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Monitoring and reducing the consumption of home electric appliances

Master's thesis

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Table of Contents

List of Figures

List of Tables

1. Introduction

One of the biggest problems facing Europe today is the challenge caused by increased energy consumption and the increase of greenhouse gas emissions. In response the EU has defined the EU 20-20-20 target which is aiming for a 20% reduction in Europe's annual energy consumption, a cut of at least 20% in EU greenhouse gas emissions and that 20% of EU energy consumption comes from renewable energy sources by 2020 (1). As energy costs are increasing, more and more consumers are becoming actively interested in reducing their energy consumption. New technologies available today have been claimed to have the potential to save at least 40% of residential electricity consumption in most types of appliances (2) but not all consumers are willing or in the position of acquiring such appliances whilst their old appliances are still serviceable.

There were 211,922,500 households (3) recorded in the EU-27 alone in 2012. A vast majority of these households can be assumed to be equipped with the majority of needed appliances. With the coming of Smart meters, a meter that records electrical consumption in intervals of an hour or less as well as communicating that information back to the utility for monitoring and billing purposes (4), and Smart appliances, a household appliance that is able to communicate with other smart appliances as well as the electrical grid in order to reduce power consumption and increase the quality of life (5), it is evident that these will not replace old equipment in all of these households today. We need a way for consumers to manage their consumption whilst using their existing appliances. In addition, we are surrounded by more and more electrical appliances and gadgets, in such a way that we are unaware of the consumption around us. Many households can count between 20 and 30 separate electronic devices spread within their walls (2). These appliances become ubiquitous to us in the sense that we do not even realize that we are consuming electricity, as many appliances today are left on a standby mode, such as the case of several types of multimedia appliances surrounding the TV, which might not be turned off manually each time the TV is turned off. The great increase of gadgets within a household has a great impact of the amount of electricity we are consuming. They may not consume great amounts of electricity on their own, but collectively when many are added up the consumption increases. We need to make consumers more aware of their own electricity usage and supply them with options to manage usage and reduce waste.

1.1 Current situation

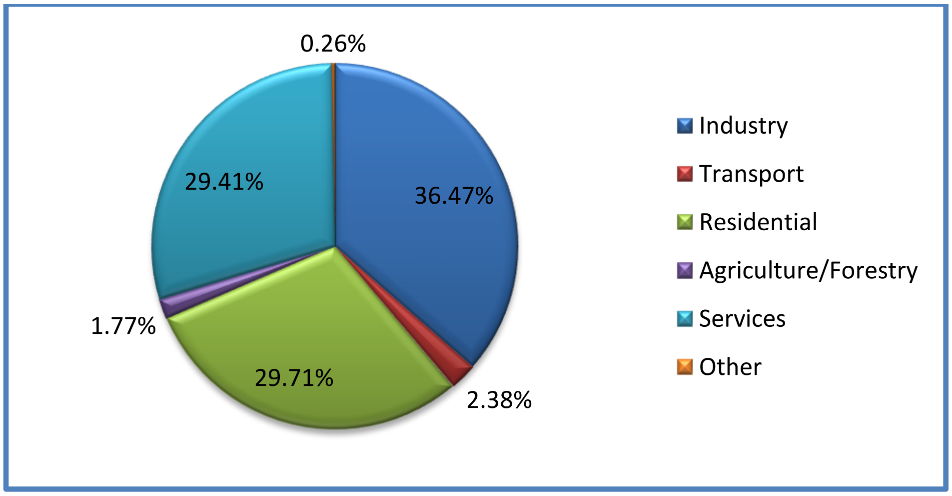
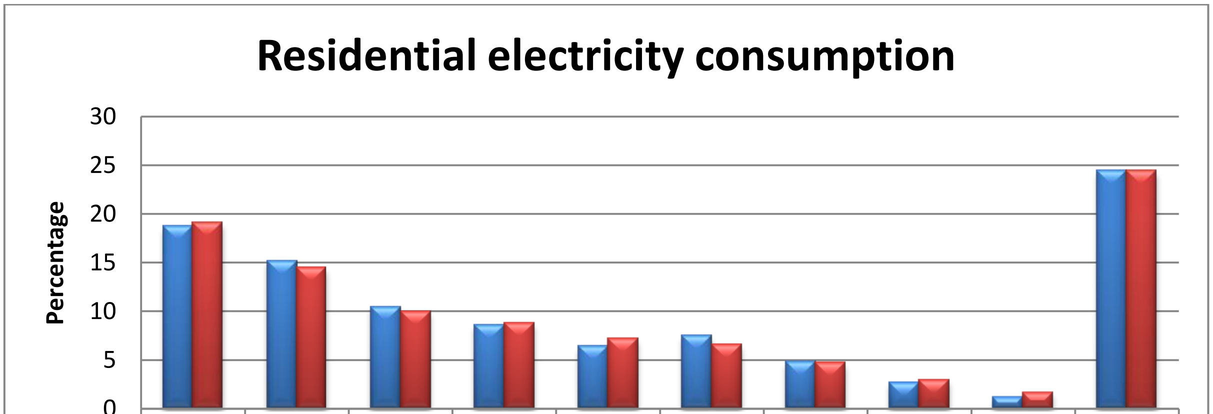


Figure 1: Final electricity consumption by sectors in the EU-27 (6)

Figure 1 shows the electricity consumption in the EU-27 in 2010 where the residential sector is responsible for the second highest consumption. This shows that there is a need to put a greater emphasis on efficiency in the use of electrical household appliances and equipment.

In the Energy Efficiency Report 2012 (6) it is stated that final electricity usage decreased in the year 2009, but the final residential electricity consumption per capita did not decrease between the years 2008 and 2009. It increased by 1.58%, which shows that the overall decrease in electricity consumption per capita (-4.96%) was not achieved from within the residential sector. However, on the other hand, the growth rate reported in the EU-27 is the second lowest in 2010, or 0.42%, over the period 2000-2010. The lowest growth rate was reported in 2007, or -0.80%, which they state can be related to higher temperatures during that year, which implies less energy use for heating.



	Heating systems /electric boilers	Cold appli-ances	Lighting	Water heaters	Washer /Dryer	Electric ovens & hobs	Ventilation & Air-conditioning	Dish-washers	Set top boxes	Other
2007	18.7	15.2	10.5	8.6	6.4	7.5	4.8	2.7	1.2	24.4
2009	19.1	14.5	10	8.8	7.2	6.6	4.7	3	1.7	24.4

Figure 2: Breakdown of the EU-27 residential electricity consumption, 2007 and 2009 (7) (6)

Figure 2 shows a comparison of breakdown of residential electricity consumption in the EU-27 between the years 2007 and 2009. Heating systems, cold appliances, lighting and water heaters are responsible for almost half of the total consumption. The category “other” includes home appliance standby consumption, entertainment devices, office equipment, vacuum cleaners, coffee machines, etc. In 2007 the home appliance standby consumption was 5.9% or 47.5 TWh/yr, which means that it was consuming more than air-conditioners and ventilation. This shows that there is a great need to give more focus to standby consumption. Even though appliances and devices are becoming more efficient due to energy efficiency measures taken, the general trend is that the residential sector consumption is increasing.

1.1 State of the art

The smart grid (8) can be seen as the successor of the conventional electrical infrastructure which uses information and communications technology to automate the production and distribution of electricity. One innovation of the smart grid is that consumers of the network can become an energy supplier as well, that is consumers can become prosumers. Any user of the smart grid with an energy source will be able to sell excess energy to the grid. The energy usage and supply will be measured by smart meters (4), where the EU directive to its member states is to have 80 percent smart meters installed by 2020 (9). A smart meter is an electrical meter that records consumption of electric energy and communicates that information back to a device for monitoring and billing purposes. The smart grid promises to provide us with dynamic pricing in the future while today the trend in most countries is to provide consumers with a choice of several electricity providers as well as different electricity tariffs depending on the time of use (10). Today most new appliances produced have the potential to use up to 40% less electricity (2) which is not enough to put them into the category of smart appliances. One aspect of smart appliances is that they are produced to be able to measure their own consumption and make use of that information to save electricity and money, as well as being programmable. Smart appliances are in their infancy but are starting to emerge on the public market. On the other hand there are several home automation solutions available which make use of wireless technologies as well as existing home wiring to connect and automate appliances.

There are several research projects devoted to the smart grid, new emerging electrical technologies, customer participation and behaviors. One of the largest is the Pecan Street Project (11), which is a smart grid research project founded in the city of Austin Texas in 2008. The residents of the Mueller community in Austin are early adopters residing in 1000 homes. Some of these homes are “green-built” houses and others are traditional built houses. The houses are equipped with energy management systems and most of the advanced smart grid technologies are incorporated. The Pecan Street Project is used to evaluate different smart grid standards in terms of interoperability, analyze different dynamic pricing models, as well as study the effects of incorporating PHEV’s, solar panels, energy storage and smart appliances. The residents are rewarded by financial assistance when purchasing equipment such as solar PV cells, solar water heaters and efficient air conditioners, as well as providing rebates for home efficiency measures.

1.2 Problem statement and research question

The emergence of the smart grid, smart meters and smart appliances provide consumers of electricity with new means to observe their energy consumption more closely and to have the option to change their consumption habits to improve on their savings. With increased awareness of the possibilities of decreasing electricity consumption and the possibility of saving money on their electricity bill residents of existing homes should be looking for solutions. With an existing home I am referring to people who own their home and already own all the electrical appliances they need, or are renting their home which does include all the electrical appliances needed. These people might be in the position of not wanting to buy for example a new refrigerator or washing machine in order to decrease their electricity consumption but still wish for possible solutions to optimizing their existing home’s electricity usage. Additionally, not all homes are equipped with smart meters today. Is there a way to make existing appliances smarter by use of existing technology? In other words, can we provide home automation to an existing home without forcing the use of smart appliances and smart meters? And finally, when being faced with consumption higher than that of air-conditioners and ventilation as shown in chapter 1.1 the following question arises: how do we make residents more aware of their wastage of electricity in regards to standby power?

In order to reach the goal of optimizing electricity usage (even out the electricity usage and only use the electricity needed) in an existing residence the following research question must be answered:

Can optimization of electricity and automation of appliances provide a solution which aids a resident in reducing electricity consumption in an existing residence with existing appliances today?

In order to answer this question the following sub-questions have to be answered.

- What is ‘state of the art’ in Smart appliances?
- What types of electricity measurement solutions are available for existing appliances today?

- Can we create effective standby power detection on the appliances measured?
- Can we reduce peak periods and flatten peaks using the optimization application?
- Can we provide a mean to see if different types of electricity tariffs are resulting in savings in cost?

1.3 Thesis contribution and organization

Many parties are finding ways to enable residents to optimize electricity usage in existing homes (12) (13) (14) as well as many home automation solutions being available (15) (16) (17) (18). In order to answer the research question and sub-questions in the previous chapter I do research regarding what solutions are available, both which have been implemented such as smart appliances and which are suggested in published works. In order to optimize the electricity use in an existing residence with existing appliances I use a home automation system which measures the electricity consumption of individual appliances. In addition, the home automation system allows for automation of the appliances in the form of the end-user being able to determine timing schedules to turn appliances on and off. For the purpose of optimization an application which aids the end-user in creating these schedules was needed, which lead to me designing and implementing the Home Energy Planner (HEP[1]). The HEP includes standby power detection and a scheduler which suggests times to run appliances in order to flatten peaks and reduce peak periods. I explain the design and concepts implemented in the development of HEP. I do extensive evaluation on the work completed in HEP in regards to flattening of peaks, reducing peak periods and standby power detection, which proves to be effective in HEP.

The content of this thesis is organized in the following manner:
In Chapter 2 related work is researched. I look at published work in regards to end-user behavior as well as inventions regarding Smart Home solutions.
Chapter 3 presents the background, where I research existing solutions in labeling and incentives, new smart appliances and solutions provided for existing appliances.
Chapter 4 describes the design and methodology of HEP. This includes the system context, algorithm for standby power detection, scheduling of appliances and how the data was collected.
Chapter 5 is dedicated to the implementation of HEP where we describe the main components of the system, the logical view as well as describing the most used runtime views.
In Chapter 6 the evaluation of the HEP is presented. This includes the experimental setup, the objective results from all the experiments and concludes with a discussion of the results.
Finally Chapter 7 presents further work and conclusion. I summarize my findings during research and evaluation of HEP and propose further development in the design and development of an optimization application such as HEP.

