A Study of the Potential Impact of Smart Thermostats on Residential Energy Efficiency and Demand Response in North America

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Submitted to MIT Sloan School of Management on May 6, 2016 in Partial fulfillment of the requirements for the Degree of Master of Science in Management Studies

ABSTRACT

This thesis evaluates the potential impact of smart thermostats on the residential energy efficiency and demand response in North America. Smart thermostats are rapidly gaining popularity, and our estimations indicate that today there are more than nine million units already installed in North America. Electric utilities have recently started pilot programs known as Bring Your Own Thermostat (BYOT) through which they subsidize part of the smart thermostat that their customers install in their homes in exchange for taking command of the settings certain hours per day during for a few summer days. Currently, there are only about 50,000 homeowners enrolled in BYOT programs in the USA, but the expectation that smart thermostats can impact energy efficiency and change the residential demand response (DR) landscape is high.

Using System Dynamics, this thesis has examined this potential, and the results show that the smart thermostats, in the business as usual case, can save about 60 TWh/year of electricity (or the continuous production of about fifteen 500MW coal plants – or Rosenfelds by 2025). If programs such as BYOT, where part of the thermostat is subsidized, were going to be popularized, this number can almost double. And additionally, this technology is creating an important potential in the residential demand response space, which is also studied in this thesis.

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INTRODUCTION

Background

In November 2011, Nest launched the first smart thermostat (according to the definition of smart thermostat considered in this thesis). Soon after other vendors such as Ecobee or Honeywell launched competing products to the market. Popularity has been phenomenal, and our estimations indicate that today there are more than nine million smart thermostats already installed in North America.

Smart thermostats are beautifully designed; learn your habits, so you don’t have to worry about changing settings, they “smile” at you in the morning, adapt the temperature considering the weather, etc. In summary, they make your home more comfortable, and you can even control and monitor them through The Internet while saving energy at the same time. These last two characteristics, the access through The Internet and the energy savings factor place the smart thermostats in an unusual position in the crossroads of residential energy efficiency and demand response.

Electric utilities have realized that this small device can open the doors of their customers for them. Several utility companies in the USA (mostly) and Canada (See Appendix II for details) have started some pilot programs known as Bring Your Own Thermostat (BYOT), a new concept of residential demand response (Lacey). Through these programs, utilities subsidize part of the thermostat in exchange for taking command of the settings a certain number of hours per day during a few summer days. So far, there are only about 50,000 homeowners enrolled in BYOT programs across North America (“Bring Your Own Thermostat Demand Response”), but the expectation that this technology can change the residential demand response landscape is high.
The residential sector in the USA accounts for as much as 21% of the total energy needed, including 37% of the electricity consumed in the country. So, it represents an excellent opportunity with a lot of potential, but it is challenging to reach given the high number of customers, geographical distribution, significant fragmentation with multiple utilities operating in different territories and smaller loads on a per individual basis compared with Commercial and Industrial customers. Demand response in the residential sector has been traditionally limited to utility level programs, whereas Independent System Operators (ISOs), the entities that ensure the stability of the grids in the different territories, have not considered residential demand response within what they call “Load Resources”, or load available to curtail when needed.

Why is demand response so important? Unfortunately, electricity cannot be stored at large scale yet. This particular characteristic determines the dynamics of the technology, infrastructure, and markets for electricity. An example of this is the problem of the Peak Demand. The popularization of A/C systems in residences and the recent warmer summers are creating significant demand at certain hours of the day for a few days each year.

![Figure 1: Percent of homes with AC in USA](graph.png)
To cover this demand and avoid grid blackouts the electrical systems are designed with large overcapacity, both in generation and transportation and distribution, which remain idle or unutilised most of the year, waiting to provide the required power. Additionally, the introduction of more and more renewable sources in the grid is adding fluctuation to the generation capacity, which also needs to be accounted for to guarantee grid stability.

Demand response programs are a way to reduce this variability by actively acting on the demand side. In the USA, for several years, many electric utilities have run various types of demand response programs aimed at the residential sector by free issuing to their customers’ switches or thermostats to disconnect some loads such as the water heater or the A/C remotely during the critical hours of the day. But these programs are costly and require a high logistical effort for the utilities. Also, they have the main drawback of the lack of feedback or confirmation on whether the customer accepted the shutdown command or otherwise opted out of the event. In this situation, the utility does not have full clarity on the amount of load that they can count on.
for that particular event ("Residential Demand Response"). The arrival of Smart Thermostats and programs such as BYOT can change this landscape dramatically, and this is what is analyzed in this paper.

BYOT resolves most of the main problems of the traditional Demand Response Programs mentioned above. The cost for the utilities is lower since they don’t have to invest in creating a dedicated connection network or providing and installing the thermostats. Additionally, they can know in real time what is the acceptance rate of the settings indicated, so the available load for curtailment is more visible and transparent ("Bring Your Own Thermostat Demand Response"). For the customers, it seems that the modified settings do not impact much on their comfort, given the high rate of acceptance of the settings reaching up to 86% in some pilots (Rush Hours Rewards), while saving energy and money at the same time.

Objectives of Thesis and Approach to Address the Problem

The aim of this thesis is to analyze in detail the potential of the smart thermostats concerning energy efficiency and demand response in the residential sector in North America. And more particularly, we will examine in detail the case of HVAC systems fed from electricity: Air Conditioning and Electric Furnaces and Heat Pumps. The savings associated with less consumption of natural gas has not been studied in this paper.

The approach to addressing the problem is as follows: First, the potential for energy savings on a per thermostat basis is analyzed considering both, information from vendors as well as studies from several independent entities. For smart thermostats the energy efficiency part comes intrinsically associated with the technology, so, once the product is installed, the savings start to accumulate. Second, using a System Dynamics model we have modeled the adoption and diffusion of the technology in North America under different scenarios such as complete lack of
subsidies to heavy subsidies through BYOT. If the utilities want to be able to control the settings of their customers’ thermostats, they will need to persuade these customers to join the utility’s BYOT program, and most likely this will need to be done through financial incentives.

It is not the objective of this thesis to analyze the competition between the different vendors of smart thermostats. Instead, the goal is to understand the dynamics of the diffusion of the technology in the market and evaluate the impact that this innovation can have in the energy efficiency and demand response in the residential sector.

**Data Collection Methods**

For this thesis, we have required historical data about the current penetration of the technology in the market, about prices and also about the performance of the devices on their capabilities regarding energy efficiency and demand response. In particular, there are five primary variables that we required collecting data about; Purchase Rate, Adoption fraction and Average Price as well as Energy Savings per Unit and Demand Response Load. Out of those five, the most difficult to obtain has been the Purchase Rate, given that the main market players such as Nest, Ecobee or Honeywell do not publish their sales.

The data included here has been obtained taking as a basis the information from several research companies that have issued priced reports with their analyzes and forecasts. By doing this research, we observed that these numbers vary considerably from company to company, so a rationalization of the data using additional sources was required before selecting our final data. The fourth section of this paper develops this process in detail.

**Summary of Thesis Sections**

Including this introductory section, this thesis has seven sections. The second section contains a description of the main smart thermostats in the North American market, including
features, technologies and platforms. The third section discusses some of the demand response and energy efficiency programs currently run in the USA and frames BYOT within this landscape. The fourth section develops the historical data collection process, rationalization and our final selection of the data. The fifth section explains the System Dynamics model used for this thesis, as well as the results of the simulations for different case scenarios. The sixth section contains a hypothetical case study applied to ERCOT, the independent system operator (ISO) in Texas, and the seventh and last section is the conclusion.

SMART THERMOSTATS

This section develops several aspects of the smart thermostats. The first sub-section details our definition of smart thermostats and compares it with a different type of thermostats known as connected. The second part describes each one of the five top smart thermostats in the North American market today and contains technical data about the devices, their key characteristics, compatibility with home automation platforms, etc and is organized following the launching date of the products, from older to newer.

Smart Vs. Connected

As previously indicated, this paper focuses only on smart thermostats. It is required then to clarify what is a smart thermostat and compare it with connected thermostats. And this is not a simple distinction. Even within the industry, different manufacturers have different opinions of what smart means (Anesi). Some manufacturers call smart thermostats to those that can time-period scheduling, automatically control humidity and temperature and efficiently control comfort, are compatible with other home automation systems and are accessible through the
Internet. In this thesis, this type of thermostats is considered as connected or communicating thermostats.

