured at 12% in the winter months of 2017 whereas there was an increase in hot tap water consumption of 11% during the same period in 2018 [9].

![Figure 17. The start time of washers](image17)

![Figure 18. Quarterly mean relative change in hot tap water consumption in condo households](image18)
3.1.7 The interviews

The Smart Energy City program performed interviews with fourteen of the tenants of the program apartments. A summary of the key findings is presented below, whereas the full report can be found in the report “Smart homes, home energy management systems and real-time feedback: a lesson for changing energy consuming behavior from a Swedish field study”[12].

The initial perception of the smart home solution was solely positive, and the interviewees expressed curiosity to gain increased behavioral awareness as well as increased comfort. In addition, the interviewees recognized both cost savings and environmental incentives as motivations to use the solution. Here, a strong majority of the interviewees mentioned the latter as the most important, partly as the current energy price was believed to be too low to yield significant cost savings. Even though the interviewees expressed intentions to reduce electricity consumption, many perceived their current electricity consumption as already low, with no room for further reductions. Several activities were considered difficult to change without negatively affecting the households living standards, such as cooking, laundry, and cleaning but also hot tap water use [12].

“Everything has a price I guess... I mean, I love taking a bath, but if I would find out that it costs me like 10 000 SEK per month to take a bath every day then I would need to really start thinking if it's worth it...”

As the technology was implemented, most of the interviewees believed the energy visualization tool had partially increased their knowledge of energy consumption behavior. The most mentioned type of gained knowledge was the increased awareness of the individual electricity consumption levels. The interviewees stated that they could recognize certain figures as their “standard level” or “individual baseline” of consumption [12].

“It's always there, so I threw an eye on it all the time. Like - what's our status, oh, I forgot the bathroom lamp. Then I turn it off.”

Thus, although households found it hard to interpret their own consumption level as low, high or medium, they recognized when their individual consumption was much higher than usual [12].

“This meter says 256 watts right now. It tells me nothing... am I high or low?”

As a response to the gained awareness, some interviewees could recognize sudden peaks compared to the reference point and consequently acts upon this information. Furthermore, several interviewees reported that they had the intention to use less
hot tap water, as an effect of more informed decision related to energy consumption [12].

“It [hot tap water consumption] is very easy to understand… to visualize in my head what I have used... like - oh, there goes ten liters during brushing my teeth - maybe I should have turned off the tap for a while…”

Concerning the comprehensiveness of the visualization tool, many interviewees expressed challenges in understanding the feedback to identify and optimize energy savings efforts. For example, there was a wish for feedback to be disaggregated to an appliance-specific level, at least on high consuming appliances such as a stove or dishwasher. In the absence of such feedback, interviewees used the historical comparison functionality to try to identify trends and remember the reasons why some days stood out from the rest. Furthermore, a majority stated that interpreting and relating to kilowatt-hours or CO₂ were perceived as difficult, while hot tap water consumption was easy to relate to. Thus, many interviewees requested a more relatable unit such as money, although no clear suggestion of how the signal could be designed was expressed [12].

“I’m not sure but maybe like... rain forest. It would be cool to sit at a dinner and say like – yesterday we saved X amount of rainforest. Especially as the economic savings are so small... I mean, compared to – yesterday we saved two kronor [laughs]…”

Furthermore, the interviewees perceived it difficult to use the scheduling function to run a washing machine or tumble dryer [12].

“It’s just much easier to use the display on the machine, to delay the cycle. I mean, I’m already there filling up the machine, there is just no reason to go find the display to start it from that”

3.2 Results of the Smart Grid

The Smart Grid has investigated the possibility to improve the availability and capacity of the network by reducing losses and improving predictive maintenance and fault repair by e.g. installing technology allowing for advanced monitoring and replacing signal cable network with wireless communication.

3.2.1 Reduce no-load losses in secondary substations

The first approach to disconnect one transformer during off-peak hours showed through simulations that the losses would decrease by between 0.1 and 20 percent, depending on the surrounding conditions such as the specific load curve and the transformer’s $P_0$ value [14]. With the implementation of EU’s Ecodesign Directive, the larger focus has been put on the no-load losses compared to the load losses. Since the approach is less useful for transformers with low $P_0$, the idea was skipped.
Next, for ABB’s dry-type transformer with the amorphous metal core, the no-load losses were 650 W, seen in Figure 19. This should be compared with $P_0 = 1800$ W for a dry-type 800 kVA 11/0.42 kV transformer in 2012, according to Ellevio’s internal policies the A-weighted sound power level for the transformer with the amorphous core (82 dB$_A$) is much higher compared with a transformer from Ellevio’s frame agreement 2012 (67 dB$_A$). Since decibel (dB) is a logarithmic unit, an increase with 10 dB means that the perception of the sound would be twice as strong. Since the transformers were to be installed in basements of residential buildings, the high sound noise level made it impossible to use a transformer with the amorphous core in these cases.