[1] Home Energy Planner will be referred to as HEP from this point in the remainder of the document.

2. Related work

When faced with electricity trends and the design of the new Smart Grid several solutions to energy savings have been presented. T. A. Nguyen and M. Aiello summarize and compare several studies on building energy and comfort management (BECM) systems (19) where simulation results show up to 58% savings on energy for lighting and 10-40% for HVAC system. In the commercial sector a study conducted by Georgievski et al. (10) showed an average economic savings of about 35% by presenting an approach based on measuring consumption on individual devices as well as measuring the production on generating units. In addition end users where able to determine requirements which lead to policies for each device and energy contracts were closed for short-term time intervals dynamically from different providers. This approach assumes that the Smart Grid is available and that it is able to offer dynamic prices from different energy providers. In the following two sections we will take a closer look at solutions presented, where some deal directly with the Smart Grid, assuming that the end-user is connected to the Smart Grid, has a Smart Meter and Smart Appliances and others focus on the behavior of the end-user and what role they have in energy and consumption savings.

2.1 End-user behavior

"We can't be using that much… It's just the 2 of us… in this 2 bed flat ... I am out all day… and we are on income support… I just don't know how the bills are so high... I think there is something wrong with them" – a female, 30s, London, commenting whilst in broad daylight lights were on in most rooms and a TV and radio were playing in an unoccupied bedroom, and all appliances in the sitting room (TV, DVD, stereo, computer) were on standby. (20) This comment, recorded in a qualitative study performed on several households in the UK, shows that the end-user needs to be made aware of how they are consuming electricity in their homes. Several studies have been conducted were end-user behavior is the focus. Gill et al. (21) conducted a custom-made behavioral survey on inhabitants of a UK EcoHomes site. They state that "*The significance of information feedback and simple explanation of electrical consumption in terms understood by the users (cost being the only one referred to by any occupants) is crucial to reducing electrical energy waste in dwellings*".

In most homes today the electricity meters are tucked away out of sight and only give the end-user a total consumption usage of all electrical appliances in the home. Goncalves Da Silva et al. (22) conducted a survey in 2011 which was open to the public for a period of 2 months on the NOBEL[2] project website. Even though this survey was intended to better understand residential prosumers some of the conclusions are relevant for all end-users, that is, also for residential consumer devices, such as real-time consumption and historical consumption. In the survey over 90% wanted a better overview of their electricity consumption, as well as a better understanding of the impact individual devices could have on their energy bill and behavior. By providing a means for the end-user to visually monitor individual appliances as well as the potential for savings by changed behavior, there is a potential for reduction in electricity consumption for the end-user.

[2] http://www.ict-nobel.eu/

2.2 Smart Home solutions

A trend of smart homes which can aid the inhabitants in energy consumption reduction has emerged. This is achieved by ways of monitoring and controlling devices, by rescheduling the operation times according to different criteria. Several good solutions have been presented, three of which are summarized below.

Solution I - SmartCap

Due to the challenges involved in demand-side management, Barker et al. (12) designed SmartCap, which is a system that automatically monitors and controls household electricity usage, by focusing on quantifying the benefits of scheduling transparent background electrical devices. These background devices are air-conditioner, refrigerator, freezer, dehumidifier and heat recovery ventilation system (HRV). Their method is an online approach that uses each appliance's current slack (the time period an appliance can be disconnected from electricity while still meeting its operational goal) as a heuristic to determine its priority at any time. An intelligent smart home gateway is the focal point of their system. In addition the system uses Insteon (23) products to monitor and control the appliances. The gateway receives consumption data from appliances (via Insteon), real-time electricity prices, generation data from renewable energy sources (via Insteon), as well as holding the scheduling policy. In order to compute the slack for each appliance, temperature and humidity sensors are placed inside or near each appliance. Their method is able to flatten household demand over each day; more exactly the absolute average deviation from the mean power was decreased by 23% on the day they measured in a real home setting.

Solution II – Smart Home Simulation

Prýmek et al. (13) introduce a simulation model using smart appliances based on priority, where high-priority appliances are satisfied before the lower-priority ones. They satisfy the end-user behavior by instructing them to set rules for the appliances (8 rules ranging from unnecessary/time unlimited to health risk avoidance). In addition they pre-classify appliances according to their control mechanism, user expectancies and power consumption profiles. This simulation software can be used both with virtual appliances as well as with real appliances. The purpose is to give the end-user a way to simulate results of different scenarios, depending on the end-users expectations as well as results from using different types of schedulers.

Solution III – Residential Energy Management scheme

Han et al. (14) propose a wireless sensor network based Residential Energy Management scheme for non-urgent appliances. The non-urgent appliances are e.g. washing machine, clothes drier, dishwasher, pool pump and plug-in hybrid electric vehicle (PHEV). Their scheme is based on time of use (TOU) tariff, Zigbee transmission technologies and uses a smart meter to measure the appliances. When the end-user wishes to turn on a non-urgent appliance their algorithm checks if power is available in the renewable energy generations and storage battery. If it is available it runs the appliance, if not it calculates the price of running the appliance now and at a later time and gives the end-user the postponement option together with the different prices. Based on this information the end-user makes their decision of running the appliance now or at a later time. This means that the end-user is deciding on when to turn on the appliance based on one running cycle.

2.3 Discussion and Home Energy Planer contribution

When comparing the Smart home solutions presented in the previous section we see that all solutions aim to reduce electricity consumption peaks and thereby optimizing the electricity consumption. Table 1 provides an overview of the methods and technologies used in all three solutions for comparison purposes.

Table 1: Summary of devices and methods in relevant solutions

	Solution I	Solution II	Solution III
Existing appliances	X		X
Smart appliances		X	
Smart Meter			X
External measuring device	X		X
Sensors	X		
Appliance type restriction	Yes	No	Yes
End-user classification of appliance type		X	
Automatic control	X		
Show potential savings (euro and/or kWh)		X	X
Show potential difference in pricing plans			
Standby power detection/removal			
Reduction of electricity consumption peaks	X	X	X

While Solution I allows for the use of existing appliances with an external measuring device it requires the use of sensors, diminishes the control of the end-user by keeping the scheduling fully automatic and puts a restriction of the type of appliances. Solution II allows for all types of appliances and gives the end-user the control of classifying them according to their own requirements, but it requires Smart appliances. Solution III uses existing appliances with an external measuring device but puts a restriction on the type of appliances and requires a Smart meter.

The HEP solution presented in this paper differs by adding standby power detection and removal from the total consumption of each appliance as well as providing differences in potential savings by using a single tariff plan or TOU tariff plan, which none of the other solutions provide. It also allows the use of existing appliances with an external measuring device without putting a restriction on the type of appliances used and gives the end-user information about potential savings in euro and kWh.

3. Background

The EU has enforced measures in order to improve energy efficiency in new appliances. There are measures taken in regards to labeling, incentives and regulations.

3.1 Labeling and regulations regarding energy efficiency in the EU

Directive 2009/125/EC is the most resent eco-design framework for the minimum energy performance standards (MEPS) which appliances in the EU must meet in order to be eligible for sale (24). These standards are determined for each type of appliance (and other products using energy) where each type is given a minimum energy efficiency index (EEI[3]) within each energy efficiency class. These minima are revised and lowered which results in phasing out of lower energy efficiency classes and effectively banning product sales in the EU of appliances that do not comply with these standards. The case of incandescent lamps is an example of a successful phase-out which started in September 2009 and finished at the end of September 2012 (25).

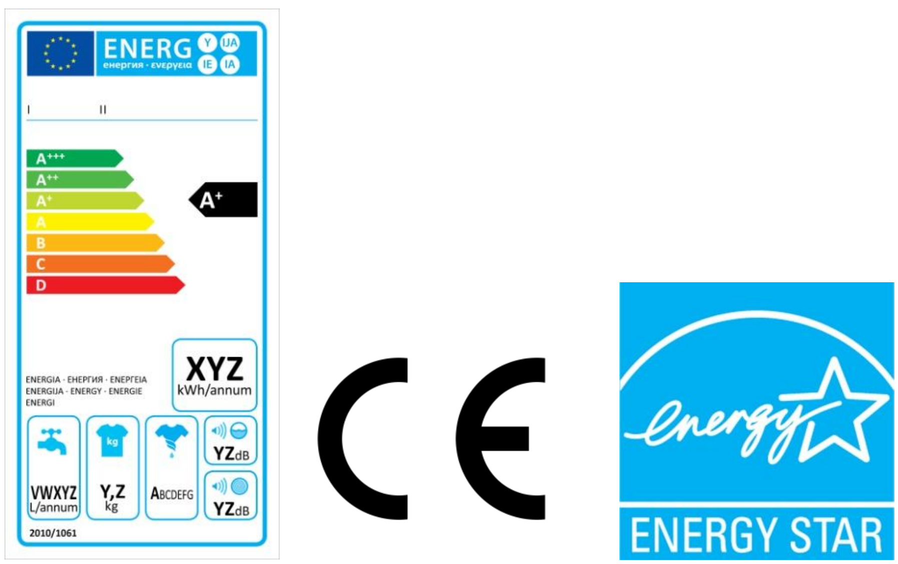


Figure 3: a) New EU energy label, b) CE marking and c) EU Energy Star label

The European energy labeling scheme was established by directive 92/75/EC in 1992. In May 2010 a new directive 2010/30/EU (26) was adopted and became effective in July 2011. The new directive introduced three new energy efficiency classes (A+, A++, A+++) in addition to the previous classes (A-G) as well as providing the information with pictograms rather than words. The labels, as shown in Figure 3 a), give the energy efficiency based on these classes, which are determined by a given appliance’s EEI, given in kWh per year. In addition the labels give information about noise, consumption, capacity, standby-power etc. (based on the type of appliance). This type of labeling is created to give the end-user performance

[3] Example given for washing machine: “For the calculation of the Energy Efficiency Index (EEI) of a household washing machine model, the weighted annual energy consumption of a household washing machine for the standard 60 °C cotton program at full and partial load and for the standard 40 °C cotton program at partial load is compared to its standard annual energy consumption.” (48)

information in order to be able to compare with other products, with the objective of encouraging the purchase of more energy efficient models (27).

Other well known types of labeling are the European Conformity mark (28) or "CE marking" (29) and the EU ENERGY STAR label (30) shown in Figure 3 b) and 3 c). These types of labels are meant to give the end-user the knowledge that a product complies with minimum EU performance standards before being placed on the market. The EU Energy Star label was implemented in 2006 and is an appliance specific label focusing on office equipment, identifying equipment that meets certain energy efficiency standards. This has proved to be effective in moving the market to a greater efficiency (31); between the years 2008 and first half of 2009 the percentage increased from 45% to 66% in EU ENERGY STAR registered models. In the second half of 2009 a new more demanding specification was implemented which resulted in a decrease down to 30% of EU Energy Star registered models, but by the end of 2010 it had increased again to 50%.

3.2 Incentives in the EU

Several countries within the EU are offering subsidies and/or tax benefits to end-users who purchase energy efficient appliances.

In January 2007 the Italian Government introduced a tax subsidy program, in order to promote the sales of highly efficient cold appliances. End-users who bought an A+/A++ refrigerator or freezer could deduct 20% of the appliance cost (up to a maximum of 200 euro) from their income tax. As a result there was a growth in the sales of A+ class cold appliances by a factor of 2.5 in 2007 compared to the previous year. The share of A+ appliances in sales reached 45.5% in 2008 and 62% in 2010 (6).