Other manufacturers are more specific and define smart thermostats as those that respond to inputs such as occupancy, weather and customer preferences. Also, can make decisions based on the data they receive from other system components, making adjustments in the operation that go beyond a simple response to set points and can do this without user input. This is achieved through backend platforms and data gathering and analytics oriented to optimize HVAC settings for comfort and energy consumption. This definition of a smart thermostat is the one that we consider in this paper.

**Main Smart Thermostats in the North American Market**

The North American market for smart thermostats is growing quickly, and many new makes and models appear continuously. However, covering all the products in detail is not the purpose of this thesis. Here, we are covering the five most popular products in North America today: Nest, Ecobee 3 and Ecobee Smart Si, Honeywell Smart and Honeywell Lyric.

**Nest Labs Learning Thermostat**

Considering our accepted definition for smart thermostats, Nest represented the first of this type to be brought to the market. First Nests were shipped in November 2011 (Fehrenbacher, “Introducing a Thermostat Steve Jobs Would Love”). With a beautiful design and a learning algorithm, this product changed the concept of thermostats.

Nest learns what temperature the customer likes at different times and builds a schedule around this. And most importantly, the vendor claims that since 2011, the Nest Thermostat has saved more than 4 billion kWh of energy in millions of homes worldwide. Nest calculates total savings by estimating how much energy all their customers would have used if they hadn’t
bought a Nest Thermostat and just left their old thermostats at a constant temperature. Additionally, independent studies showed that it saved people an average of 10-12% on heating bills and 15% on cooling bills ("Meet the Nest Learning Thermostat").

![Nest Thermostat](image)

**Figure 3: Nest Thermostat**

Regarding connectivity and platform, Nest has created what they call "Works with Nest" ("Nest Introduces Nest Weave, Creating Most Comprehensive Developer Platform for the Home"). "Works with Nest" is an online platform where Nest-compatible products such as home appliances, security, fire sensors, lighting, etc. can be purchased. All these products communicate using Nest Weave, a protocol created by Nest (IPv6 based) for all the connected devices.

Concerning energy savings, Nest has created what they call Rush Hours Rewards ("What Is Rush Hour Rewards?"). Rush Hour Rewards is the Nest platform that the electric utilities use when they offer BYOT programs to their customers. Unlike other smart thermostat vendors that allow third parties to control their thermostats, Nest integrates the service from end to end. We will see more of this in the section dedicated to BYOT.
Ecobee's Smart SI Thermostat

The Ecobee Smart SI Thermostat was the second product of this type to be launched to the market in April 2012 (Castle). In fairness, we must say that Ecobee was the first company to put in the market an Internet Wi-Fi connected thermostat back in 2009 ("Ecobee Smart Si Smart WiFi Thermostat"), but this first model did not have any learning or smart capabilities as we have defined it for this Thesis. The first smart Ecobee thermostat considered here was, therefore, this one:

![Ecobee's Smart SI Thermostat](image)

**Figure 4: Ecobee's Smart SI Thermostat**

The Ecobee Smart SI Thermostat Smart Si intuitively understands when to turn on the heating or cooling equipment based on customer home's unique energy profile and the weather outside.

Honeywell's Wi-Fi Smart Thermostat

Honeywell’s Wi-Fi Smart Thermostat was launched in April 2013 ("Honeywell Renovates The Thermostat Market With An Elegant Wi-Fi Connected Thermostat For Do-It-Yourselfers"). The Honeywell Wi-Fi Smart Thermostat takes more of a traditional approach to effective heating and cooling. It has a rectangular design that mimics a lot of the programmable thermostats on the market today. But, it also manages to offer a similar Nest learning algorithm style of functionality.
Honeywell’s Wi-Fi Smart Thermostat learns your heating/cooling cycles and then optimizes to deliver the right temperature at the right time.

**Honeywell's Lyric Thermostat**

Honeywell Lyric was launched to the market in August 2014 ("Honeywell Launches Lyric Smart Thermostat to Take on Nest | Gigaom") and it was designed to compete directly with the Nest. But, instead of a Nest-style learning algorithm or Ecobee3-type adaptive sensors, the Lyric relies on geofencing. Geofencing allows setting up either a 500-foot or 7-mile range on the smartphone and when it senses that the owner is out of range, it will auto-set to Away mode. When it detects the smartphone back within range, it will resume the Home mode to prepare the home for arrival. Also, the Honeywell Lyric considers the outdoors temperature and humidity to adapt the internal temperature of the home.
Honeywell Lyric works with Apple’s Homekit and Samsung’s SmartThings, two of the most popular smart home platforms in the market. The partnership with Apple’s HomeKit is recent; it was announced just in January 2016 (Kastrenakes).

Regarding energy management, Honeywell has partnered with EnergyHub to allow consumers to enroll Honeywell thermostats in utility programs such as BYOT ("Honeywell API and Ecosystem Integrations").

Ecobee’s Ecobee3 Smart Thermostat

Ecobee 3 was launched in September 2014 ("What Was the Release/Launch Date of the ecobee3?"). Its approach is slightly different to the others since it uses additional sensors distributed around the home to detect and learn the customer’s habits. According to the manufacturer website ("ecobee3: Smart Algorithms and Features | Smart WiFi Thermostats by Ecobee"), it uses thousands of data points to make intelligent and personalized heating and cooling decisions to save energy, improve customer’s home heating and cooling performance, and make it more comfortable.
Ecobee3 understands how the home heats up and cools down, and uses Wi-Fi to track the local weather throughout the day. It uses this information to determine the best way to bring home to the desired temperature and maintain it while minimizing energy consumption. Additionally, ecobee3 remote sensors allow different temperatures in different rooms.

Ecobee 3 was the first thermostat to be included in Apple’s HomeKit in July 2015, (Tilley) and is also included in Samsung’s SmartThings platform.

As Honeywell, Ecobee has also partnered with EnergyHub to allow consumers to enroll Ecobee’s thermostats in utility programs such as BYOT (“HydroOne Enroll My Thermostats”).

**HOME ENERGY MANAGEMENT**

The residential sector accounts for as much as 21% of the total energy consumed in the USA and about 37% of the electricity consumed in the country. So, it represents an excellent opportunity but is challenging to reach given the number of customers, geographical distribution, the existence of multiple utilities operating in different territories and smaller loads on a per individual basis compared with Commercial and Industrial (C&I). However, new technologies such as cloud computing and IoT are changing this landscape.
As already introduced in the description of the thermostats in the previous section, Honeywell and Ecobee have partnered EnergyHub to offer to the electric utilities the technology required for the deployment of BYOT programs. We also saw that Nest has developed their system called Rush Hours Rewards, avoiding the partnerships with third parties. These are examples of Home Energy Management Systems (HEMS): Software platforms developed independently of a particular device that can openly connect to and control communicating thermostats through application programming interfaces (APIs). These platforms are cloud-based, and though they include a standard control portal for customers (i.e., a web portal, a mobile app, or both), their value is in optimizing energy efficiency (EE), demand side management (DSM) or the integration of both.

Bring Your Own Thermostat (BYOT) is an example of demand response programs (DR), a subtype of DSM. Another example of DSM is dynamic pricing: variable price depending on the timing, which is supported by Advanced Metering Information (AMI).

On the Energy Efficiency side, examples of applications of new technologies are energy bill disaggregation, fault detection, efficiency feedback, personalized energy reports, smart appliances and lighting and also smart thermostats.

Navigant Research on their report *Assessment of Strategy and Execution for 16 HEM Vendors* assess the software or platform aspect of the market: “the emphasis is on vendors providing insight and engagement applications across the HEM continuum that enable residential users to attain greater energy efficiency in their homes” (Leuschner, Strother, and Callaway).
Navigant identifies Opower and Google (Nest Labs) as the leaders in the HEM market in Strategy (aspects such as Vision, Go-to-Market, Partners, Technology and Geographic Reach) and Execution (aspects such as Sales and Marketing, Product Performance, Product Quality and Reliability, Product Portfolio, Ecosystem and Staying Power).

As already discussed, EnergyHub has developed a platform that serves as an interface between the thermostat manufacturers and the electric utilities.
In this section, we focus mainly on the two areas where smart thermostats are having most of the prominence these days: demand response through BYOT and energy efficiency through savings in the operation of the HVAC system. Additionally, a subsection highlighting a new potential area of interest called behavioral demand response and energy efficiency is included.