The final approach put requirements of maximum values for $P_0$, $P_k$ and $L_{WA}$ on the transformers delivered by ABB to the Smart Energy City program. The differences in the no-load losses for the transformers delivered by ABB compared with Ellevio’s standard transformer are $-630$ W, $+105$ W and $-130$ W in 2012, 2014 and 2017 respectively. Therefore, the reduction of the no-load losses for the secondary substations in the program compared with Ellevio’s standard secondary substations built during the period 2012-2017 were about 15 % on average [13].

Figure 19. Transformer losses [13]
3.2.2 Improved grid reliability

The concepts connected to grid reliability were tested for a relatively short time period compared to the high quality of the existing network. Thus, not enough incidents were reported to be able to draw long-term conclusions. Furthermore, the digital technology of substations was not installed in one complete loop to be able to fully automate corrective maintenance. While one outage occurred during the testing period, routines had not been updated to test the scenario of acting on more specific information during faults with secondary substations. Although more detailed fault information reached the network operating center, the specific location was already associated with one frequently occurring issue and the information was not observed. Thus, the technology for monitoring substation works successfully, but there is a need for establishing routines when dealing with the data if it were to be implemented.

The technology behind data collection proved to work successfully, although there is a need to specify the collection to improve asset health and predictive maintenance. For example, the Smart Energy City program collected maximum, minimum and average values for data such as current, voltage and temperature. The ambient temperature can estimate the loss of life of transformers as higher temperatures can cause shorter life expectancy. For secondary substations based inside, a sudden increase in ambient temperature can help to identifying a fan that has stopped working, and actions can be taken to increase asset health. If more detailed alarms and events were to be sent to network operating centers and proper routines would be implemented, it’s likely to assume that maintenance times would be shortened. Furthermore, if the data collected would be used to improve asset health and predictive maintenance, grid components would probably enjoy improved operations and life expectancy. Although the time frame of the Smart Energy City program is too short to make confident assumptions, CAIDI and SAIDI are likely to be improved due to the above results [13].

4 DISCUSSION

The following chapter will present the conclusion based on the findings in Chapter 3. Furthermore, the chapter will discuss the meaning of the findings on a larger scale, the lessons learned and the recommended future work within the field.
4.1 Conclusions
The conclusions are based on the results from the academic research that have been conducted in parallel with the Smart Energy City program. This section will analyze the obtained reductions in energy consumption and consumer flexibility and discuss its triggers and incentives.

4.1.1 HEMS can reduce electricity consumption
The first step towards change is awareness. To create a change in energy behavior, we need to inform households about their consumption levels, historical patterns, environmental and financial impact etc. Our findings show that using feedback related to energy consumption, energy cost, and environmental impact, has the potential to achieve reductions in households’ electricity consumption. In fact, although the results suggest wide variations across different types of household segments, several cases of significant reductions were observed. The reductions in this program could be the result of several factors: the price/environmental signal, the energy awareness, the interaction with technology etc. A key finding from the interviews with the tenants explains that the visualization tool worked as a speedometer for energy, providing the households with a standard level that helped households understand their individual electricity consumption. This type of awareness was particularly mentioned by interviewees with a fixed display installed in the hallway, rather than a free-standing display, where the accessibility allowed for more frequent interactions. Thus, although households found it hard to interpret their own consumption level as low, high or medium, they recognized sudden peaks compared to the reference point and could act upon this information. In addition, the tenants reported that the historical comparisons allowed for more informed decisions in terms of energy consumption, although more disaggregated feedback would considerably help households to further gain useful energy knowledge. Overall, tenants found it harder to comprehend the environmental signal and how it was related to actual environmental impact.