In 2009 and 2010 Austria ran a scrapping bonus program on cold appliances during two periods; September-December 2009 and September-November 2010, where the end-user could apply for reimbursement when replacing an old appliance with a new A++ appliance (up to a maximum of 100 euro). During the first period the campaign resulted in 30% sales in Sep-Oct 2009 and 34% sales in Nov-Dec 2009, which was a considerable increase from the 15% in the months before (Jul-Aug 2009). The second period did not see quite as large an increase; in the months between the two periods the sales where between 21 and 25% whereas they rose to 38, 40 and 39% (Sep, Oct and Nov 2010, respectively) during the campaign, which was concluded to be due to early replacement buyers already being triggered by the first campaign (32).

3.3 New Smart Appliances

Smart appliances have been introduced by many manufacturers for some time now (33) (34) (35), but it was not until 2012-13 that they became available to the public. Whirlpool and LG are two of the companies which have produced lines of smart appliances that are only available in the US at this time. Below is an example of smart appliances which these companies have produced, but the information gathered only refers to electricity savings.

Whirlpool's Smart Appliances with 6th Sense Live™ Technology (5) came out in spring of 2013 and offers washing machines, dryers, refrigerators and dishwashers equipped with a technology which gives the end-user the ability to manage energy usage and control features remotely via Wi-Fi using a Smart phone, tablet or computer. These appliances are equipped with Whirlpool Rate Revealer, a software that checks for TOU prices offered by the electricity companies (this is done on-line via connection to the electricity company and therefore there is no need to be connected to a Smart Grid or having a Smart Meter) so that the end-user can choose a cost-effective time to run the appliance. In addition they are equipped with a Smart Delay feature which schedules energy-intensive tasks at cost-effective times, such as running the defrosting of the freezer or running the dishwasher (36).

In 2012 LG came out with NFC tagged appliances. LG Smart ThinQ™ line consists of washers, dryers, refrigerators and an electric oven range with grill (37). These appliances are equipped with a full range of Smart ThinQ technologies, where they can be monitored from a Smart TV or smartphone via their Wi-Fi device-to-device connectivity. In addition LG offers a Home Energy Management System (HeMS) which aids the end-user to manage their smart appliances, lighting and HVAC in a more power-efficient manner (38). The HeMS collects the energy usage via a smart meter, which can be viewed on a PC or smartphone, and suggests ways to reduce overall energy consumption. This solution only works for end-users that have a smart meter and are connected to a Smart Grid enabled power company.

3.4 Old appliances – A Home Automation solution

There are several companies offering solutions in home automation allowing the use of existing appliances by means of reading the energy usage information via the socket of individual appliances (18) (15) (16) (17) (39). In the development of this application the Home automation equipment from Plugwise (39) was used, because it is easy to use and install, as well as being successfully deployed in other experimental setup (10).

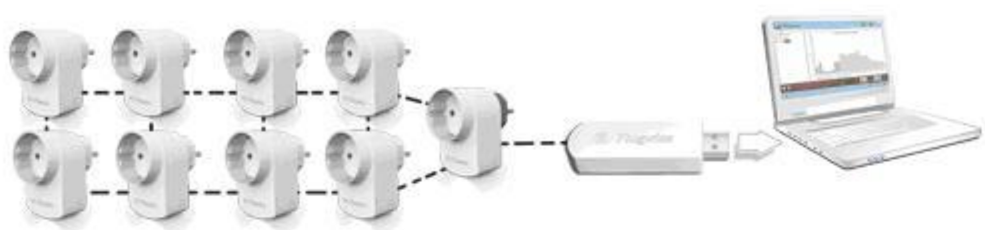


Figure 4: A Plugwise network (27)

The basic network modules (Figure 4) consist of:

- Circle — This is the actual plug which plugs in between the socket and the appliance plug. It measures the energy consumption of the connected appliance, stores the data and transmits it to the Source software, using a wireless ZigBee-mesh network. In addition it switches the appliance wirelessly on or off according to switching schemes and/or standby rules set in the Source.
- Circle+ — This plug has the role of the coordinator in the network. It keeps track of all the other Circles and communicates to the Stick. In addition it contains a clock which

the Circles use to synchronize their time stamps. Once it has been configured it can serve the role of a regular Circle.

- Stick — This is a USB dongle which communicates wirelessly with the Circles via a ZigBee-mesh network. It receives power consumption data from the Circles and provides it to the Source as well as transmits the switching schemes and standby rules from the Source to the Circles.
- Source — This is the software used to control the whole network. It allows you to view your energy consumption as well as create schemes and standby rules to automatically switch appliances on or off.

The communication protocol used by Plugwise is ZigBee (40). ZigBee is optimized to consume as little energy as possible which limits the broadcast range of a single module (Plugwise recommends 5-10 meters between modules) in the Plugwise network, but since each module can pass information to other modules one is able to cover large areas (41).

4. Design and methodology

In the research and design of the HEP a simple workflow was applied, as shown in Figure 5.

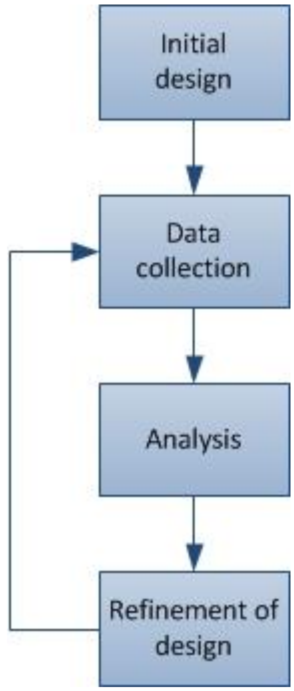


Figure 5: Iterative workflow

The initial design included defining the system context and requirements. Data collection, analysis and refinement of the design were performed in several iterations, where the design focused on optimizing the electricity consumption in a real home setting.

4.1 System context and requirements

HEP was designed to provide the end-user with a suggestion on how to optimize energy usage on existing appliances, using a home automation system. When using a home automation system such as Plugwise, the end-user is provided with the consumption of individual appliances and is able to create schedules which will turn appliances on and off, as well as standby power killers. HEP provides the end-user with information which will reduce the work of the end-user and could add to the incentive of the end-user by doing more than measuring the energy usage and possibly reducing the actual usage of individual appliances.

In order to get an overview of what the HEP's functions are a set of functional requirements where defined:

Table 2: HEP Functional Requirements

ID	Functional Requirement
	Home Energy Planner (HEP)
FR 1	The HEP shall find standby values of end-user defined appliances when applicable.
FR 2	The HEP shall provide a schedule with proposed running times of end-user defined appliances within a 24 hour period.
FR 3	The HEP shall provide the existing usage of appliances chosen.
FR 4	The HEP shall provide analysis information based on single tariff and/or split tariff.
FR 5	The HEP shall provide existing cost of appliances chosen.
FR 6	The HEP shall provide proposed usage savings of appliances chosen.
FR 7	The HEP shall provide proposed cost savings of appliances chosen.
FR 8	The HEP shall show results lexically and graphically.
FR 9	The HEP shall be easy to use in terms of supplying the end-user with information on input needed in order to complete analysis.
	End-user
FR 10	The end-user shall have control over which appliances are used in analysis.
FR 11	The end-user shall have control over which appliances are used in scheduling.
FR 12	The end-user shall have control over which time period is used in analysis.
FR 13	The end-user shall have control over tariff cost used in analysis.

4.2 Data collection

A home lab was set up in order to collect the data which was used in the design of HEP. Plugwise home automation system was used to collect the electricity consumption from individual appliances. This system is composed of a Circle+, seven Circles, a Stick and the Source application as described in chapter 3.4. The Source was installed on a laptop running Windows 7 operating system. A total of 8 appliances were measured in order to perform the required analysis needed for the design:

Table 3: List of appliances measured

Appliance
Refrigerator
Coffee maker with bean grinder
Oven
Dishwasher
Central heating system
Set-top box
DVD player
TV

4.3 Appliance classification

In using the HEP the end-user has complete control. It is up to them to classify the appliances used in the application in accordance with their own expectations and needs. There are only two classifications which the end-user needs to assign to each appliance:

1) Strict appliance (SA): These are appliances which the end-user does not want to be given schedules because they need to run all the time or be on demand from the end-user. These are typically appliances such as refrigerators, heating systems, entertainment devices, etc.
2) Flexible appliance (FA): A flexible appliance can be assigned a schedule and be run at different times within 24 hours. These could be appliances such as washing machines, dishwashers or phone chargers, which are appliances which need to be run but this can be completed within a timeframe as opposed to an exact time (such as phone needs to be charged before 7:00 am).

4.4 System overview

After careful examination of the usage data it became apparent that in order to optimize the electricity it would be most convenient to move one session of an FA to a period where electricity consumption was low. In conclusion the following steps were identified which need to be taken in HEP:

1. Determine standby power consumption for all appliances
2. Remove standby power consumption from existing data readings for all appliances
3. Add together total SA power consumptions
4. Determine power consumption, time to run and usage per session, for each FA
5. Assign slot priorities to FA based on average power consumption per session
6. Determine schedules for FA
7. Calculate estimated savings in power consumption (kWh) and cost (euro)

4.5 Standby calculation

Close analysis of the standby values versus the running values resulted in the following 3 rules:

1) The value has to occur at least twice in a row and be followed by a zero reading (no power consumption) in at least one session
2) If the appliance is never turned off (never has a zero reading) the value has to occur at least two times in a row
3) The ratio of *the value/highest reading per session* cannot exceed 7%

A closer examination of the calculation is shown in Algorithm 1, where the numbers 1), 2) and 3) correspond to the numbers of the rules above.

i = hour, 1 to 24
j = day included in analysis; days are selected by the end-user
x(*i,j*) = consumption value at given hour *i* and day *j*
high = highest value found
low = lowest value found
y(*j*) = temporary variable holding lowest values found for each day in analysis
standby-value = standby value found in analysis

Algorithm 1:

```
i := 1, j := 1
repeat
        high := x(i,j), low := x(i,j)
        if ( high < x(i+1, j) ) then high := x(i+1, j)
        if ( low > x(i+1, j) ) then low := x(i+1, j)
        i := 3
1)      repeat
                if ( high < x(i-1, j) ) then high := x(i-1, j)
                if ( low > x(i-1, j) ) then low := x(i-1, j)
                if ( x(i, j) = 0 and x(i-1, j) > 0 and x(i-1,j) = x(i-2,j) )
                        and if ( y(j) < x(i-1, j) ) then y(j) := x(i-1, j)
                else if ( x(i, j) = 0 and x(i-1, j) = 1 and x(i-2,j) > 0 and x(i-2,j) = x(i-3,j) )
                        and if ( y(j) < x(i-1, j) ) then y(j) := x(i-2, j)
        i := i+1
        until The end of 24 hours
2)      // Find lowest value if never powered off
        if ( low > 0 ) then i := 1
        repeat
                if ( x(i, j) = low and x(i+1, j) = low ) then y(j) := low
        until The end of 24 hours
3)      //The ratio of the value/highest reading per session cannot exceed 7%
        if ( high > 0 and (y(j) / high) > 0.07 ) then y(j) := 0
j := j+1
until All days in analysis have been read
standby-value := most frequent value in y(j)
```

All appliances go through the standby calculation because when the data was examined it became apparent that appliances with standby power consumption would give a misleading reading in regards to the time period these appliances run in one session.

4.6 Scheduling the appliances

Appliances which are identified as FA by the end-user are given a schedule time. In order to optimize energy consumption it is important to try to assign high consumption appliances to different timeslots that do not overlap. In the case of the end-user with a split tariff contract, assigning timeslots to the flexible appliances in off-peak timeslots is of value. The schedule times are determined by the following process:

1. All appliance readings are stripped of their standby values, according to standby rules in previous section
2. SA are added together as strict usage
3. FA are analyzed and each appliance is given the following:
    a. Hours needed to run one session (highest occurrence)
    b. Electricity consumed in one session
4. FA are given slot priority values based on average electricity consumption in one session, with the highest being assigned slot priority one and ascending
5. Total hours needed to run all FA, one session each
6. Find concurrent timeslots for the total times needed to run one session of each FA:
    a. Single tariff finds lowest total strict usage
    b. Split tariff finds lowest total strict usage including off-peak time period
7. Assign timeslots to flexible appliances based on slot priority values

4.7 Usage and savings

The HEP provides the end-user with estimated average usage in kWh's per day, estimated savings in kWh's and Euros per year. These calculations are based on the results from the previous sections as well as the tariffs provided by the end-user.