**Demand Response: Bring Your Own Thermostat (BYOT)**

**Background**

Utilities across the United States have been piloting bring your own thermostat (BYOT) demand response (DR) programs since 2012. BYOT refers to utility policies that allow customers to purchase their device from multiple potential vendors but still participate in DR and other load curtailing programs managed through the utility. BYOT DR programs take advantage of two-way communicating smart thermostats, and can help utilities reduce acquisition costs and improve customer satisfaction. Typically, homeowners in the areas served by the participant utilities can get a partial rebate on the purchase of a smart thermostat if they join the program. Through these programs, the utility and the homeowner will sign an agreement for typically two years whereby the utility can act on the settings of the thermostat remotely to control the temperature in the situations of peak demand. The conditions vary slightly from utility to utility but these tend to include a variation of up to 4 degrees and 12 to 15 events per summer.

The idea is not new: Thermostats have been used in the past as part of residential demand response programs since, in many US states, the demand peak was aggravated by the increasing number of A/C machines. However, the innovation now comes with the technology employed. In the past, the thermostats were utility free-issued, one-way communicated, so and the utility did not have any feedback about reception or acceptance of events. The new Wi-Fi thermostats allow
for a much more full communication and continuous monitoring during the event, as well as precooling before the rush hour.

**Current Deployment**

Today, about 50,000 customers are engaged in utility pilot-scale BYOT DR programs across North America ("Bring Your Own Thermostat Demand Response"). These customers are mostly concentrated in five states of the country: California, Texas, NY, Illinois, Minnesota and Pennsylvania. The following figure shows the geographical distribution of the current deployment.

![Utility BYOT Deployments, United States: 2010-2015](image)

**Figure 10: BYOT Deployments in the USA**

Additionally, Appendix II contains a chart summarizing the different programs and their primary characteristics.

The author has been able to interview several representatives of some of the utilities that have implemented pilot programs and they indicate that the customer acceptance and interest on the programs is very high (Stoll).
Compatible HVAC Systems

For BYOT DR programs, the critical load considered so far has been the air conditioning machine in the summer time. However, some vendors such as Nest have already extended the concept to the winter season. For these systems to work properly, the air conditioning must be of centralized type and the heating system must be a heat pump or electric furnace. These systems may deliver heat through in-floor or wall mounted radiators or forced air vents. And obviously, the smart thermostat must control them.

Energy Efficiency: Savings with Smart Thermostats

Background

Twenty-four states are currently implementing energy efficiency resource standard (EERS) policies requiring electricity savings.

An energy efficiency resource standard (EERS) is a long-term (3+ years), binding energy savings target for utilities or third-party program administrators. Savings are achieved through...
energy efficiency programs for customers. An EERS is one of the most effective ways for a state to guarantee long-term energy savings. In 2013, states with an EERS achieved incremental electricity savings of 1.1% of retail sales on average, compared with average savings of 0.3% in states without an EERS (*State Energy Efficiency Resource Standards (EERS)*).

How can smart thermostats help utilities to achieve this? As we mentioned in the introduction and will develop in the following subsection, one of the key characteristics of the smart thermostats is their energy saving feature. If we superimpose Figures 10 and 11, we see that all the current BYOT deployments are found in states with EERS. This might be a good indicator of the willingness of the utilities operating in those states to explore new ways of making their systems more efficient and reliable.

![Figure 12: Superposed of Figures 10 and 11 – BYOT and EERS policies in the USA](image)

**SMART THERMOSTATS - DATA AND FORECASTS**

As discussed in the Smart vs. Connected section, the first smart thermostat considered in this thesis is Nest, and that shipped for the first time in November 2011. So, the historical data goes only about four years back in time.
As we will see later, to calibrate our System Dynamics model we need data on five variables, which are divided into two groups:

- Purchase Rate, Adoption fraction, and Average Price: These three variables are historical data related to the adoption and pricing of the smart thermostats.

- Energy savings and demand response capability: We have obtained these two variables from various pilots and studies.

Out of those five variables, the most challenging to get has been the Purchase Rate. Finding actual data about the number of Smart Thermostats sold up to date has proven tough. The main market players such as Nest, Ecobee or Honeywell do not publish their sales, so we have obtained the data included from several research companies such as Berg Insight, Parks Associates, IOT Analytics, Navigant Research and Mordor Intelligence that have issued priced reports including their analyzes and forecasts. Unfortunately, these reports have not been available for us, so the data included here has been obtained from the free excerpts in the form of summaries or press releases that these companies offer in their websites, and that contain highlights and the essential information about their findings.

As we will see in the following sub-sections, the findings of these companies differ considerably from one another. Also, the geographical focus of the studies varies from company to company: Info from Parks Associates refers to the USA only, Berg Insight’s information relates to North America, and the other three data sources are worldwide focused. The case of IOT Analytics is particular insofar it provides data for the world and market share for North America so that it can be utilized for both.

The next subsections further describe these datasets as well as the assumptions and techniques employed to select our final dataset.
Historical Data on Purchase Rate, Installed Base and Growth Forecasts

Parks Associates

Parks Associates is a market analyst and research company providing information to companies offering technology-based products. It was founded in 1986 in Dallas, Texas.

Parks Associates’ report on the Smart Thermostats market (Kerber) focuses on the USA market only. As we can see in the Figures 13 and 14, according to Parks Associates, the number of Smart Thermostats sold during 2013 was about 2 million in the US market alone. The quantities represented on these graphs for the subsequent years, including their forecast, translate to a growth of about 20% CAGR.

![Thermostat Units Sold in U.S. (#M)](image)

Figure 13: Thermostat Units Sold in the US – Parks Associates

It is also interesting to see how Parks Associates estimate that most of the sales will come from retail channel and from HVAC channel.
IOT Analytics

IOT Analytics is a market research/industry analysis firm focused on the Internet of Things and founded in 2014 in Germany. According to IOT Analytics ("Global Smart Thermostat Market Grew 123% in 2015, Smart Home Becoming Mainstream"), the number of Smart Thermostats sold worldwide in 2015 was more than 4.8 million out of which 70% were sold in North America which equals to 3.4M. IOT Analytics has come up with these numbers based on a model that considers the number of downloads of thermostat-related apps.

On the same report, IOT Analytics forecasts growth for Smart Thermostat to be approximately 60% in the short term (We assume it refers to 2016) and 35% annual growth foreseen for the next six years.
Global Smart Thermostat unit sales grew +123% in 2015
Sales topped 800k devices in December 2015; increase largely driven by Q4/2015

Smart Thermostats market (# of devices sold worldwide per month)

Source: IOT Analytics

Figure 15: Global Smart Thermostats sales – IOT Analytics

Navigant Research

Navigant Research is a market research and consulting team that provides analysis of clean technology markets. According to Navigant’s Smart Thermostats Report (Levy, Callaway, and Lockhart), worldwide shipments of communicating and smart thermostats are expected to grow from 926,000 annually in 2014 to 19.2 million by 2023, or about 40% CAGR.

Berg Insight

According to Berg Insight, a Swedish market research firm, the number of homes in North America and Europe with a smart thermostat grew by 105 percent to 3.2 million in 2014. The North American market recorded a 107 percent growth in the installed base of smart thermostats to 2.5 million by the end of 2014. Berg Insight forecasts that North America will remain the largest market at the end of 2019 with 24.6 million homes that have smart thermostats.
("The Number of Homes with Smart Thermostats Doubled in 2014"). So, for the North American Market, this means a CAGR of about 58% from the beginning of the series in 2013.

**Figure 16: Installed base according to Berg Insight**

**Mordor Intelligence**

Mordor Intelligence is a small market research and consulting firm located in Hyderabad, India. In their report "Global Smart Thermostat Market – By Geography and Vendors – Forecasts, Trends and Shares (2015-2020)", the company estimates that there were more than 1 million installed thermostats in 2014. And that this number will go up to 30 million by the end of 2020, or about 76% CAGR ("Global Smart Thermostat Market | Smart Thermostat Market Analysis").

**Comparison of Data**

As we have seen in the previous sub-sections, the available data is not homogeneous regarding values, geographies, growth rates, etc. The following graph summarizes the data collected from the different mentioned above:
There are a few important points to highlight. For example, the worldwide numbers for 2014 according to Navigant Research are close to one million units, whereas the other two companies report higher numbers for North America and USA alone. Parks Associates indicates 3.4M units in the USA only and IOT Analytics report circa 2.5M for the North American market. Also, the growth expectation changes considerably from company to company.