4.1.2 Variations explain the factors behind consumer flexibility
The findings of this program indicate that the success of consumer flexibility varies widely across different types of households, the incentives being used and what time the flexibility is requested. There are several potential explanations for the observed variations in effects. For instance, it is reasonable to believe that the number of obstacles for reduced household consumption increases by the number of residents, where differences in priorities and attitudes among household members may prevent energy-saving efforts. Single households, for example, are often younger people who assimilate technology better than the older generation.
Family households with children could also be more tied to fixed routines compared to single and couple households, not able to hold off activities such as cooking, cleaning, and washing to off-peak hours. Furthermore, our findings of greater reductions among rentals compared to tenant-owned households could potentially be explained by the fact that households living in rental apartments, a less expensive type of dwelling compared to tenant-owned, are more inclined to reduce electricity consumption for economic reasons.

The annual variations suggest that there is a larger potential for reduction in both absolute and relative terms during the winter months. As the electricity consumption is often larger during winter – we are in-home more, watch TV more, have our lights turned on longer etc. meaning that the awareness and total potential for energy savings increases. In contrast, the largest electricity reductions were performed during off-peak hours as opposed to peak hours. The household’s aspiration to reduce electricity consumption is not limited to peak hours only, while some peak hour-activities, such as having dinner, were perceived as non-negotiable to reduce or shift in time. In addition, it is possible that the number of flexible loads that could be shifted to off-peak hours without negatively impacting comfort was perceived as limited. Thus, the largest reduction in electricity consumption was achieved during off-peak hours, when the ability to be flexible was at its greatest.

These findings further suggest that the reductions were not exclusively a result of variations in price or environmental impact. As the largest reductions occurred during off-peak hours, it is reasonable to assume that the households took electricity reduction measures regardless the time of the day. Further, the interviews indicate that the financial incentive of 1 SEK/kWh used in the program was insufficient to create behavioral change. It is, therefore, a reasonable assumption that larger variations in electricity price could have greater impacts than in this program. Despite this, the results indicate a strong advantage of financial incentives as the more efficient strategy to boost consumer engagement. This result is particularly interesting when noting that the studied population differs from the national average in terms of both educational level as well as a higher income. In addition, these households live in an urban area with a strong sustainability profile. Interviews with households presented the reduced environmental impact as the main motivation behind energy conservation efforts, mentioned in section 3.2.6, however the environmental signal that was tested in the project showed a different result. The discontent expressed by the households related to the environmental signal could in part be explained by the communication, absolute value, and design of the signal.
4.1.3 Consumers’ flexibility offer ability to shift load
Despite the predominantly relative negative load shift, the findings demonstrate that all occasions of positive shift (41%) occur during weekends or holidays. During these times, tenants tend to be more flexible and was, therefore, more willing to reduce their consumption when needed. Thus, the load shift occurred both during peak load and off-peak load, although the off-peak load reductions were larger. It is likely that households aim to act towards being more responsive and flexible but are at the same time lacking the actual ability to do so. Dependent on various factors such as household type and size, time of the day and year etc. households are locked into daily routines that limit the ability to change energy behavior. Interfering with these routines and causing potential inconvenience does therefore probably require larger incentives, also backed up by the interviews held. Several interviewees expressed that their electricity consumption lacked room for further reductions without a significant negative impact on living standards. Simultaneously, all interviewees stated that the economic incentive would have been more motivational if energy prices would increase significantly from today’s levels. It’s reasonable to conclude that as the day ahead spot electricity price is an instrument with low volatility on the Swedish market, it’s not properly reflecting the demand of flexibility and consequently resulting in too low incentives for load shifting.

4.1.4 Average washer delay time tells us about future flexibility
The findings indicate a significant low utilization rate of the delay function on the appliances, even though a third of the households tried it at least once. However, it is possible that the households delayed the machines manually, also indicated by the interviews held. This could explain why most of the delayed cycles were activated during weekdays when the tenants were not at home and could control the laundry from the apartment. The washes were mostly shifted from peak to off-peak hours, therefore contributing to a positive load shift. Given the price difference between peak and off-peak hours of 0.7 – 0.8 SEK/kWh, the largest cost savings could reach around 1 SEK/cycle. Hence, the price signal is a relatively weak incentive in the program. Larger price differentiation and cost savings could most likely improve future consumer flexibility. Lastly, the limited use of the delay function could be explained by the uncertainties regarding its functionalities and purpose. Thus, it’s important to recognize the feedback from the households to optimize the user-friendliness of the visualization tool in the future, as explained in chapter 4.2.