5. Implementation

This chapter describes the implementation of HEP by first describing the hardware and development tools used. Then I continue by explaining the main components and the data flow between them, the main classes and their rational, and finally the most important runtime views of the system.

5.1 Development tools

The HEP was developed on an Asus K53S laptop running a Windows7 Premium operating system. The programming language chosen was Java and the developer tool was Eclipse Java EE IDE, Indigo Service Release 2. GUI components were implemented in Java Swing which is the primary Java GUI widget toolkit and the JFreeChart 1.0.14 API was used for the creation of the graphs.

5.2 System components

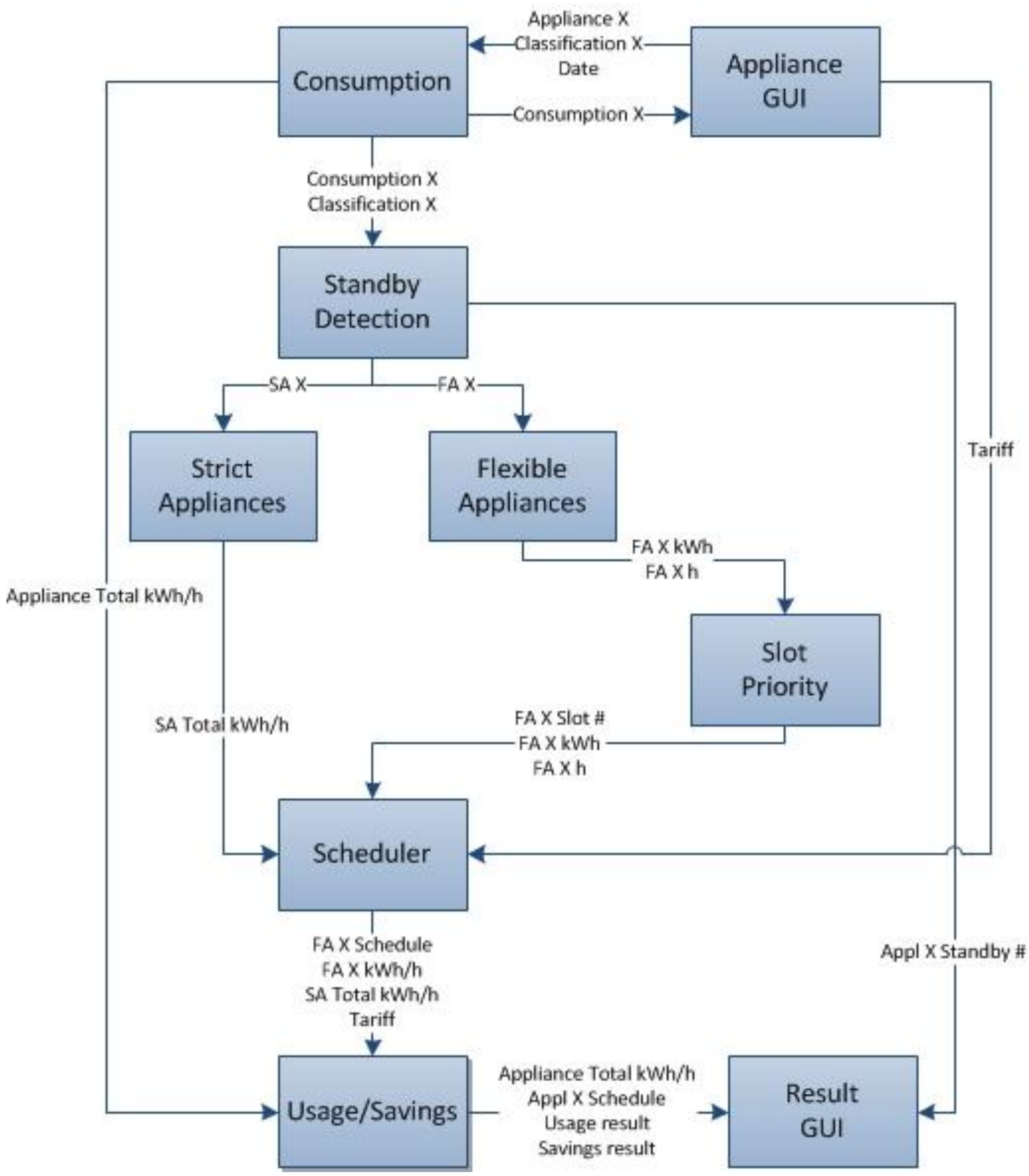


Figure 6: System components and data flow (X = id, #= number/value)

Figure 6 depicts the HEP components and the main data flow between them. In Table 4 a detailed description of each component including the data flow between them is specified.

Table 4: HEP components and data flow description

Component	Description
Appliance GUI	A Java Swing component where the end-user chooses the appliances, classifies them as strict appliance (SA) or flexible appliance (FA), chooses the dates to use in the analysis and inserts single tariff or split tariff. JFileChooser, a Java swing component is used for the uploading of the consumption files. Appliance id (Appliance X), its classification (Classification X) and dates (Date) to use in the analysis is sent to the Consumption component. The tariff information is sent to the Scheduler component (Tariff). Existing consumption for each appliance (Consumption X) is received from the Consumption component and displayed in table format.
Consumption	A Java component which reads the consumption data from the uploaded files chosen in the Appliance GUI component. It adds together the total existing kWh/h consumption for all appliances and sends it to the Usage/Savings component (Appliance Total kWh/h). It sends the existing consumption for each appliance (Consumption X) to the Appliance GUI component and Standby Detection component. In addition it sends the appliance classification (Classification X) to the Standby Detection component.
Standby Detection	A Java component which receives existing consumption data on all appliances from the Consumption component. It detects the standby values of all appliances and sends them to the Result GUI component (Appl X Standby #). In addition it removes the detected standby value from the existing consumption data for each appliance. After removing the standby consumption from all appliances it sends each Strict Appliance stripped consumption data (SA X) to the Strict Appliances component and each Flexible Appliance's stripped consumption data (FA X) to the Flexible Appliances component.
Strict Appliances	A Java component which receives each Strict Appliance's stripped consumption data (SA X) from the Standby Detection component and adds the total stripped consumption data per hour (SA Total kWh/h) and sends it to the Scheduler component.
Flexible Appliances	A Java component which receives each Flexible Appliance's stripped consumption data (FA X) from the Standby Detection component. For each Flexible Appliance it finds the highest total kWh needed to run each appliance for one session (FA X kWh) as well as finding the longest time in hours to run each appliance for one session (FA X h), which is then sent to the Slot Priority component.
Slot Priority	A Java component which assigns slot priority to all Flexible Appliances based on highest kWh needed (FA X kWh) and the largest amount of hours needed (FA X h) to run one session of an appliance in ascending order, which data was received from the Flexible Appliance component. Each Flexible Appliance slot priority number (FA X Slot #) is then sent to the Scheduler component along with FA X kWh and FA X h.
Scheduler	A Java component which creates the schedule of all Flexible Appliances. It receives the total kWh/h consumption for all stripped strict appliances from the

	Strict Appliance component and tariff information (Tariff) from the Appliance GUI component. In addition it receives the highest kWh needed (FA X kWh) and the largest amount of hours needed (FA X h) to run one session of each Flexible Appliance along with each Flexible Appliance slot priority number (FA X Slot #) from the Slot Priority component. It adds up the total amount of hours needed to run one session of all Flexible Appliances based on FA X h. Depending on the tariff, it locates a continuous time period where the consumption data of the SA appliances is lowest if the tariff is a single tariff, and assigns the times (FA X Schedule). In the case of a split tariff, it takes the time period where the tariff is off-peak and assigns the times (FA X Schedule). If the off-peak time period is too short it calculates whether the overlapping time slots should be added before, after or combined, based on lowest consumption data from the Strict Appliances. Then it adds each Flexible Appliance's consumption data per hour (FA X kWh/h) and sends it to the Usage/Savings component along with FA X Schedule, the total kWh consumption per hour for all Strict Appliances (SA Total kWh/h) and the tariff information (Tariff).
Usage/Savings	A Java component which calculates existing usage and cost based on total existing usage (Appliance Total kWh/h) received from the Consumption component and tariff information (Tariff) received from the Scheduler component. In addition, it calculates the following based on the stripped information received from the Scheduler component: • Proposed average power consumption usage per day (kWh/day) • Proposed kWh savings a year (kWh/year) • Whole cost of existing usage based on single tariff (€) • Cost of existing usage per day based on single tariff (€/day) • Whole cost of proposed usage based on split tariff (€) • Cost of proposed usage per day based on split tariff (€/day) • Estimated € savings per year (€/year) It sends the schedule for all stripped FA appliances along with total stripped SA appliances times and usage information (Appl X Schedule) to the Result GUI component. In addition, it sends all the results from the calculations of usage (Usage result), the calculations of savings (Savings results) and total existing usage (Appliance Total kWh/h) to the same component.
Result GUI	A Java Swing component where the results from the analysis and existing information is displayed. From the Usage/Saving component it receives the schedule for all stripped FA appliances along with total stripped SA appliances times and usage information (Appl X Schedule), all the results from the calculations of usage (Usage result), the calculations of savings (Savings results) and total existing usage (Appliance Total kWh/h). In addition it receives the standby values of all appliances (Appl X Standby #) from the Standby Detection component. A lexical representation of existing usage and cost, proposed usage, cost and savings (in kWh and €) is provided based on chosen single or double tariff. In addition, the times to schedule Flexible Appliances along with standby killer values for all appliances are shown lexically. JFreeChart API is used to display existing and proposed usage information graphically.

5.2 Logical view

The logical view of HEP is depicted in graphical format in Figure 7, showing the main classes, variables and methods. In addition, Table 5 describes the rationale of the main classes.

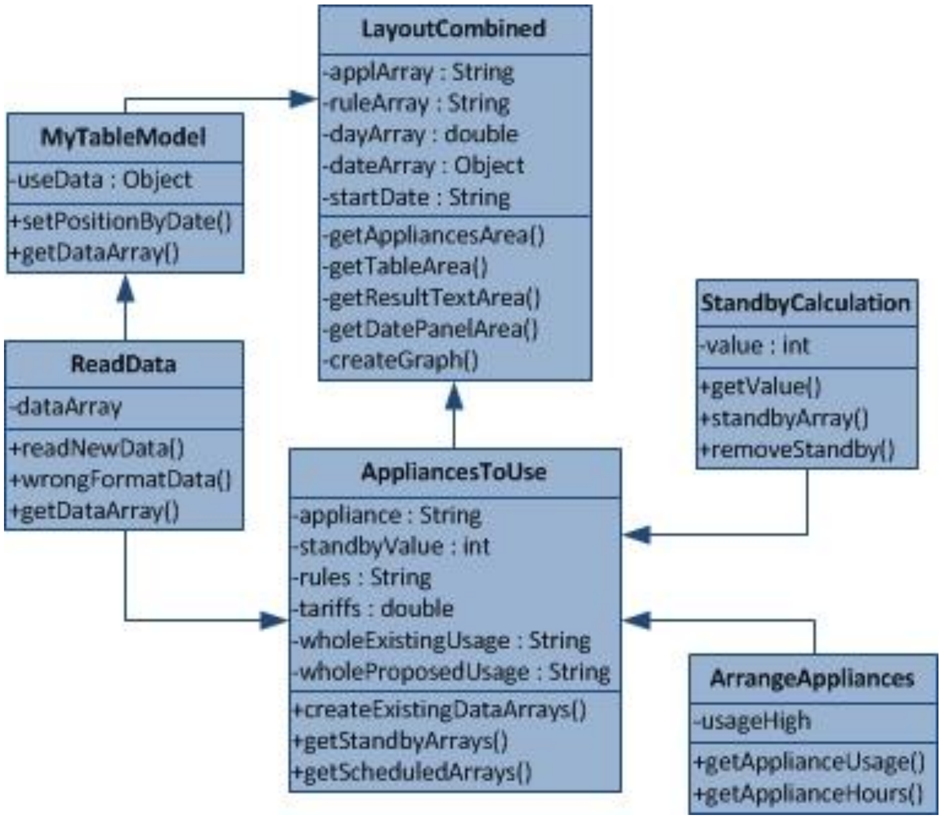


Figure 7: HEP classes showing main variables and methods

Table 5: Rationale of the main classes

Class	Rationale
LayoutCombined	The main class of the application and the GUI. (see Appendix I)
AppliancesToUse	Adds up existing power consumption usage of all chosen appliances. Adds up proposed power consumption usage of all chosen appliances. Provides all usage and cost calculations: • Whole existing power consumption usage (kWh) • Existing average power consumption usage per day (kWh/day) • Proposed average power consumption usage per day (kWh/day) • Proposed kWh savings a year (kWh/year) • Whole cost of existing usage based on single tariff (€) • Cost of existing usage per day based on single tariff (€/day) • Whole cost of proposed usage based on split tariff (€) • Cost of proposed usage per day based on split tariff (€/day) • Estimated € savings per year (€/year) Calculates proposed scheduling times of FA.
ReadData	Reads the power consumption data from the CSV files chosen by the end-user.