Certain variability in the growth forecasts was anticipated, but the vast differences observed in the data regarding the past years sales was unexpected by the author.

**Data Selection and Reasoning**

Given this variability in the data about the number of units sold so far, we have analyzed additional sources of information to try to figure out a final set of data to calibrate our System Dynamics model. To do so, we have considered different events such as the dates of the launch of the various products, significant changes such as entering or exiting from Apple Stores and
expansion to Europe. Also, we have gathered additional data from other sources regarding estimations of sales and other types of news such as CEO declarations or comparisons regarding market share. In other words, we have used many different sources to try to create a set of numbers that made us feel confident enough to proceed. The next paragraphs, along with the numerical data in Appendix I put all of this together.

Nest represented the first smart thermostat that appeared on the market in November 2011 (Fehrenbacher, “Introducing a Thermostat Steve Jobs Would Love”). Second was Ecobee Smart SI Thermostat, launched in April 2012 (Castle). Third was Honeywell Wi-Fi Smart Thermostat in April 2013 (“Honeywell Renovates The Thermostat Market With An Elegant Wi-Fi Connected Thermostat For Do-It-Yourselfers”). Fourth was Honeywell Lyric launched in August 2014 (“Honeywell Launches Lyric Smart Thermostat to Take on Nest | Gigaom”) and fifth and last was Ecobee 3, in September 2014 (“What Was the Release/Launch Date of the ecobee3?”). Ecobee 3 was included in Apple’s HomeKit in July 2015, which helped them boost their sales in the second half of the year (Tilley). At the same time, Apple removed Nest from their stores (Tomek) and finally Honeywell Lyric joined Apple’s HomeKit in January 2016 (Kastrenakes). These are the main players in the North American market of Smart Thermostats, and this timeline is relevant to reason our final data.

Reasoning for 2013 final data

In January 2013, Nest raised $80 million of funding, and that event attracted a lot of attention. Several media news estimated that between 40,000 and 50,000 Nests were getting shipped per month at that point (Fehrenbacher, “Nest Has Raised Another $80M, Now Shipping 40K+ Thermostats a Month”). When Nest was acquired in February 2014 by Google, some
commentators argued that Nest had sold in total one million thermostats up to then (Higginbotham).

Additionally, almost at the same time in February 2014, Ecobee’s CEO Stuart Lombard declared that Ecobee had sold a little less than 500,000 thermostats since their founding in 2007 (Higginbotham). It is to be noticed that the first Ecobee’s smart thermostat considered here is their April 2012 model. Finally, in April 2013, the Honeywell’s Wi-Fi Smart Thermostat was launched. So, how many units can we reasonably consider in 2013?

If we accept the given numbers, by February 2014 Nest had sold one million units of their thermostat since they started in November 2011. And we also know that in January 2013 they were shipping about 40,000 to 50,000 units per month and growing. If we assume a linear progression, starting at 40,000 in January 2013 and ending at 62,000 in December 2013, or an average of about 51,000 units per month during 2013, this gives us about 612,000 Nests sold in 2013.

Ecobee’s CEO declarations in February 2014 about having sold less than 500,000 units since their beginnings along with the launch of their first truly smart device in April 2012 give us some clues. If we assume their Smart SI Thermostat was accounting for a little more than half of that total cumulative 500,000 by February 2014, and a progressive ramping from the launch in April 2012, this gives us some 186,000 Ecobees sold in 2013.

Honeywell data is the scarcest. We know little, but we are aware that they launched their first Smart Thermostat in April 2013. If we assume a sales rate somehow double than that of the beginnings of Ecobee (given Honeywell’s extensive commercial network and experience), we obtain a number of about 90,000 Honeywell Smart Thermostats in 2013.
Once we add the above numbers for Nest, Ecobee and Honeywell, we obtain 888,000 Smart thermostats sold by these three manufacturers in 2013 in North America.

Appendix I develops these figures on a monthly basis.

**Reasoning for 2014 final data**

The available data for 2014 is not much. We know that Google (now Alphabet) has reported in their 2015 10-K that the increase of revenues of $315 million of their “Other Bets” during 2014 is primarily due to their acquisition of Nest (Alphabet 2015 10-K 28). Selling at about $250 per unit, this represents about 1.2 million Nests shipped in 2014 or an average of 100,000 units per month, representing an increase of about 100% Nest sales from previous year: from about 612,000 to 1.2 million.

If we consider the same increase in sales for Ecobee, we have a number of about 360,000 units sold in 2014. Ecobee launched their Ecobee 3 in September.

Finally, for Honeywell, who also launched their Lyric thermostat in August 2014, given the reasons explained before of their commercial network, expertise, etc. we have considered a monthly rate of sales slightly more than that of Ecobee, giving a number of Honeywell Smart Thermostats sold of about 400,000 during 2014.

Putting all this together, we have a number close to the two million smart thermostats from these three vendors in 2014.

**Reasoning for 2015 final data**

On the same 10-K report, Alphabet declares 2015 revenues of “Other Bets” at $448 million. Alphabet does not break this income down, but clarifies as follows: “Revenues from the Other Bets is derived primarily through the sales of Nest hardware products, internet and TV services through Google Fiber and licensing and R&D services through Verily”. So, if we
assume about 400 of those 448 million revenues coming from Nest, at the same selling price of $250 per unit, this represents about 1.6 million units sold in 2015.

2015 Some estimators believe that Ecobee sold about one million Thermostats in 2015 ("Global Smart Thermostat Market | Smart Thermostat Market Analysis") and Honeywell was third closely to Ecobee. In Appendix I – Monthly Calculations, we can see that we have considered 978,000 units of Ecobee and 936,000 of Honeywell.

Putting all of this together, it gives us a total of a bit more than 3.5 million in 2015 for these three manufacturers.

Conclusions

As explained in the previous sub-sections, using a combination of multiple data sources, we have estimated units sold for the three main vendors in the North American market during 2013, 2014 and 2015. We are going to assume that these three vendors account for about 90% of the market share, so we will add a fourth group to account for all the rest of the competition starting in 2013.

Also, to close the gap until November 2011, which will be considered the first month of this technology, we have considered that about 250,000 Nests and about 45,000 Ecobees were sold in 2012. Honeywell did not have any smart thermostat in the market yet.

The summary of the numbers that we will consider for our model is as follows:
Including the market share taken by “Others” the numbers finally considered are as follows: For 2011 is about 12,000, for 2012 about 300,000, for 2013 about 1 million, for 2014 2.1 million and for 2015 3.9 million. On Figure 18 we have also represented the smart thermostat installed base that results from this data.

Our estimation is reasonably close to that of IOT Analytics for the studied period. Those of Parks Associates are slightly higher (and only account for the USA), and those of Navigant Research and are much lower than ours and account for the whole world. Figure 19 shows this.
The research and reasoning carried out to come up with our final numbers as well as the comparison with the information from the research companies, give us confidence that what we are proposing is reasonable.

**Data on Energy Savings and Demand Response**

**Energy Savings**

The energy savings data considered in this thesis comes from four studies:

- **The Energy Trust of Oregon study** of Nest thermostats used with electric heat pump heating. The Energy Trust found that the thermostats saved 12% on heating electricity use. This represents 781kWh per year or 4.7% of total electric usage (Energy Trust of Oregon - Nest Thermostat Heat Pump Control Pilot Evaluation 1–1).

- **Vectren**, an electricity and natural gas utility in southern Indiana, carried out a study of Nest thermostats and found that they saved 14% on air-conditioning electric usage (Aarish et al., *Evaluation of the 2013-2014 Programmable and Smart Thermostat Program - Prepared for Vectren Corporation*). This represents 429kWh per year for cooling or about 4% of the total electric use.

- **NIPSCO**, an electric and gas utility in northern Indiana did a similar study with similar results: 16% savings on air-conditioning electric usage (Aarish et al., *Evaluation of the 2013-2014 Programmable and Smart Thermostat Program - Prepared for Northern Indiana Public Service Company*). In this case, this represents 388 kWh per year for cooling or about 3.9% of the total electric use.

- **Nest** has done its own study on Nest users across the country (624 homes in 39 different states) and found an average 17.5% savings on air-conditioning electric usage (Energy
Savings from the Nest Learning Thermostat: Energy Bill Analysis Results. This represents 585 kWh per year.