Taking advantage of consumer flexibility to improve balancing the electric grid can be expanded to several different types of white goods, where a few could even be
considered as more suitable for demand response compared to the washing machines and tumble dryers in the Smart Energy City program. The manual step of moving the laundry between the washing machine and dryer forces the households to be at home at least in close connection to the washing machine’s finishing time. Thus, using more flexible white goods without the need for manual interference could potentially give more clear results. The Smart Energy City program has demonstrated that the technical potential exists to use home appliances as flexible resources to balance renewable generation and shaving peak load etc. Thus, it is important to quantitively understand the duration and capacity of the end consumers flexibility before a specific technical solution is delivered. Therefore, knowing how many people are willing to shift their laundry time and the acceptable length of delay brings valuable insights to those aspects. According to the findings, this key finding of the average delay time amounts to 5.5 hours.

4.2 Lessons learned

The Smart Energy City program has been developed in a cross-industry ecosystem spanning the electricity, automation, home appliance as well as information and communication technology business sector. This ecosystem has brought creativity and innovation but has also challenged the partners through communication and collaboration. The collaboration has highlighted the technical and commercial similarities and the difference in requirements in the telecom and utility industry. At distance, the similarities might shadow the differences. When penetrating the industry logic, business context, legacy, and requirements, there are also significant differences that are easy to underestimate. Without a doubt, the utility industry will be consuming a lot of IoT and cellular technologies, wireless, in its digitalization that has already started. Still, dominant design of IoT and cellular (5G) technologies for Smart Grids and utility industry is not yet fully ready, we will likely see new business and go-to-market models – partly depending on regulation and lack of international standards – addressing the industry before we see the exponential growth many analysts and experts expect.

Connected products tend to link several industries and companies together and call for a close collaboration to ensure a proper customer experience. For example, the solutions of the Active House were connected to a combined system with components from Electrolux, Ericsson, and Fortum. If any part of the system were to break, the Smart Energy City program must ensure proper customer support without necessarily knowing the root cause for the problem. Thus, customer services must be adapted to this ecosystem to ensure proper support if parts of the systems fail.
4.3 Learnings lead to business opportunities

The experiences of the Smart Energy City program have brought forth new commercial products that accelerate the development towards a more dynamic electricity market. Fortum’s SmartLiving has emerged to meet the growing demand for smart home products and acquired Tingcore, a platform for several new services and products used in the Smart Energy City. Another example is Electrolux, who have gained valuable experiences and insights in terms of delivering connected products, that have been used to develop and commercialize new connected products.

The findings from the Smart Energy City program have also given rise to several new projects to further develop results and outcomes. To understand the specifications and need for data storage in substations, Ellevio has worked together with key partners such as ABB and Ericsson to further develop and establish new best Smart Grid solutions and practices with learnings from the program. Ellevio has engaged Foreseeti, a start-up in cybersec originating from Innoenergy, to review the risks in the Smart Grid. Furthermore, the Smart Energy City program has strengthened the digitalization trend and the company works to customize and install related technology such as fault indicators.

4.4 Recommendations

Based on the learnings from the Smart Energy City program, four key recommendations have been formed to guide future projects, initiatives, and solutions.

1) A differentiated technology need calls for individual solutions

The expectations and requests for new technology among end users show large variation that must be met when new solutions are developed. For example, some users enjoy the detailed information and are motivated by profound and wide-ranging data while others prefer a high-level overview to grasp new information. Thus, technology such as the HEMS solution must be able to meet the needs of multiple users, by offering several modes and functionalities. The Smart Energy City program recommends that tools associated with providing information to end users in the Active House offer multiple modes and that each consumer can customize its features to fit their individual need.
2) **Demand response requires multiple mediums to be efficient**
   The day ahead market was used in the Smart Energy City program to generate daily signals regarding price and environmental impact. However, short-term balancing gaps are often discovered in short notice, calling for additional solutions to trigger demand response. The intraday market is on an hourly basis and could be one option that better responds to immediate differences in supply and demand. Furthermore, automatic systems could be an even better alternative in terms of faster responsiveness to demand response signals, such as a brief modification of room temperature.

3) **Solution design must focus on meaningful visualization**
   How units and signals are described is a vital component to make energy visualization comprehensible. E.g. failing to describe a unit that quantifies the environmental impact in a way that is understood by the energy consumer negatively impacts the probability for behavioral change. The environmental impact such as carbon dioxide emissions and energy-related measurements such as kilowatt hours are not easily understood by the average end consumer. Although changes in historical patterns are clearly visualized, it’s important to put these values in a context: are they high or low? Both more meaningful information and information that is easier to comprehend should be visualized so that a technical understanding is not required from the end customer.