	Verifies that the uploaded files are of correct format.
MyTableModel	Model for the tables showing power consumption data given in the CSV files, using the dates chosen by the end-user.
StandbyCalculations	Finds standby values associated with each appliance where applicable.
ArrangeAppliances	Finds one session of an appliance running, total hours and power usage.

5.3 Runtime Views

I describe four runtime views which are identified in the form of use cases. There are other views involving the HEP but these are the most important and most used views. The “Success Scenario” row depicts the flow when the use case is correct while the “Alternative Flows” row depicts the use case based on several possible inputs which lead to a different flow and show the alternative flows along with error messages when applicable.

5.3.1 Add appliance

The end-user is in control of which appliances to use in the analysis and therefore has to select the appliance consumption files. In this use case the end-user is selecting one appliance to add to the selection, which can be done at anytime during a session in HEP.

Name	**Add an appliance**
Actors	End-user
Trigger	End-user clicks the “Add appliance” button
Preconditions	End-user elects to add a new appliance to the HEP
Post conditions	A new appliance is added to the HEP
Success Scenario	1. End-user clicks the “Add appliance” button 2. HEP displays a file-upload pop-up window 3. End-user selects a file to upload and clicks “Open” button 4. HEP displays the newly selected appliance in the list of appliances
Alternative Flows	*3a. File selected has already been uploaded* 4. HEP displays the previously selected appliances in the list of appliances *3b. File selected is in wrong format* 4. An alert box with the message “The file you chose is not the right format. Choose another file.” is displayed 5. End-user clicks the “OK” button on the alert box 6. HEP displays the previously selected appliances in the list of appliances

5.3.2 Save tariff information

The end-user inserts the tariff information into HEP. There is an option for using a single tariff and/or a split tariff. This can be done at any time after an appliance has been uploaded. The end-user is able to see the difference in cost and savings based on type of tariff as long as the chosen tariff type is saved before further information is chosen (such as 5.3.3 “View existing usage” if estimated cost information is wanted and 5.3.4 “View proposed usage”).

Name	**Save tariff information**
Actors	End-user
Trigger	End-user clicks the “Save tariff” button
Preconditions	Use case 5.3.1 is completed
Post conditions	Tariff has been saved to the HEP
Success Scenario	1. End-user clicks the “Save tariff” button 2. HEP displays the tariff information inside the input fields
Alternative Flows	**Single tariff:** *1a. Nothing has been typed into the Single tariff field* 2. An alert box with the message “The Single tariff format is wrong. (ex. 1.5601)” is displayed 3. End-user clicks the “OK” button on the alert box 4. HEP displays the previous view with the empty Single tariff field *1b. The format of the input in the Single tariff field is wrong* 2. An alert box with the message “The Single tariff format is wrong. (ex. 1.5601)” is displayed 3. End-user clicks the “OK” button on the alert box 4. HEP displays the previous view with the wrong input in the Single tariff field **Split tariff:** *1a. Nothing has been typed into the Offpeak tariff field* 2. An alert box with the message “The *Offpeak* tariff format is wrong. (ex. 1.5601)” is displayed 3. End-user clicks the “OK” button on the alert box 4. HEP displays the previous view with the empty *Offpeak* tariff field as well as other previously correctly inserted fields *1b. The format of the input in the Offpeak tariff field is wrong* 2. An alert box with the message “The *Offpeak* tariff format is wrong. (ex. 1.5601)” is displayed 3. End-user clicks the “OK” button on the alert box 4. HEP displays the previous view with the wrong input in the *Offpeak* tariff field as well as other previously correctly inserted fields *1a. Nothing has been typed into the Peak tariff field* 2. An alert box with the message “The *Peak* tariff format is wrong. (ex. 1.5601)” is displayed 3. End-user clicks the “OK” button on the alert box 4. HEP displays the previous view with the empty *Peak* tariff field as well as other previously correctly inserted fields *1b. The format of the input in the Peak tariff field is wrong* 2. An alert box with the message “The *Peak* tariff format is wrong. (ex. 1.5601)” is displayed 3. End-user clicks the “OK” button on the alert box 4. HEP displays the previous view with the wrong input in the *Peak* tariff field as well as other previously correctly inserted fields *1a. Nothing has been selected in the days checkboxes* 2. An alert box with the message “You have to select at least one day for a split tariff” is displayed 3. End-user clicks the “OK” button on the alert box

	4. HEP displays the previous view with the empty *day* fields as well as other previously correctly inserted fields *1a. Nothing has been selected in the start dropdown box* 2. An alert box with the message "You have to select start time for a split tariff" is displayed 3. End-user clicks the "OK" button on the alert box 4. HEP displays the previous view with the empty start fields as well as other previously correctly inserted fields *1a. Nothing has been selected in the end dropdown box* 2. An alert box with the message "You have to select end time for a split tariff" is displayed 3. End-user clicks the "OK" button on the alert box 4. HEP displays the previous view with the empty end fields as well as other previously correctly inserted fields

5.3.3 View existing usage

When the end-user wishes to view existing consumption usage based on chosen appliances and time period the following steps in this use case need to be taken. This will give the information regarding usage in kWh in both written and graphical format along with a list of appliances chosen. If estimated cost information is also desired use case 5.3.2 needs to be completed in addition. This use case can be performed at any time after an appliance has been chosen or added.

Name	**View existing usage**
Actors	End-user
Trigger	End-user clicks the "Existing energy use" button
Preconditions	End-user elects to view the existing energy usage, use case 5.3.1 is completed
Post conditions	The existing energy usage is displayed
Success Scenario	1. End-user clicks the "Existing energy use" button 2. HEP displays existing energy use in a graph and in written format
Alternative Flows	*2a. Use case 5.1.2 has been completed* 2. HEP displays existing energy use in a graph and in written format, as well as the existing estimated cost *2a. End-user wishes to see information about estimated cost* 2. End-user clicks on "Appliance List" button 3. End-user completes use case 5.3.2 4. End-user clicks the "Existing energy use" button 5. HEP displays existing energy use in a graph and in written format, as well as the existing estimated cost

5.3.4 View proposed usage

The following use case shows the actions which need to be taken when the end-user wishes to see the outcome of the analysis, or the proposed usage. Proposed usage displays the appliances chosen along with their proposed standby values, the proposed scheduling times of Flexible Appliances and estimated usage and saving information in kWh and euro. In addition, it shows average kWh per day in a graphical format.

Name	**View proposed usage**
Actors	End-user
Trigger	End-user clicks the “Proposed energy use” button
Preconditions	End-user elects to view the proposed energy usage and has completed use case 5.3.2
Post conditions	The proposed energy usage is displayed
Success Scenario	1. End-user clicks the “Proposed energy use” button 2. HEP displays proposed energy use in a graph and in written format
Alternative Flows	*1a. Rules have not been assigned to appliances* 2. An alert box with the message “You have to assign rules to all appliances. (strict/flexible)” is displayed 3. End-user clicks the “OK” button on the alert box 4. HEP displays the previous view with the empty rule field as well as other previously correctly selected fields

6. Evaluation

It is important that the HEP gives the end-user correct and accurate results since the main objective of the system is to aid the end-user in optimizing energy usage. Quantitative evaluations were performed as well as a verification of the requirements listed in chapter 4.1.

6.1 Objective and metrics used

In order to evaluate the HEP the two major functions of HEP were examined:

1. Standby power detection of appliances by the HEP.
2. The extent of optimization resulting in applying schedules suggested by the HEP.
   What is the result of the optimization scheduling? How much data is needed?

6.1.2 Standby power detection

Standby power detection is based on the 3 design choices (rules 1-3) defined in chapter 4.5. By applying Algorithm 1 (chapter 4.5) which resulted from these design choices to the appliances that were measured I was able to determine the standby power on five (the coffee machine, dishwasher, washing machine, stereo system and fan on a timer) out of six appliances which measured standby power. The appliance (the CD player) which was not identified had very little difference in active usage power consumption and standby power consumption. If I removed rule number 3 in order to detect this appliance two more appliances were wrongly identified to have standby power (the central heating system and DVD player). I determined that it was more accurate, for the analysis calculations as well as usefulness of the HEP for the end-user, to determine standby power on fewer appliances than the actual count, rather than giving false conclusions on appliances that should not be turned off.

I examined the correctness of these design choices by means of recording the appliances found with and without standby values according to the following test cases:

1. How well does the standby detection perform with the algorithm complete?
2. How well does the standby detection perform without rule 1 (The value has to occur at least twice in row and followed by a zero reading (no power consumption) in at least one session)?
3. How well does the standby detection perform without rule 2 (If the appliance is never turned off (never has a zero reading) the value has to occur at least two times in a row)?
4. a. How well does the standby detection perform without rule 3 (The ratio of the value/highest reading per session cannot exceed 7%)?
   b. How well does the standby detection perform if the ratio is 8%?
5. How well does the standby detection perform when none of the rules from chapter 4.5 (test cases 2-4b) are applied; in other words by means of finding the highest occurrence of the lowest value found for each appliance in one day, excluding a zero reading when other values are found in that particular day.

Each test case was recorded by means of the standby value detected for each appliance or “None” (if a standby value was not detected) using the same appliances and the same data files in all cases. By measuring these results I was able to prove the extent of correctness as well as incorrectness of the algorithm designed to detect standby values by calculating precision, recall, F-measure, specificity and accuracy.

6.1.2 Optimization

In order to evaluate the results of the optimization three time periods were processed; 1, 3 and 5 months using the same consumption data. The possible flattening of peak energy usage resulting from processing appliances in the HEP was examined. The results are quantified by the use of average absolute deviation from the mean power. I show comparative results between existing usage and suggested usage and compare the results in order to identify whether the time periods used in the analysis make a difference. In addition, the result of applying single or split tariff was examined by comparing the outcome of the scheduling as well as the monetary values resulting from the same appliance measurements.

6.2 Experimental setup

The application HEP was designed and developed using real life consumption data collected in a residence occupied by a family of 3 in the Netherlands. Plugwise (chapter 4.2) home automation system was used to measure appliances and collect consumption data. In addition, in the case of not being able to use the Plugwise home automation system to measure consumption, real life usage of appliances was timed and recorded.

Figure 8: The home lab including the Plugwise ZigBee-mesh network

Figure 8 shows the actual floor plan of the home lab with the setup of the appliances measured, which are identified as follows:

- Circle+. Refrigerator
1. Coffee maker with bean grinder
2. Hand-vacuum cleaner / additional appliances
3. Fan on a timer / additional appliances
4. Oven
5. Dishwasher

6. Central heating system
7. Set-top box / additional appliances
8. DVD player
9. TV
10. Router
11. Stereo system / additional appliances

6.2.1 Measured appliances

During the design and development of HEP I used one Circle+ and seven Circles. In order to get a larger variety of appliance readings, as well as more accurate total appliance consumption in 24 hours, the data collection began by identify appliances which had consistent usage and therefore the runtime without using a Circle could be documented.