Additionally, Ecobee declares on their website that customers in the US save 23% of their heating and cooling costs ("Saving Money with Ecobee Smart WiFi Thermostats | Smart WiFi Thermostats by Ecobee").

**Demand Response**

The individual potential for demand response reducing power has been tested in several pilots (see Appendix II) and also by Nest (Rush Hours Rewards 3) and found to be in the range of 0.79 to 1.18 kW.

**Historical Data on Price**

Nest sells at $249 and it has had the same price from its launch in 2011 (Smith). Ecobee 3 and Honeywell Lyric also have the same price. To calculate the price we have discounted this price to date using the historic official inflation in the US ("Historic Inflation United States – Historic CPI Inflation United States"). Historic inflation United States (CPI) compares the December CPI to the December CPI of the year before.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Price @ 2016 value S</td>
<td>268.7</td>
<td>261.0</td>
<td>256.5</td>
<td>252.7</td>
<td>250.8</td>
<td>249.0</td>
</tr>
</tbody>
</table>

**Table 1: Historical Price for Smart Thermostats**

**Historical Data on Adoption Rate**

For the calculation of the Adoption Rate, we consider only the occupied households in USA and Canada. The rest of the countries in North America need to develop their markets for smart thermostats yet (Callaway and Strother), so they are disregarded. In 2015 there were about 125 million occupied households in the USA ("Number of Households in the U.S. 1960-2015 |
Statistic”) and about 13.8 million in Canada (“Canadian Households in 2011: Type and Growth”).

Data from 2009 indicates that, in the USA, about 65% of the dwellings have central air conditioning and about 12% use electric heat pump (US Census Bureau Public Information). The US Census Bureau also indicates that in 2009, 38.6 million of the 113.1 million occupied homes used electricity as heating fuel or a percentage of 34% of the used homes, showing that about 24% of the American dwellings should use electric or dual fuel furnaces.

![Table showing heating fuel usage in the United States in 2009](image)

Source: U.S. Census Bureau, 2007-2009 American Community Survey

**Figure 20: Heating fuel for US residences in 2009**

In Canada, in 2009, half of the homes (50%) reported having some air conditioning system. There were two types of air conditioning systems used in Canadian households in 2009: central air conditioning (central AC) and standalone air conditioning (standalone AC). More than two-thirds of Canadian households that used air conditioning to cool their homes were equipped with central AC (68%) in 2009 (“EnviroStats: Summertime Control of Temperature in Canadian Homes: How Canadians Keep Their Cool”). If we apply these percentages to the 13.8 million used homes in Canada, it gives about 5 million homes with central AC.
Regarding the heating system for Canadian homes, the type of heating fuel used is related to the kind of heating equipment used. In 2011, natural gas was used to heat 50% of Canadian homes, followed by electricity (39%) (Government of Canada).

<table>
<thead>
<tr>
<th>Year</th>
<th>USA</th>
<th>Canada</th>
<th>Central AC</th>
<th>% Cent AC</th>
<th>Electric Heating</th>
<th>% Elect Heat</th>
<th>Smart Th Installed Base</th>
<th>Adoption Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>124.59</td>
<td>13.84</td>
<td>85.69</td>
<td>69%</td>
<td>47.76</td>
<td>38%</td>
<td>7.3198</td>
<td>5.288%</td>
</tr>
<tr>
<td>2014</td>
<td>123.23</td>
<td>13.71</td>
<td>84.76</td>
<td>69%</td>
<td>47.24</td>
<td>38%</td>
<td>3.4115</td>
<td>2.491%</td>
</tr>
<tr>
<td>2013</td>
<td>122.46</td>
<td>13.57</td>
<td>84.21</td>
<td>69%</td>
<td>46.93</td>
<td>38%</td>
<td>1.2808</td>
<td>0.942%</td>
</tr>
<tr>
<td>2012</td>
<td>121.08</td>
<td>13.43</td>
<td>83.27</td>
<td>69%</td>
<td>46.41</td>
<td>38%</td>
<td>0.304</td>
<td>0.226%</td>
</tr>
<tr>
<td>2011</td>
<td>118.68</td>
<td>13.3</td>
<td>81.67</td>
<td>69%</td>
<td>45.54</td>
<td>38%</td>
<td>0.012</td>
<td>0.009%</td>
</tr>
</tbody>
</table>

Table 2: Summary of findings on Adoption Rate

SYSTEM DYNAMICS MODEL

The System Dynamics model used in this thesis is based on the model developed by Professor John Sterman and studied in the Introduction to System Dynamics Course at MIT Sloan (Sterman and Keith) and (Sterman 359). The model was originally developed to study the adoption and diffusion of the videocassette recorder (VCR) industry and is based on the traditional S-Curve. The S-Curve is a framework to analyze the dynamics of new products and technologies. Many products go through S-Curve type lifecycles. Examples include the telephone, microwaves, DVD players, mobile phones, VCRs and Facebook. The growth in S-Shaped curves arises from reinforcing feedbacks that, with time, become less dominant and yield to balancing loops as the population still to adopt becomes less numerous.

For this thesis, the original model developed by Professor Sterman has been adapted to account for certain particularities that we want to study here, but fundamentally it has the same structure that the original model.

VCRs and Smart Thermostats are products with many similar characteristics from the point of view of adoption mechanisms. This observation drove the idea of applying Professor
Sterman’s model here. The next sub-section is dedicated to outlining the main similarities and differences between the VCR and the Smart Thermostats.

**VCR vs. Smart Thermostats**

**Similarities**

- Both technologies mainly designed for residential use and could be subjected to similar learning curve for cost reduction
- Both technologies gain value with complementors or contents - In the case of the VCR the abundance of pre-recorded movies was one of the key winning points of the VHS format vs. Betamax. In the case of Smart Thermostats, the mentioned programs from utilities, but also the existence of other smart home gadgets such as security, CCTV, lighting, automatic blinds, etc.
- Strong WOM - Especially between friends and family
- Path Dependence - “Works with Nest”, Apple’s Homekit or Samsung SmartThings are platforms with different communication protocols for all the connected devices. So, as soon as the customer buys either one, and some additional hardware to make their homes smarter, the switching cost is large, and the customer is locked in that particular platform
- Typically is a “one piece for family” kind of product
- Comfort and Savings: both technologies help customers to be more comfortable in their homes. VCRs allowed people watching movies in their homes whenever they wanted and maybe even save some money vs. going to the cinema. Smart Thermostats have some of the same characteristics: a mixed of comfort and savings (but on this case savings might be more relevant than on the VCR case)
- Probably similar life expectancies 6-8 years
Differences

- Utilities, residential builders, home automation providers, and heating, ventilation, and air conditioning (HVAC) system installers are key stakeholders in the adoption of smart thermostats, often acting as the primary gateway for end-user adoption.
- Unlike the VCR, the smart thermostats will replace an existing device.
- The installation of the smart thermostat can be a technical problem for some households, who might need to call a professional in and pay the installation fee.
- The Environmental Reasons component that might exist in the Smart Thermostat did not exist in the VCR. In the Smart Thermostat case, some people may justify the purchase from a green perspective.
- The existence of Internet and social networks as a way of facilitating the marketing and WOM did not exist back in the VCR time.
- The VCR manufacturers did not have a recurring source of revenues from the movies. Nest has a potentially large recurrent source of revenues from the utilities, so they have, in principle, a greater margin on the price of the hardware.
- The fact that users are giving away their personal data related to their homes is important.
  - They did not provide any personal data when they were buying a VCR.

Problem Articulation

The problem studied with this model is the adoption and diffusion of smart thermostats in North America. The final objective is to evaluate what can be the overall impact of this technology on energy efficiency and demand response in the residential market under different scenarios of subsidies (no subsidy, moderate and strong). The focus of the paper is the study of those households with central A/C and/or electric heating.
It is not the goal of this model to study the competitive dynamics between the different manufacturers or models of smart thermostats studied. The main reason is that we are assuming that, regarding EE and DR, all the thermostats studied here have similar capabilities and serve similar goals.

**Model Overview**

The model consists of several views or sectors that are summarized in the table below and further developed in this section.