4) **Wireless technology for monitoring of secondary substations**
   Wireless technology is a suitable communication for several of the electric grids requirements. Wireless technologies are much cheaper to deploy, and the cellular technology used in the program has proven to be robust in various weather conditions. Furthermore, the solution is much more flexible and scalable compared to wired solutions. Wireless technology is also secure, but it requires different methods and solutions than wired connectivity. Thus, it is important to consider the right security measures when using wireless communication specifically suitable for each different application in the grid to ensure cybersecurity.
5 COMMUNICATION

The learnings and findings from the Smart Energy City program have been shared in several forums by the partners as well as other actors on behalf of the program.

5.1 Events

In Table 4 the events related to the Smart Energy City program are summarized. The events include kick offs, demonstrations, presentations and panel discussions among else and have taken place throughout the world.

<table>
<thead>
<tr>
<th>Event title</th>
<th>Location</th>
<th>Date</th>
<th>Presented by</th>
</tr>
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<tbody>
<tr>
<td>Kick off</td>
<td>Stockholm</td>
<td>29 April 2015</td>
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<tr>
<td>Why doesn’t EMS take off in the consumer market</td>
<td>European Utility Week, Vienna,</td>
<td>4 November 2015</td>
<td>Marcus Törnqvist &amp; Johan Ander</td>
</tr>
<tr>
<td>Why doesn’t EMS take off in the consumer market</td>
<td>Engerati</td>
<td>19 November 2015</td>
<td>Marcus Törnqvist &amp; Johan Ander</td>
</tr>
<tr>
<td>SRS Panel i Almedalen</td>
<td>Visby</td>
<td>5 July 2016</td>
<td>Johan Ander, Marcus Törnqvist, Anders Hellqvist among others</td>
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<tr>
<td>Inauguration</td>
<td>Stockholm, Fortum Campus Värtan</td>
<td>17 November 2016</td>
<td></td>
</tr>
<tr>
<td>Launch of <a href="http://www.smartenergycity.se">www.smartenergycity.se</a></td>
<td>Web</td>
<td>27th of June 2017</td>
<td>NA</td>
</tr>
<tr>
<td>I Norra Djurgårdsstaden är smartahemsprojektet i full gång, vad visar de första resultaten</td>
<td>Visby, SRS Panel in Almedalen</td>
<td>4th of July 2017</td>
<td>Johan Ander, Marcus Törnqvist, Mats Nissling, Sara bargi, Pia Brantgärde Linder, Cecilia Nord</td>
</tr>
<tr>
<td>IoT based HEMS delivers energy efficiency in Stockholm Royal Seaport</td>
<td>European Utility Week, Amsterdam</td>
<td>4th of October 2017</td>
<td>Marcus Törnqvist &amp; Johan Ander</td>
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<tr>
<td>IoT based HEMS delivers energy efficiency in Stockholm Royal Seaport</td>
<td>Engerati, webcast</td>
<td>10th of November 2017</td>
<td>Marcus Törnqvist &amp; Johan Ander</td>
</tr>
<tr>
<td>Demonstration at Utility Week</td>
<td>Barcelona</td>
<td>14-16th of November 2016</td>
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<tr>
<td>Demonstration at CES 2017</td>
<td>Las Vegas</td>
<td>5-8th of January 2017</td>
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<tr>
<td>Demonstration at Mobile World Congress</td>
<td>Barcelona</td>
<td>27th of February-2nd of March 2017</td>
<td></td>
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<tr>
<td>CIRED International Conference on Electricity Distribution</td>
<td>Glasgow</td>
<td>12 - 15 June 2017</td>
<td>Joar Johansson</td>
</tr>
<tr>
<td>Demonstration at Net Futures</td>
<td>Brussels</td>
<td>28-29th of June 2017</td>
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</table>

### 5.2 Awards and recognitions

The awards and recognitions of the Smart Energy City program are shown below.

- **Swedish Embassies** global campaign of Swedish innovations, Smart Energy City program is one of 10 programs on display, 2017-2018.