Fan on a timer (Circle 3) was running on a timer and therefore showed the same reading every day; four hours running with 15-16 kWh (x0.001) for three hours, one hour with a 10 kWh (x0.001) reading and the remaining twenty hours had a reading of 1 kWh (x0.001). The set-top box (Circle 7) had a consistent reading of 8 kWh (x0.001) when plugged in (no standby setting available). In addition it was consistently turned on when the TV (Circle 9) was turned on in the morning and turned off when the TV was turned off for the last time in the evening. Therefore the reading of the set-top box is calculated by using the timing measurements from the TV. The Hand-vacuum cleaner (Circle 2) and the Stereo system (Circle 11) where extremely sparingly used, therefore the readings collected from them are only used when determining the algorithms used in the analysis on standby power consumption.

6.2.2 Timed appliances

Washing machines and clothes dryers where responsible for 7.2% of the average household power consumption in 2009 (6). These types of appliances are high in consumption and are appliances which do not have to run on command, but the end-user can schedule the runtime within a time period. Therefore, these two appliances were important to include in the design and analysis of the HEP. The washing machine and clothes dryer in the residential setting used for collection of data where not connected to power through conventional sockets and therefore the Circles were not an option. In order to simulate the power readings of these two appliances we documented the times and dates the two appliances were powered on and off, as well as documenting the program that the washing machine was using (delicate, 40°C and 90°C). We then used the technical information contained in the users' manuals (dryer: (42), washer: (43) to determine the total average usage per load.

The washing machine manual states that the delicate program runs for 50 minutes and consumes 0.3 kWh, a 40°C program runs for 110 minutes and consumes 0.55 kWh, and a 90°C program runs for 110 minutes and consumes 1.90 kWh, which was consistent with my documented timeframes. The manufacturer's data is based on each load of wash being a fully loaded machine (except only half full for the delicate wash) there will always be a variation on the weight of the load, and therefore I assume that each load's power consumption could vary ±0.2 kWh. The randomly generated total consumption of each load was divided randomly into the documented timeslots. Finally, a standby consumption of 0.002 kWh is assumed, since the washing machine does not power off when the program has completed, but there is a light blinking which indicates that the program has finished. The standby consumption value is the same as the standby consumption value measured from the dishwasher, which also does not power off when completed but has a blinking light indicating that the program is finished.

The clothes dryer always ran for 80 minutes for each load and once completed, it does not consume any standby power. In the manual it is stated that a 5kg load of clothes which comes from a washing machine using a 1200 spin cycle consumes 2.7 kWh. Even though each load of wash was for a fully loaded machine there will always be some variation in weight. Therefore, it was assumed that each load can vary within 2.7±0.2 kWh, and assigned randomly generated numbers divided into the documented time slots.

6.2.3 Data collection during experiment

A Plugwise mesh-network was set up as seen in Figure 8. Energy consumption data was collected over a period of 5 months continuously, in an existing residence of 3 persons in the Netherlands, on the following appliances:

1. Refrigerator
2. Coffee maker with bean grinder
3. Oven
4. Dishwasher
5. Central heating system
6. Set-top box
7. DVD player
8. TV

In addition to the continuous reading by the Circle's, each appliance's state was recorded in order to detect actual standby power readings.

In order to get a greater variety, the following appliances were measured while plugged in over a period of 1 week. In addition each appliance's state was also recorded (i.e. Film recorder charging, Film recorder fully charged):

9. Router
10. Fan on a timer
11. Hand-vacuum cleaner (charger)
12. Stereo system
13. CD player
14. Wireless doorbell unit
15. Bread toaster
16. Film recorder (charger)
17. Radio

The router and the fan on a timer (appliances 9 and 10 respectively) were observed as appliances running on a pattern, as explained in chapter 6.2.1, which was applied to their readings in order to produce 5 months of data.

The following appliances' power consumption was documented by way of the runtimes of each session used and program used, over the same 5 month period as for appliances 1-8 above, as explained in chapter 6.2.2:

18. Washing machine
19. Clothes dryer

6.2.4 Data processing

The Plugwise user manual states that the consumption data can be exported to a CSV file (44), but that facility is only available in the Source Pro which I did not have access to. Therefore, I manually inserted the measured data from Source to the CSV files. The structure of the file is assumed to be the same as the table views in Source (Table 6) where the first column represents weekdays and columns 2-25 represent 24 hours in one day.

Table 6: Data representation in table format as shown in Source

T	32	43	47	38	48	26	42	42	43	47	22	63	24	60	20	59	46	43	54	24	57	33	57	25
W	52	37	49	40	30	44	33	56	28	48	29	60	29	48	33	56	39	44	43	47	39	35	48	44
T	42	36	36	49	34	40	25	53	37	41	36	40	52	34	48	28	54	31	60	22	56	28	49	35
F	46	36	40	38	33	39	30	49	31	50	26	53	28	50	34	47	36	47	42	41	44	36	47	32
S	50	25	56	19	57	15	59	13	60	18	61	24	53	31	46	40	40	50	37	50	34	53	32	58
S	25	54	28	46	35	36	41	30	45	29	47	34	46	44	40	51	30	58	29	54	27	53	34	43
M	48	29	50	28	46	27	44	34	46	33	45	37	44	41	42	41	50	36	55	32	46	42	39	45

The consumption data from Source was manually inserted into CSV files named after each appliance type using the following structure:

Table 7: Structure of the CSV files

The following is repeated for each week used in analysis		
Row	**Column**	**Data type**
1	3-27	timeslots
2-8	1	date
2-8	2	weekday
2-8	3-27	usage readings per hour (shown in orange above)

The data for the router, the fan on a timer, the washing machine and the clothes dryer were inserted in the same manner using the measured, timed and calculated values as described in chapter 5.1.

6.2.5 Observed appliance values, standby values and classifications

Close examination of recorded data for each appliance resulted in the findings of; actual standby value (ASV), the range of measured values (lowest to highest consumption reading larger than zero), whether there is a zero reading on an appliance without turning it off. These findings are shown in Table 3 as ASV, Range and Zero reading, respectively.

In order to determine the actual standby value for each appliance the recorded consumption data was examined, with further tests being carried out when needed. The methodology for each appliance is as follows.

Appliances determined to have standby values:

- **Coffee maker with bean grinder** (appliance 2) has a built in programmable standby function which was active between 20:00 and 07:00 each night and returned a consistent reading of 4.
- **Fan on a timer** (appliance 10) activated the fan four hours each day and returned a constant reading of 1 for the remaining eighteen hours.
- **Stereo system** (appliance 12) and **CD player** (appliance 13) both had a light indicating that they where plugged in, but an on/off button needed to be pushed, either on the appliance itself or on a remote control, in order to activate them. The initial reading (without pushing the on/off button) returned constant readings of 2 for the stereo system and 6 for the CD player.
- **Dishwasher** (appliance 4) had a blinking light which turned on as soon as a program was selected, but an on button needed to be pushed in order to activate the session. In addition, when the session was completed the light remained blinking until the program knob was turned to off. The readings before and after activation of the session returned 2 (the test was completed for three hours both before and after running a session).
- **Washing machine** (appliance 18) was observed to perform in the same manner as the dishwasher, with a blinking light indicating that a program had been selected, an on button to activate the session and a blinking light remaining lit until the program knob was turned to off. This resulted in the assumption that it had a standby value which was determined to be 2, the same as the dishwasher.

Appliances determined not to have standby values:

- **Refrigerator** (appliance 1) and **central heating system** (appliance 5) are appliances which are constantly running and cannot be turned off by use of the Plugwise standby killer alone since they would need an additional mechanism to be turned on again automatically. Therefore, they are both noted as not having a standby value in this evaluation. The refrigerator did not return a low value larger than zero which could indicate a standby value, but the central heating system returned the value 7 constantly for periods of one to four hours which could indicate a standby value. Since we did not desire to detect this value rule 3 (The ratio of *the value/highest reading per session* cannot exceed 7%) was applied to the standby detection algorithm in chapter 4.5.
- **Oven** (appliance 3), **bread toaster** (appliance 15) and **clothes dryer** (appliance 19) are all appliances which are turned on, show a different reading every time which is quite high and are either turned off (oven) or turn themselves off, with a 0 reading, when a session is completed (bread toaster and clothes dryer).
- **Set-top box** (appliance 6) and **router** (appliance 9) are appliances which need to be turned on and off with a button and have the same constant reading when turned on and 0 when turned off. An exception did occur in some instances in the first hour (when turned on) and/or the last hour (when turned off) of a session, where the value was lower or higher. It was determined that

this was the cause of turning the appliance on/off in different timeframes within an hour since when these appliances were tested for exactly three hours, starting at 1 minute past the first hour and ending at 59 minutes past the third hour, this variation did not occur.

- **DVD player** (appliance 7) showed a reading of 4 or 5 when turned on, whether there was a disc playing or not. An exception did occur in some instances in the first hour (when turned on) and/or the last hour (when turned off) of a session, where the value was lower or higher. It was determined that this was the cause of turning the appliance on/off in different timeframes within an hour since when these appliances were tested for exactly three hours, starting at 1 minute past the first hour and ending at 59 minutes past the third hour, this variation did not occur.
- **TV** (appliance 8) showed a reading of 44 or 45 when turned on and a reading of 0 when turned off, both with a button on the appliance and with a remote control. An exception did occur in some instances in the first hour (when turned on) and/or the last hour (when turned off) of a session, where the value was lower or higher. It was determined that this was the cause of turning the appliance on/off in different timeframes within an hour since when these appliances were tested for exactly three hours, starting at 1 minute past the first hour and ending at 59 minutes past the third hour, this variation did not occur.
- **Radio** (appliance 17) showed a constant reading of 3 at all times when turned on and 0 when turned off.
- **Hand-vacuum cleaner (charger)** (appliance 11) and **film recorder (charger)** (appliance 16) are both chargers which showed a constant reading when the appliance was positioned in the charger unit and 0 when it was taken out of the charger unit. An exception did occur in some instances in the first hour (appliance in charger unit) and/or the last hour (appliance removed from charger unit) of a session, where the value was lower or higher. It was determined that this was the cause of inserting and removing the appliance in different timeframes within an hour since when these appliances were tested for exactly three hours, starting at 1 minute past the first hour and ending at 59 minutes past the third hour, this variation did not occur.
- **Wireless doorbell unit** (appliance 14) is an appliance which is always plugged in and has no on/off function. This appliance showed a reading of 2 and 3 at all times.

Table 8: Appliance readings and classifications based on outcomes of data measurements

ID	Appliance	ASV	Range	Zero reading	On/Off	Type
1	Refrigerator	None	1-88	Y	N	SA
2	Coffee maker with bean grinder	4	1-103	N	Y	SA
3	Oven	None	465-1468	N	Y	SA
4	Dishwasher	2	1-946	N	Y	FA
5	Central heating system	None	7-91	N	N	SA
6	Set-top box	None	1-14	N	Y	SA
7	DVD player	None	1-6	N	Y	SA
8	TV	None	1-66	N	Y	SA
9	Router	None	1-10	N	Y	SA
10	Fan on a timer	1	1-17	N	N	FA
11	Hand-vacuum cleaner (charger)	None	2-3	Y	N	SA
12	Stereo system	2	2-46	N	Y	SA
13	CD player	6	6-11	N	Y	SA
14	Wireless doorbell unit	None	2-3	N	N	SA
15	Bread toaster	None	28-51	N	Y	SA
16	Film recorder (charger)	None	4-9	Y	N	FA
17	Radio	None	3	N	Y	SA
18	Washing machine	2	1-1076	N	Y	FA
19	Clothes dryer	None	510-2324	N	Y	FA

In addition to the above findings Table 7 shows two classifications; an on/off appliance, and finally whether an appliance type is classified as Strict Appliance (SA) or Flexible Appliance (FA). An on/off appliance classification is based on whether it is an appliance which is turned off and on, by way of a button or automatically turned off after one running session. The type classifications SA and FA are selected in order to simulate the input of the end-user. In the case of the appliance not having a standby value "None" is recorded in the ASV column. All numerical results are shown in kWh (x 0.001) and finally the zero reading and on/off appliance is denoted with Y=yes and N=no.