<table>
<thead>
<tr>
<th>Model View</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adoption</td>
<td>Potential adopters, adopters, adoption Rate</td>
</tr>
<tr>
<td>Installed Base and Energy Calculations</td>
<td>The installed base, purchases, product retirements</td>
</tr>
<tr>
<td>Price and Learning Curve</td>
<td>Price of the product as it depends on the learning curve</td>
</tr>
<tr>
<td>P&amp;L Statement</td>
<td>P&amp;L Statement for the industry and modeling of R&amp;D effect on the performance of technology</td>
</tr>
<tr>
<td>Dashboard</td>
<td>Control panel with parameters and graphs of key variables</td>
</tr>
</tbody>
</table>

Table 3: Model overview summary

**Adoption**

The adoption view of the model consists of the Bass diffusion model, augmented to allow for changes in the fraction of the population willing to adopt the product as well as the growth in the population.
For the purpose of modeling the adoption of smart thermostats, the potential adopters considered are households, because typically each household will want to buy one smart thermostat, independently of the number of people living in the home.

The fraction of the population willing to adopt the product depends on the product price and on the perception of performance. To account for this, the Bass model has been modified, dividing the total population into three non-overlapping subpopulations: Adopters, Potential Adopters and Not Willing to Adopt.

The population willing to adopt consists of the Adopters and the Potential Adopters. Potential Adopters are those that would adopt if they were aware of the product and its attributes. The flow from Potential Adopters to Adopters is determined by the Adoption process, which gives idea of this awareness.
The flow of population from not willing to adopt to potential adopters is defined by the rate Becoming Interested, which is a function that adjusts the Adopter or Willing To Adopt population (sum of P and A) towards the indicated value of Population Willing to Adopt.

In this model we assume that The Fraction Willing to Adopt depends on price and on the perception of performance of the technology. This is modeled in two different parts:

FWA = 0.8*Pricing Part + 0.2*Perception of Performance Part

For the price part, weighted 80% of the FWA, we assume a linear relationship, bounded between 0 and 1, Where the Reference Price is defined as the price at which the Fraction Willing to Adopt falls to zero. The formulation generates a linear demand function in which the pricing part of the fraction willing to adopt falls from 100% when the price is zero to zero when the price reaches the reference. In this model, the Average Price is generated by the learning curve.

The Perception of Performance part of the FWA is explained on the subsection P&L Statement below.

The model also contains a formulation to account for the population growth. The Fractional Net Population Increase Rate parameter is set to .019/year (1.9%/year), which is the CAGR of households from 1960 to 2015 ("Number of Households in the U.S. 1960-2015 | Statistic"). New households join either those who are potential adopters, or those not willing to adopt; FWA determines what fraction of new households go to the P stock and what fraction go to U. The total population is always the sum of the adopters, the potential adopters, and those who are not willing to adopt.
The other part of the model, the flow from Potential Adopters to Adopters, is the classical Bass diffusion model where the Adoption Rate depends on the adoption from Advertising and from Word of Mouth. The adoption from advertising creates a balancing loop (the depleting effect). The adoption from Word of Mouth is a reinforcing loop, and that accounts for the growth that we see in the S-Shape traditional curve.

**Installed Base and Energy Calculations**

This view has to main parts, the model of the installed base (smart thermostats in use) and the calculation of energy efficiency and demand response.

On the first part, the Installed Base, it is important to realize that the purchasing is modeled separately from the Adoption, though they are obviously related. The purchase rate is the flow of actual purchases (measured in units/year). Each adopter desires a certain number of units, which for this model will be a constant equal to one.

![Diagram of Installed Base part of the model](image)

**Figure 22: Installed Base part of the model**

Product retirements are modeled as a material delay of the purchase rate, using one of the built in material delay functions in Vensim. Note that product retirements occur after an average
delay determined by the Useful Life of Product. The delay function used allows us to capture the fact that the useful life is an average, with some units retired before, and some after.

The total desired installed base is then given by the number of adopters and the desired number of units per adopter. Adopters' purchase behavior adjusts the purchase rate above or below the replacement of retired units so as to bring the actual installed base up to the desired number of units. The adjustment for the installed base creates a balancing feedback that closes any gap between the desired and actual installed base of the product. It takes time for that stock adjustment to occur: having made the decision to adopt, people must decide which make and model to buy, then find the time to shop for it. Research suggests that the average time between the decision to buy and purchase was about one month or 0.0833 years (Sterman and Keith).

The second part is where we calculate the energy savings and demand response capabilities. For the calculation of the energy savings, we consider the Installed Base of smart thermostats and we proportion this to account for the percentage of households that are using the smart thermostats to control central AC and electric heating systems. Even though the smart thermostats control most types of residential heating systems with other fuels, the objective of this paper is to focus only on those systems fed by electricity.
Figure 23: Energy Calculations part of the model

Regarding the capacity of demand response, we have used a linear relationship in the variable Fraction of Installed Base with Central AC Joining BYOT. This linear relationship is bounded between 0 and 0.25. It means that 25% of the households with Smart Thermostat and Central AC would remain in a BYOT program if the Subsidy were equal to the Reference Subsidy and 0% of the households would join under no subsidy. For the reference subsidy we have considered initially $150. BYOT programs start in 2017 using a Pulse function.

Price and Learning Curve

Cost reductions can arise from combinations of learning-by-doing, scale economies, and other processes. In this model, we will model price as depending on cumulative production experience using a standard learning curve. For a wide range of products, unit costs fall by a certain fraction every time cumulative production experience doubles.
We also assume that the average price of smart thermostats is determined by unit costs and a constant markup.

The learning curve is formulated as follows:

Unit Cost = Initial Unit Cost * Effect of Experience on Cost

Effect of Experience on Cost = (Cumulative Experience / Initial Experience) ^ Learning Curve Strength

where the exponent, Learning Curve Strength, is a computed constant,

\[
\ln(1 - \text{Cost Reduction per Doubling of Experience}) / \ln(2)
\]
determined by the Cost Reduction per Doubling of Experience.

In the model, Production Experience (which accumulates to drive the learning curve) is purchase rate generated in the Installed Base sector.

Finally, the average price is discounted by the subsidy. Subsidies from BYOT programs start in 2017 using a Pulse function.
P&L Statement

This view of the model contains a simplified P&L statement as well as the modeling of the effect of R&D on the performance of technology. We referenced this section when we described the Fraction Willing to Adopt formulation in the explanation of the Adoption view. Here we will go through the view in full detail.

Figure 25: P&L Statement View of the Model

The Cumulative Profit is the accumulation of Net Income. Net income is Gross Profit less Fixed Costs (assumed here to be a percentage of revenue, for both, General and Administrative costs and R&D expenditure). Gross Profit is Revenue less the Cost of Goods Sold (COGS). Revenue is determined by the Purchase Rate and Average Price; COGS is determined by the Purchase Rate and Unit Cost. Operating Income is Gross Profit less the mentioned expenses and finally the net income is calculated after taxes. This simple formulation omits a number of accounting subtleties such as when revenue is recognized, depreciation, and the structure of the firm’s balance sheet, but is adequate for our purposes.
The second part of this view deals with the modeling of the Perception of Performance. This is formulated using an index that is a function of the accumulated R&D expenditure, which is bounded between 0 and 1 as per the lookup graph below. The index takes a value of 0 for no R&D investment and grows to 1 as the total investment in R&D reaches $3B.

![Graph Lookup - Effect of RD on Performance](image)

**Figure 26: Lookup Graph for Effect of R&D on Performance**

The shape of the graph considers the typical phenomenon of diminishing returns on R&D investment: During the first years of the live of a technology, each dollar invested in R&D has a larger impact in the performance than towards the maturity of the technology life.

The reasoning behind the $3 billion considered for our graph is that, assuming an expense of 5% of revenue in R&D, and given the best possible conditions of the market (highest level of subsidies), the total cumulated expenditure in R&D during the 10 year period modeled here is slightly above $3B. We can see this on the following picture.
The model also contains two delays that represent the time required to realize the investment in R&D and the time required for the potential customers to appreciate the advantages of the technology. Any investment in R&D will require some time to materialize in better features, better products or services, and after, consumers will need some time to become familiar with the advantages or improvements of the technology and to figure out how this technology can help them. We are assuming these delays to be 1 year for the time to realize R&D investment and 6 months for the time to perceive the improvements by the customers.

The Perception of Performance is included in the formulation of the Fraction Willing to Adopt with a 20% weightage as we discussed on the Adoption section.

**Dashboard**

The dashboard contains most of the graphs and parameters required to understand the behavior of the important variables and to compare them with the available historical data. As we can see on the figure below, there are a few parameters indicated as the key parameters to calibrate the model to the available historical data.
Model Calibration

We have used the data obtained in the section “Smart Thermostats – Data and Forecasts” as historical data to calibrate our model. We need to bear in mind that the historical data only goes back to 2011, so the calibration is limited to this data.