- **Permanent Demonstration of Smart Energy City program concept in Ericsson Studio in Kista**, 2017-2018. More than 20 000 visitors seeing the demo every year from all over the world. Many of them participating in workshops including the topic of Smart and Sustainable Cities with Smart Energy City program as the key reference.
6 REFERENCES


7 APPENDICES – LIST OF PUBLICATIONS

7.1 Appendix 1: Original program goals

The original objectives of the Smart Energy City program can be summarized in the following seven goals, where (1), (2) and (3) belongs to the Active House concept and (4), (5), (6) and (7) belongs to the Smart Grid concept.

7.1.1 Active House goals
(1) Reduce CO2 emissions from 633 kg per household / year to 436 kg / household and year

(2) Move 5% and 15% of energy from peak load hours by getting end users to act on price and CO2 information

(3) Identify the visualization system’s effect on customer behavior and attitude in daily life through interviews with residents

7.1.2 Smart grid goals
(4) Reduce idling losses in the substation by 15%

(5) Achieve improved outage management by 10% or more CAIDI compared to the reference area

(6) Achieve improved outage management by 20% or more SAIDI compared to the reference area

(7) Achieve reliability in forecasts for Demand Response by +/ - 10% vs. measured load reduction

7.2 Appendices 2-17: Doctoral thesis, conference papers, articles and Master theses


Appendix 3: Conference: Estimating the price elasticity of residential power demand using a bottom-up approach - Meng Song, Mikael Amelin, Department of Electric Power and Energy Systems, Royal Institute of Technology, Stockholm, Sweden
Appendix 4: Conference: **Impacts of flexible demand on the reliability of power systems** - Meng Song and Mikael Amelin, Department of Electric Power and Energy Systems, Royal Institute of Technology, Stockholm, Sweden, and Ebrahim Shayesteh and Patrik Hilber, Department of Electromagnetic Engineering, Royal Institute of Technology, Stockholm, Sweden

Appendix 5: Conference: **Improving the efficiency of a hydro-thermal power system utilizing demand-side flexibility** - Meng Song, Mikael Amelin, Department of Electric Power Systems, Royal Institute of Technology, Stockholm, Sweden


Appendix 8: Journal: **Price-Maker Bidding in Day-Ahead Electricity Market for a Retailer With Flexible Demands** - Meng Song, Student Member, IEEE, and Mikael Amelin, Member, IEEE (IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 33, NO. 2, MARCH 2018)

Appendix 9: Journal: **Purchase Bidding Strategy for a Retailer With Flexible Demands in Day-Ahead Electricity Market** - Meng Song, Student Member, IEEE, and Mikael Amelin, Member, IEEE (IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 32, NO. 3, MAY 2017)


Appendix 12: Master thesis: **Evaluation methods for market models used in smart grids, an application for the Stockholm Royal Seaport** - Mikael Skillbäck and Hany Ibrahim, School of Industrial Technology and Management,
Department of Energy Technology, Royal Institute of Technology, Stockholm, Sweden


Appendix 14: Master thesis: The potential of residential demand response to reduce losses in an urban low-voltage distribution grid – Reinout Daels, School of electrical engineering, Department of Electric Power and Energy Systems, Royal Institute of Technology, Stockholm, Sweden

Appendix 15: Master thesis: Market concepts and regulatory bottlenecks for smart distribution grids in EU countries - Yalin Huang and Henrik Olsson

Appendix 16: Journal: Household responsiveness to residential demand response strategies: Results and policy implications from a Swedish field study - Nilsson, A., Division of Industrial Ecology, Department of Sustainable Development, Environmental Science and Engineering, School of Architecture and the Built Environment, Royal Institute of Technology (KTH), Stockholm, Sweden and Lazarevic, D., Division of Industrial Ecology, Department of Sustainable Development, Environmental Science and Engineering, School of Architecture and the Built Environment, Royal Institute of Technology (KTH), Stockholm, Sweden, 2018 (Energy Policy, 122; 273-286).

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Appendix 17: Journal: Smart homes, home energy management systems and real-time feedback: Lessons for influencing household energy consumption from a Swedish field study - Nilsson, A., Department of Sustainable Development, Environmental Science and Engineering, School of Architecture and the Built Environment, Royal Institute of Technology (KTH), Stockholm, Sweden and, Wester, M., Division of Risk Management and Societal Safety, Lund University, Lund, Sweden and, Lazarevic, D., Brandt, N., Department of Sustainable Development, Environmental Science and Engineering, School of Architecture and the Built Environment, Royal Institute of Technology (KTH), Stockholm, Sweden, 2018 (Energy and Buildings; 179; 15-25)

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