6.2.6 Tariff information

Requirements FR5 and FR7 state that the system shall display existing cost and proposed cost savings respectively. In addition, requirement FR4 states that the HEP shall provide analysis information based on single tariff and/or split tariff. In order to simulate the monetary values and savings for a single tariff, real tariffs were obtained from my personal energy invoice from Essent (45), where a single tariff is 0.2241 €/kWh. A quotation via email was obtained as well from Essent regarding the split tariff, which is 0.2387 €/kWh during peak periods and 0.2125 €/kWh during off-peak periods. Peak periods are from 07:00 to 23:00 Monday through Friday and off-peak periods are at all other times.

6.3 Standby power detection evaluation

Evaluation of the standby power detection was performed by means of measuring the validity of the three rules determined during the design of the HEP:

1) The value has to occur at least twice in row and followed by a zero reading (no power consumption) in at least one session
2) If the appliance is never turned off (never has a zero reading) the value has to occur at least three times in a row
3) The ratio of the value/highest reading per session cannot exceed 7%

The test cases, numbered 1-5 in chapter 6.1.2, were performed by means of removing the appropriate functions in the implementation of the HEP. In order to detect standby power all 19 appliances listed in chapter 6.2.3 were processed through the standby power detection in HEP. One week of usage for each appliance was used, where the week of usage was chosen based on the appliance having at least one session were the standby power was measured or recorded for at least two time slots. This is done due to the design decision that the standby power algorithm only detects standby power on appliances which have this criterion as described in chapter 5.6.

Table 9: Results of experimental measurements of 19 appliances, shown in kWh (x 0.001)

ID	Appliance	ASV	1	2	3	4a	4b	5
1	Refrigerator	None	None	5	None	69	None	5
2	Coffee maker	4	4	2	4	4	4	2
3	Oven	None	None	None	None	None	None	None
4	Dishwasher	2	2	None	2	2	2	1
5	Central heating system	None	None	None	None	7	7	8
6	Set-top box	None	None	None	None	8	None	8
7	DVD player	None	None	None	None	5	None	5
8	TV	None	None	1	None	45	None	4
9	Router	None	None	None	None	10	None	None
10	Fan on a timer	1	1	1	None	1	1	1
11	Hand-vacuum (charger)	None	None	None	None	2	None	2
12	Stereo system	2	2	2	None	2	2	2
13	CD player	6	None	None	None	6	None	6
14	Wireless doorbell unit	None	None	None	None	2	None	2
15	Bread toaster	None	None	None	None	None	None	None
16	Film recorder (charger)	None	None	None	None	None	None	None
17	Radio	None	None	None	None	3	None	None
18	Washing machine	2	2	None	2	2	2	None
19	Clothes dryer	None	None	None	None	None	None	None

The results in Table 9 were then grouped together as appliances with standby power consumption which were correctly identified (true positive), appliances which were not detected (false negative), appliances which were incorrectly detected (false positive) and finally correct absence of standby values detected (true negative). Results are shown in Table 10 below.

Table 10: Summarized results of standby value evaluation

	Test cases	1	2	3	4a	4b	5
tp	Appliances correctly identified with correct standby value	5	2	3	6	5	3
fn	Appliances with standby value missing	1	3	3	0	1	1
fp	Appliances incorrectly identified	0	3	0	9	1	9
tn	Correct absence of standby value	13	11	13	4	12	6

The metrics used for evaluation are precision, recall, F-measure, specificity and accuracy. This was done by means of classification using the following five formulas (46):

$$Precision = \frac{tp}{tp + fp}$$

Precision is defined as the number of items correctly identified as belonging to the positive class, divided by the total number of items incorrectly labeled as belonging to the class.

$$Recall = \frac{tp}{tp + fn}$$

The recall is defined as the number of items correctly identified as belonging to the positive class, divided by the total number of items which were not labeled but should have been labeled as belonging to the class.

$$F_1 = 2 * \frac{Precission\ * \ Recall}{Precission\ + \ Recall}$$

The F-measure (F_1) is known as the measure which combines precision and recall into a harmonic mean where precision and recall are evenly weighted.

$$Specificity = \frac{tn}{tn + fp}$$

Specificity gives the relation between the ability of the test case applied to identify negative results.

$$Accuracy = \frac{tp + tn}{tp + tn + fp + fn}$$

Accuracy is a parameter for the test cases. It gives the proportion of both true results measured (tp and tn).

Table 11 below presents the results from the calculations.

Table 11: Precision, recall, F-measure, specificity and accuracy of standby value test cases

	Precision	Recall	F-measure	Specificity	Accuracy
Test case 1	1.00	0.83	0.91	1.00	0.95
Test case 2	0.67	0.40	0.50	0.23	0.68
Test case 3	1.00	0.50	0.67	1.00	0.84
Test case 4a	0.40	1.00	0.57	0.69	0.53
Test case 4b	0.83	0.83	0.83	0.08	0.89
Test case 5	0.25	0.75	0.37	0.60	0.47

Test case 1 shows the results when the algorithm is used in its completeness and test case 5 shows the results when a standby number is identified by simply finding the highest occurrence of the lowest value found for each appliance without applying the algorithm. The other test cases are designed around the rules in chapter 4.5, by omitting each rule from the algorithm in each test case. This is reflected in the different outcomes depending on what is being measured. As an example, we recall that rule 1 says that the value has to occur at least twice in row and be followed by a zero reading; this ensures that the value is at the end of one running session. Often appliances had a very low reading as the first and last hour of reading in a session, due to the appliance being turned on or off when only few minutes where left of the hour. These values can easily be identified as the standby value if this rule is omitted, and therefore giving a low outcome in specificity (0.23) and F-measure (0.50). Another example is when we omit rule 3, which states that the ratio of the value/highest reading per session cannot exceed 7%, we can easily identify standby values on appliances incorrectly (Table 10 shows that 9 appliances where identified incorrectly in test case 4a) which results in a very low specificity outcome (0.08).

6.4 Optimization evaluation

An optimization evaluation was performed using the appliances which I measured power consumption; over a period of 5 months (numbering is according to chapter 6.2 Experimental setup). This prototype of the HEP allows for 10 appliances to be used in one analysis and therefore I made a decision to remove two of the twelve appliances based on the classification (SA or FA), power consumption and usage. As a result of these observations it was decided to leave out the oven (appliance 3) and the DVD player (appliance 7), which resulted in the reduced list of appliances in Table 12.

Table 12: Appliances used in optimization evaluation

ID	Appliance	ASV	Type
1	Refrigerator	None	SA
2	Coffee maker	4	SA
4	Dishwasher	2	FA
5	Central heating system	None	SA
6	Set-top box	None	SA
8	TV	None	SA
9	Router	None	SA
10	Fan on a timer	1	FA
18	Washing machine	2	FA
19	Clothes dryer	None	FA

6.4.1 Graphical results – flattening of peaks

The appliances were processed through the HEP using data collected over a period of 5 months, 3 months and 1 month, with the results shown in graphical form in Figures 9-11 on the following pages. Each figure shows three graphs representing existing usage, proposed usage with a single tariff and proposed usage with a split tariff during one day.

Each graph represents in blue the average usage (vertical axis) per hour (horizontal axis), based on the data calculated over the respective periods. To further explain; the value in the first hour (0-1 Hours) of existing usage represents the total consumption of all measured appliances which were running in the first hour each day divided by the number of days in the selected period. The first hour of the single and the split tariff graphs show the predicted outcome of average usage after the scheduling calculation (Chapter 4.6) has been applied.

In order to detect the flattening of peaks the mean for each of the three datasets is displayed in red in each graph. This allows for a clear comparison of peak magnitudes and duration of peak periods. As an example when viewing Figure 9 one can see that the existing usage has one peak with duration of 14 hours (9:00-23:00) and a maximum magnitude of 0.393 kWh (20:00-21:00). The proposed single tariff usage has two peaks with duration of 2 (1:00-3:00) and 4 hours (20:00-24:00) and a maximum magnitude of 0.902 kWh (20:00-21:00), and finally the proposed split tariff has three peaks with duration of 2 hours each (4:00-6:00, 20:00-22:00, 23:00-1:00) and a maximum magnitude of 0.778 kWh (23:00-24:00).