In particular, we have imported the following data into the model:

<table>
<thead>
<tr>
<th>Year</th>
<th>Purchase Rate</th>
<th>Average Price</th>
<th>Adoption Fraction</th>
<th>Installed Base</th>
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<td>0.00942</td>
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<td>0.02491</td>
<td>3,411,500</td>
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<td>3,900,000</td>
<td>250.8</td>
<td>0.05288</td>
<td>7,319,800</td>
</tr>
<tr>
<td>2016</td>
<td>249</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Historical Data Summary

In the graphs, a thicker line represents these variables and the dataset is called ST_Data.

We can see this if we have a look at the above figure showing the dashboard of the model.

The main parameters used to calibrate the model are the following:
<table>
<thead>
<tr>
<th>Parameter (Units)</th>
<th>Value for Calibration</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advertising Effectiveness, a (1/year)</td>
<td>0.0113</td>
<td>The fraction of the willing to adopt population adopting each year as the result of advertising</td>
</tr>
<tr>
<td>Adoption Fraction, i (dimensionless)</td>
<td>0.013</td>
<td>The probability of adoption given a word of mouth contact of a willing to adopt with an adopter</td>
</tr>
<tr>
<td>Reference Price ($/Unit) (Price at which fraction willing to adopt = 0)</td>
<td>500</td>
<td>The price at which the fraction of the population willing to buy the product is zero</td>
</tr>
<tr>
<td>Useful Life of Product (years)</td>
<td>6.5</td>
<td>The number of years which the product will be useful</td>
</tr>
<tr>
<td>Cost Reduction per Doubling of Experience (Dimensionless)</td>
<td>0.0135</td>
<td>The fractional reduction in cost per doubling of cumulative experience</td>
</tr>
<tr>
<td>Initial Experience (units)</td>
<td>500</td>
<td>The initial experience level at the start of production, representing the experience carried over from prototypes, prior related products, and pilot plants.</td>
</tr>
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</table>

Table 5: Main Calibration Parameters

**Simulations**

The simulations carried out with this model start in 2011, coinciding with the launch of Nest, and extend until 2025. These simulations are divided into two main groups: the first group of simulations is aimed to understand the behavior of the model and simulate the industry as it is at present, i.e. without any subsidy. For these simulations we start with the scenario obtained by using the calibrating parameters described above and we will study the impact of varying adoption fraction (as the strength of word of mouth) and cost reduction due to experience one by one.

The second group of simulations is oriented towards getting a better understanding on how the introduction of a subsidy in 2017 can impact the industry. For this we run two scenarios, one with a moderate subsidy of $75 that is paid to the households acquiring a thermostat and the aggressive subsidy case, where we have considered a $150 subsidy.
Base Case Scenario
The base case scenario, or the business as usual scenario, is the one we have used to calibrate our model. We are ignoring the BYOT pilot programs developed so far since they only account for about 50,000 of the smart thermostats sold up to now.

The first insight from our simulations is that the penetration of smart thermostats in the market is picking up, and it seems it will continue growing for the next two to three years. Towards the end of 2018, the Adoption Rate will start to decline.

Another interesting observation is that the price of the smart thermostats is declining relatively slowly. It diminishes 1.5% for each doubling of experience. This is a relatively low number compared to other consumer electronics which, in average, reduce their price by 10% every doubling of experience (Hossain).

In this case, we can see in Figure 29 that the sales of smart thermostats will peak in 2020 at about 16 million units per year. Sales would start declining after that but after a period of about four years, they pick up again due to the retirements. Also, the continuous decrease in price and growth of population drive the sales up.

In this scenario, the installed base in 2025 would reach almost 100 million units. Out of those more than 60 million would be in homes with Central AC. The electric power savings are about 60 TWh/year in 2025, or about 36 TWh/year in 2020. A 500MW coal power plant running continuously for a year provides about 4 TWh, so 60 TWh of savings will allow shutting down fifteen typical 500MW coal power plants by 2025.

Finally, given the lack of subsidies, there is no additional demand response capacity. In other words, we are assuming that without subsidies, people will not be willing to allow the utilities to modify the settings of their thermostats, hence, no demand response capacity is generated in this scenario.
**Base Case Scenario varying adoption fraction**

This second scenario changes the adoption fraction on our previous base case. This means a change in the probability of adoption given a word of mouth contact with an adopter. Because contact rate and adoption fraction are directly related, this change would be equivalent to modify the Contact Rate, therefore just changing one of the two parameters is enough to observe the effect. This is the reason why the Contact Rate variable has been left out of the Calibration Box.

In this case we have increased the adoption fraction from 0.013 to 0.019. This would mean increasing the probability from 1.3% to 1.9%. This change, that may seem a small increase, has a very relevant effect on the model. As we can see in figure 30, the sales accelerate very rapidly and the historical data no longer fits the outcome of the simulation. The peak of sales happens in 2017-2018 instead of 2020.

This high sensitivity of the model to the changes on the parameters related with the word of mouth loop is a typical behavior for reinforcing loops.
**Base Case Scenario varying cost reduction**

This third scenario changes the cost reduction per doubling of experience. As we discussed at the beginning of this section the real price of the smart thermostats is declining relatively slowly in the market. The historical data shows that the price is reduced by 1.5% for each doubling of experience. This is a relatively low number compared to other consumer electronics which, in average, reduce their price by 10% every doubling of experience (Hossain).

For this scenario we have chosen a reduction of 5% per every doubling of experience, and as we can see on figure 31, if this was the case, today’s price of the smart thermostats would be under $150. This price would have a very large impact on the sales that would peak in 2017 to a number of about 23 million. Also, if this was the price, a subsidy of $150 would cover the whole cost and the thermostat would become effectively free for the customers.

This shows that this model is very sensitive to price. In particular we can see in figure 31 how the fraction willing to adopt increases very rapidly as the price declines. This is expected as this variable is formulated with 80% of its value being dependent on price.
Figure 3.1: Base Case Scenario + Cost Reduction

- Fraction of Population that Becomes Aware
- Contact Rate (CR)
- Advertising (AD)
- Adoption Fraction (A)
- Difference (D)
- Total Demand Response Capacity
- Electric Energy Savings
- Installed Base
- Cumulative Investment in R&D
- R&D Performance and Perception
**Base Case Scenario adding moderate subsidy**

In this scenario, we take the original base case scenario and we add a subsidy of $75 that, we are assuming, the utility companies will pay to their customers to join their BYOT programs. This is an amount similar to what most of the participants in the BYOT pilots summarized in Appendix II are offering.

The way we model this is introducing a subsidy of $75 in 2017, which effectively reduces the price that the homeowner will need to pay for the thermostat.

As we can see, sales speed up from this moment, and they peak at about 22.5 million units in 2019. This increment in sales with respect to the baseline translates into a larger installed base, which reaches 120 million in 2025. Out of those, about 80 million are central AC homeowners, out of which about 12.5% would be willing to remain engaged in a BYOT program, generating 10GW of demand response. Also, the energy savings go up to about 75 TWh/year in 2025 with an accumulated of 430TWh.
Base Case Scenario adding aggressive subsidy

In the case of Aggressive Subsidy, we are assuming that the utility companies will pay to their customers a subsidy of $150 to join their BYOT programs. This is an amount similar to what some of the participants in the BYOT pilots summarized in Appendix II are offering.

In this situation, for a homeowner wanting to acquire a smart thermostat in 2017, the cost of buying one of the market premium models would be just under $100.

As we can see, sales speed up from this moment and they peak at about 30 million units in 2019. This increment in sales translates into a larger installed base, which reaches almost 150 million in 2025. Out of those, about 100 million are central AC homeowners, out of which about 25% would be willing to stay engaged in a BYOT program, generating 25GW of demand response. Also, the energy savings go up to about 90 TWh/year with an accumulated of 531 TWh.
Figure 3.3: Aggressive Subsidy Case Scenario Dashboard

- Adoption Fraction
- Adoption Rate
- Populations
- Fraction Willing to Adopt
- Price After Subsidy
- Sales and Retirements
- Installed Base
- Cumulative Investment in R&D
- Electric Energy Savings
- Total Demand Response Capacity
- Accumulated Savings
- R&D, Performance and Perception
Critiquing the model

Henry Birdseye Weil in his paper *Why Markets Make Mistakes* discusses about bounded rationality as one of the reasons why markets make mistakes: “Classical models of technology diffusion are examples of bounded rationality. In the interest of conceptual and computational simplicity, they do not account for important interdependencies and structural fundamentals” (Weil 9). Dattée and Weil develop this idea further:

Classical models make strong assumptions on the process of innovation diffusion by considering at least one of the following: that adoption is a one-step process, the potential market size is constant, there is no repeat purchase, there is a uniform probability of dyadic interactions between prior and potential adopters, or that the innovation itself does not change over the diffusion process. (Dattée and Weil 4)

This model has addressed some of these shortfalls: population growth is included, the fraction of the population willing to adopt changes as the price of the product varies, price falls with increasing learning from cumulative experience, and the purchase rate includes both first purchases and replacement purchases. Also, the impact of R&D on Performance has been modeled, as well as the delay incurred by the potential customers to perceive the advantages of the technology. Finally, the market has been segmented into population with various types of heating systems and AC systems, so the actual savings only are applied to the electric fed devices. However, there are other points where the model can be improved: the adoption has been considered as one step and there is no try and reject. These are potential areas of work for a continuation of this thesis.
SCALE IMPLEMENTATION CASE STUDY -

The Texas Independent System Operator – Electric Reliability Council of Texas (ERCOT) operates a grid that provides electricity to about 27 million people in more than 9 million homes. The power demand increases considerably during the summer time (See Figure 34) with a record of 69.877GW during August 2015 (Magness 11).

![Actual Load Duration Curves – 2011 to 2015](image)

Source: ERCOT

**Figure 34: ERCOT Load Duration Curves 2011 to 2015**

It is interesting to see how most of this peak demanded in summer time is due to residential HVAC systems.

![Demand Comparison between March and August 2011 in ERCOT Grid](image)

Source: ERCOT

**Figure 35: Demand Comparison between March and August 2011 in ERCOT Grid**
ERCOT does not qualify any of the residential or small commercial load as Load Resources, or, in other words, they don’t consider this as load they can disconnect to stabilize the grid (See Box comment in Figure 35 above). Currently, ERCOT have at their disposal about 2.1 GW of Demand Response Resources:

![Demand Response Resources](image)

Source: ERCOT

**Figure 36: ERCOT Demand Response Resources as of now**

Using our model, we have studied how these resources would look like for ERCOT in case the utilities in the region decided to promote strongly BYOT programs. This could be done via working with the utilities operating in the region or via their own initiative.

To do so, we identified the particular conditions for Texas regarding heating and cooling and found out that about 45% of people use electricity for heating and about 84% have Central A/C.

![Figure 37: Texas Households Statistics on heating and cooling](image)
Applying these conditions, for the 9 million households in the region and considering an aggressive subsidy scenario, we have obtained the following:

![Figure 38: ERCOT case Dashboard](image)

Apart from the considerable Accumulated Energy Savings of about 40 TWh by 2025, ERCOT could achieve 1.7GW of additional demand response capacity coming from residential. This is not far from the demand response availability they have today as we saw in Figure 36 above (2.1GW).

Some states are already implementing policies to attain large implementation of residential advances. Starting this July 2016 all utilities in New York will need to offer demand response to their retail customers (Opalka), and BYOT seems to be a good candidate for this.
CONCLUSION

In this paper, using a system dynamics model, we have studied the penetration of the Smart Thermostats technology in North America and how programs such as Bring Your Own Thermostat, where customers have part of their thermostats subsidized, may impact on the dynamics of the industry. Also, we have evaluated the effect of this technology and the BYOT programs on demand response and energy efficiency in the residential sector.

A first conclusion of our study is that the potential of this technology, when applied at large scale, becomes very substantial. Our results show that the smart thermostats, in the business as usual case (without subsidies), can save about 60 TWh/year of electricity in North America by 2025 (or the continuous production of about fifteen 500MW coal plants). If programs such as BYOT, where part of the thermostat is subsidized were going to be popularized, this number could almost double. Additionally, this technology can create an important potential in the residential demand response space, a sector that has been traditionally very difficult to reach due to the large number of customers and smaller loads. On this regard, BYOT resolve many of the problems that traditional demand response programs for the residential arena faced and can become a critical element of the demand response and energy efficiency landscape. Thermostats are naturally connected to the Internet via the home Wi-Fi network, and this opens the perfect door for the utilities to access possibilities that have been traditionally more difficult to achieve.

A second conclusion is that, the fact that many electric utilities have already started experimenting with the possibilities of the Smart Thermostats is a good sign that they see potential on this technology. Also, the initial results from some of the BYOT thermostat pilots show a lot of interest and traction from the residential customers. However, smart thermostats are
still relatively expensive for many people, so incentives and rebates aimed to reduce the purchasing effort will help accelerate the diffusion of the technology. Our model captures this sensitivity to price. A related remark is that the price of thermostats is decreasing relatively slow compared to other consumer electronics.

Another important point that we have observed is that, even though the utility-based programs designed to reducing energy consumption and shaving peak demand are positive initiatives, to obtain the true potential of this technology and become a key player from a grid stabilization point of view, probably the most beneficial case would be to implement programs at the ISO level, where ISOs could work in coordination with the utilities operating in their areas; possibly contributing with financial incentives to facilitate the access to more people and/or acting to modify the regulations as we saw in the case of New York. Technically it does not seem to be any impediment to this.

Furthermore, it is important to highlight that, despite the lack of public information regarding the historical data of sales, we have been able to use multiple sources and make educated guesses to come up with a set of data that was useful to calibrate our model and that we felt comfortable with. Surely the numbers will not be accurate, but they have been useful for our purpose.

Finally, a closing remark on the importance of the energy efficiency as a key contributor to reduce CO2 emissions and to achieve the goals of limiting the global warming to 2°C. The cleanest energy is the one that is never consumed, and this is what energy efficiency is all about. We need to come up with ideas and solutions to maintain (or even improve) our life standards while consuming less energy. Technology and our willingness are key. We must put our best efforts in saving energy, saving our planet. There is no alternative.
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<td>Apr</td>
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<td>2011</td>
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</tr>
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<td>Nov</td>
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</tr>
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<td>2013</td>
<td>Dec</td>
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</table>

**Note:**
- November 2011: Nest is launched
- April 2012: Ecobee Smart SI is launched
- April 2011: Honeywell Wi-Fi Smart Thermostat is launched

---

**APPENDIX I: SMART THERMOSTATS SALES ESTIMATION**

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<th>Month</th>
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<tr>
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<td>24000</td>
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<tr>
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<td>26000</td>
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<td>May</td>
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<td>48000</td>
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<tr>
<td>Dec</td>
<td>2015</td>
<td>50000</td>
</tr>
</tbody>
</table>

**Note:**
- February 2014: Google Acquires Nest
- August 2015: Honeywell Lyric is launched
- September 2014: Ecobee 3 is launched
- September 2014: Nest Reaches Parts of Europe
- July 2015: Nest is no longer available in Apple Stores

---

**Aniza**
<table>
<thead>
<tr>
<th>Company</th>
<th>State</th>
<th>Program</th>
<th>Year Launched</th>
<th>Management System</th>
<th>Thermostats</th>
<th>Program Overview</th>
<th>Number of Customers</th>
<th>Pilot Results Demand Res.</th>
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<td>Power Partner Thermostat Program</td>
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<td>Autogrid? EnergyHub?</td>
<td>22 Eligible Thermostats from 8 vendors: Alarm.com, Ecobee, Filtrete, Lux Products, Nest, Radio Thermostat Company of America, Vivint, Nexia Home Intelligence</td>
<td>$85 Rebate</td>
<td>7,000</td>
<td>7,000 Thermostats representing 10MW of Demand Response – About 1.4kW per Customer</td>
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<td>IL</td>
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<td>2013</td>
<td>EnergyHub Nest</td>
<td>Alarm.com, Radio Thermostat Company of America, Vivint, Ingersoll Rand: Nexia Home Intelligence and Nest</td>
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<td>Bring your Own Thermostat</td>
<td>2015</td>
<td>EnergyHub (representing Alarm.com, Ecobee, and Radio Thermostat) Honeywell Nest</td>
<td>$125</td>
<td>1,000</td>
<td></td>
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<td>Hydro Ottawa</td>
<td>ON, Canada</td>
<td>Bring your Own Thermostat</td>
<td>2015</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
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Source: Own Research
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