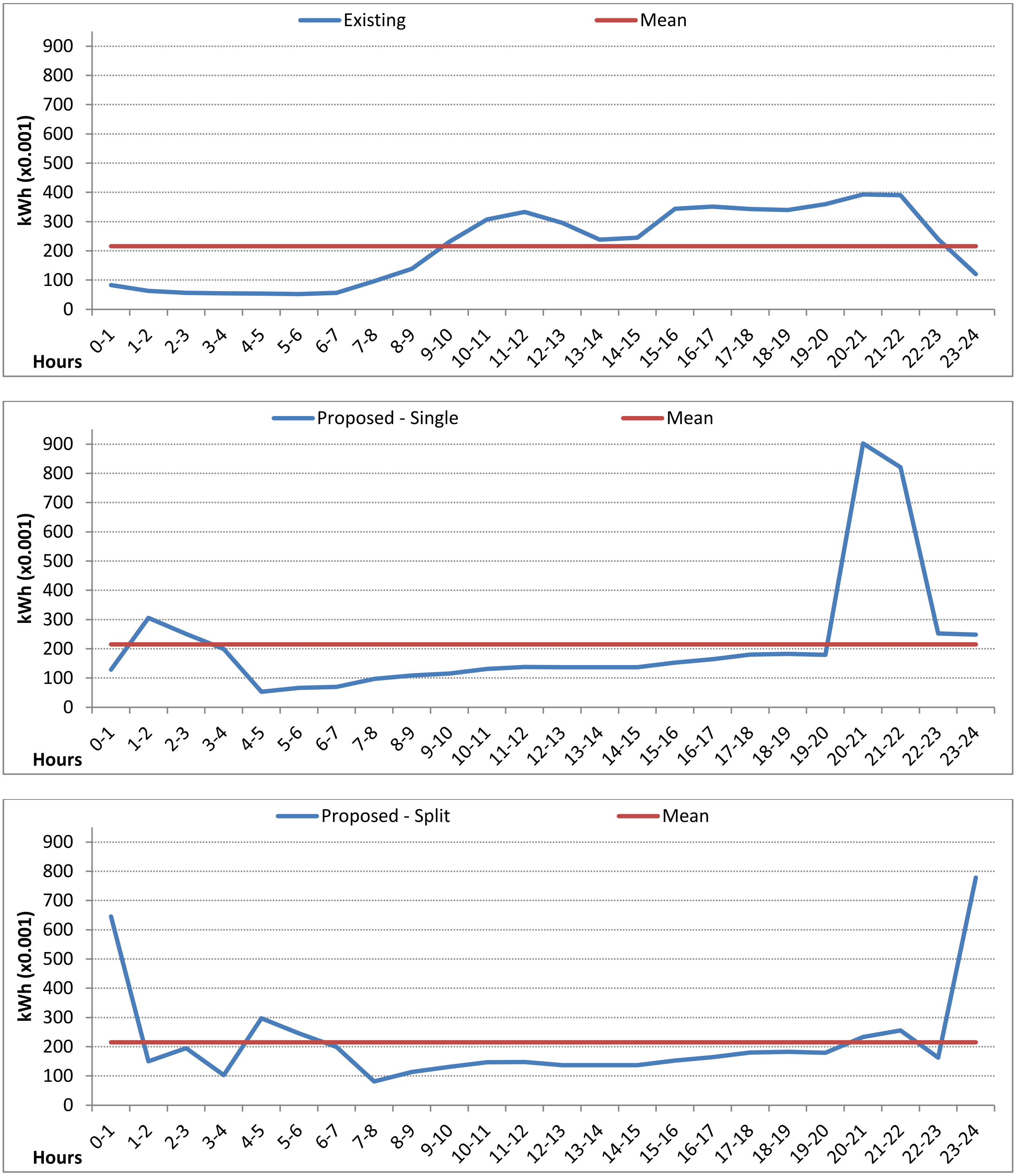


Figure 9: Average electricity consumption for one day using 5 months of data

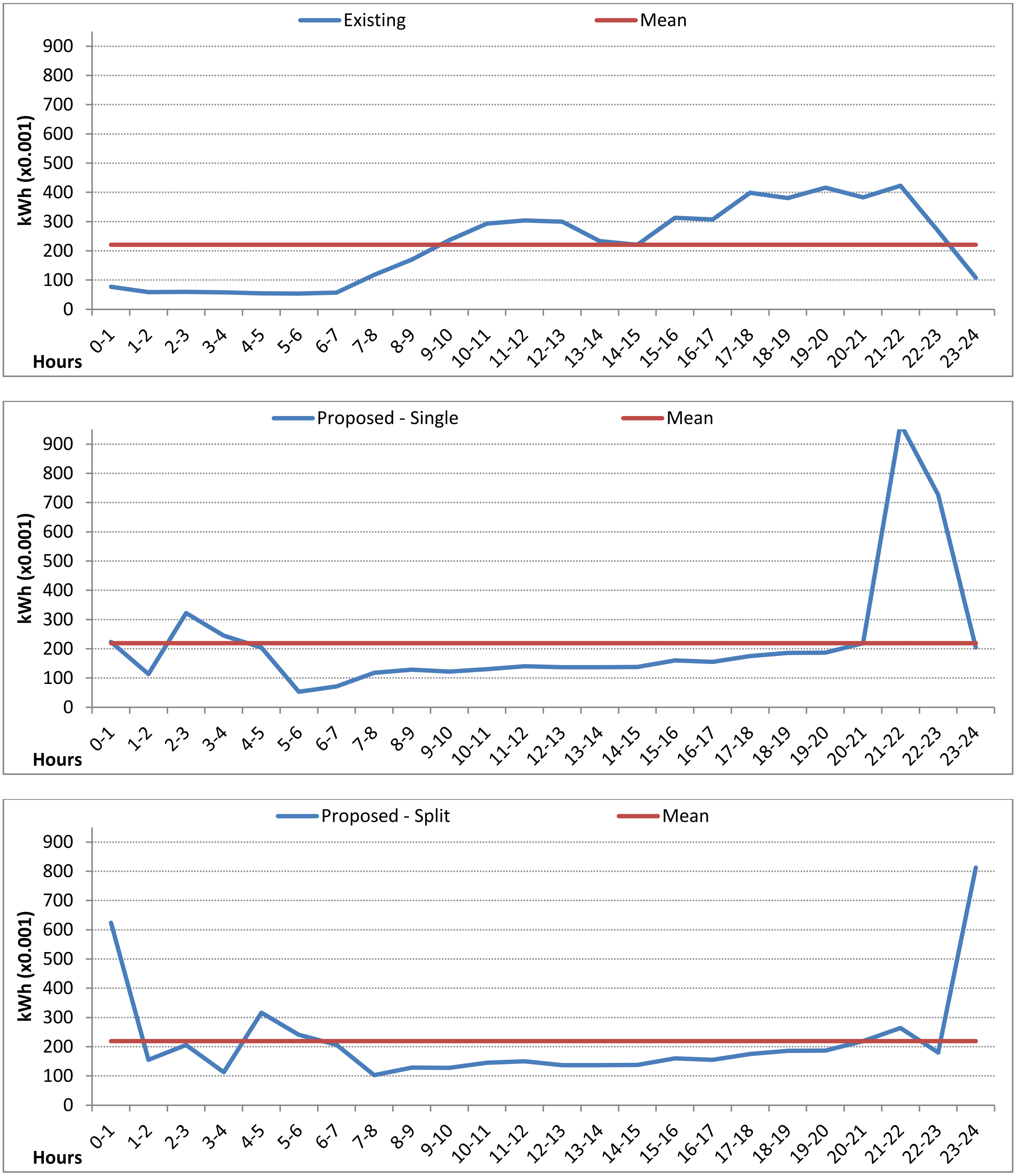


Figure 10: Average electricity consumption for one day using 3 months of data

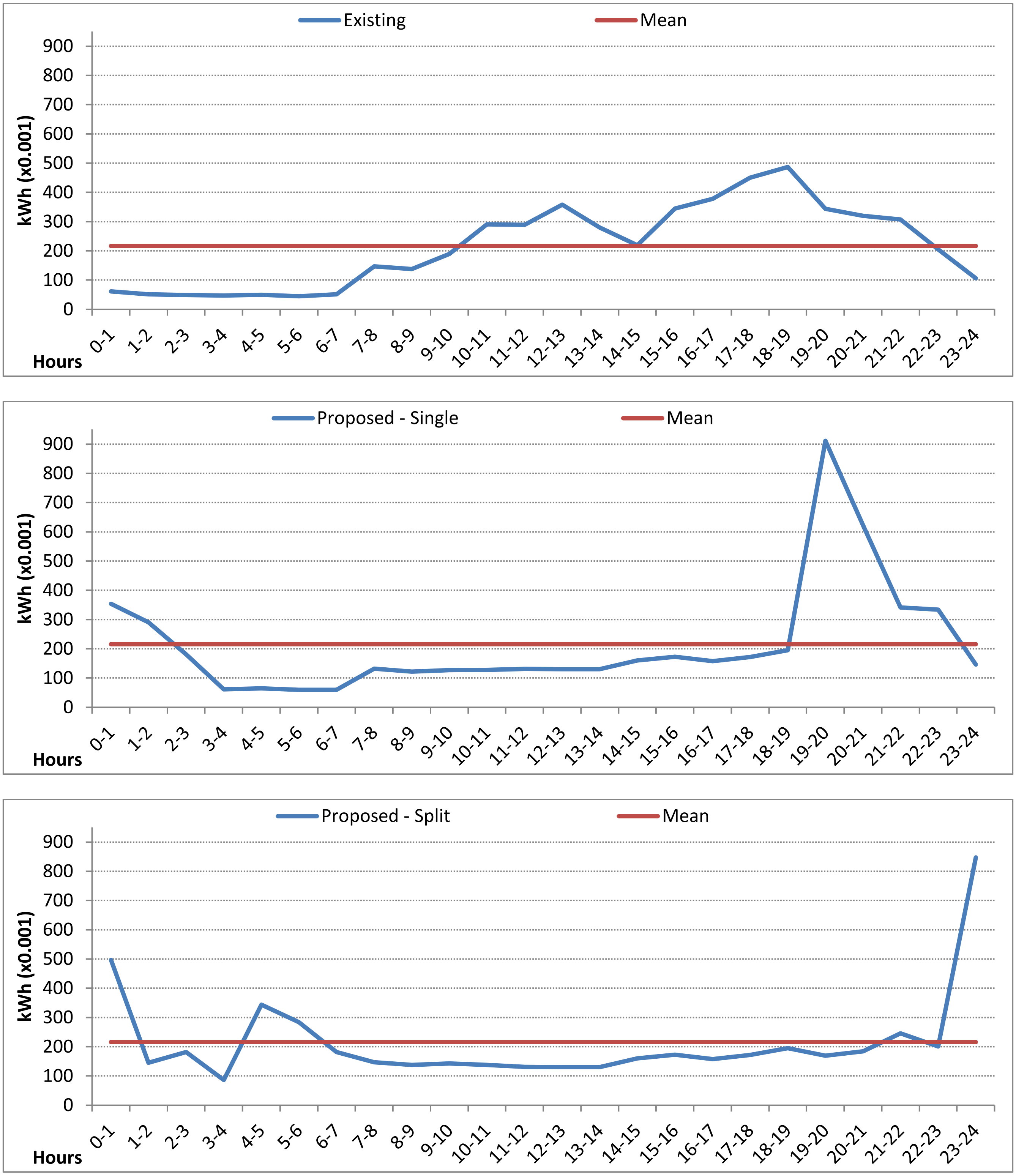


Figure 11: Average electricity consumption for one day using 1 month of data

Average absolute deviation from the mean power was used to quantify the flattening over an interval of one day's average power consumption usage in the same manner as Barker et. al. in their SmartCap project (12). The formula used was (47):

$$\frac{1}{n}\sum_{i=1}^{n}[abs(x_i - mean(\overline{x}))]$$

where $\{x_1, x_2, \dots, x_{24}\}$ is the dataset containing the consumption data (existing, proposed with single tariff and proposed with split tariff) over a period of 24 hours, x_i is the value of the consumption dataset at hour *i* and $mean(\overline{x})$ is the mean value of the dataset.

Table 13: Average absolute deviation from the mean power using 5 months of data

Average absolute deviation from the mean power in kWh (x0.001) – 5 months	
Existing	115.53
Proposed – Single	124.23
Proposed – Split	97.17

Table 14: Average absolute deviation from the mean power using 3 months of data

Average absolute deviation from the mean power in kWh (x0.001) – 3 months	
Existing	115.75
Proposed – Single	115.76
Proposed – Split	96.64

Table 15: Average absolute deviation from the mean power using 1 month of data

Average absolute deviation from the mean power in kWh (x0.001) – 1 month	
Existing	122.04
Proposed – Single	129.75
Proposed – Split	94.87

Tables 13-15 display the average absolute deviation from the mean power for 5, 3 and 1 month of data respectively. Each table shows the results for existing usage, proposed usage with a single tariff and proposed usage with a split tariff, using the given dataset. The lower the outcome of the calculation is the greater the flattening over the given interval.

All three time periods resulted in the same schedules of the Flexible Appliances which were as follows:

Table 16: Scheduling times resulting from 1, 3 and 5 months of data

	Single tariff	Split tariff
Clothes dryer	20:00	23:00
Washing machine	22:00	1:00
Dishwasher	1:00	4:00
Fan on a timer	5:00	8:00

6.4.2 Calculation results – existing and proposed usage and savings

The results of electricity usage and savings given by HEP were then recorded. Table 17 shows the results of the calculations performed by HEP displayed for the same three periods used above (1, 3 and 5 months).

Table 17: Outcomes of usage calculations performed by HEP

	Existing usage kWh	Existing usage kWh/day	Estimated usage kWh/day	Estimated savings kWh/year
Tariff	**Both***	**Both***	**Both***	**Both***
5 months	793.402	5.186	5.158	10.23
3 months	486.944	5.293	5.267	9.498
1 month	161.430	5.207	5.184	8.442
*Single and Split				

Table 17 shows the outcome of the calculations regarding electricity usage and savings in kWh. The results of the calculations are the same for both single and split tariffs in all cases and are therefore labeled “Both” in the Tariff row. The first two data columns show total existing usage in kWh’s and the average per day based on the total existing usage divided by number of days in the dataset. The following column is the outcome from the calculations performed after the scheduling calculation (chapter 4.6) has been applied, that is the estimated kWh usage per day. The final column shows the predicted savings in kWh per year based on the outcome of the scheduling calculation.

Table 18: Outcomes of cost calculations performed by HEP

	Existing cost €		Estimated existing cost €/year		Estimated savings €/year	
Tariff	**Single**	**Split**	**Single**	**Split**	**Single**	**Split**
5 months	177.8	180.14	424.16	429.75	2.29	15.36
3 months	109.12	110.55	432.92	438.60	2.13	15.46
1 month	36.18	36.69	425.99	431.99	1.89	15.96

Table 18 shows the outcome of calculation regarding cost and savings in euros. Existing cost in euro's is depicted in the first two data columns, based on existing usage in kWh and the price of single and split tariffs. Following two columns are not results from HEP calculations but are added to this table for clarity. These columns show an estimation of total cost per year based on the existing cost and usage from the two previous columns. The final two columns show the prediction of savings in euro's if the scheduling calculation (chapter 4.6) is applied and a single tariff is used on one hand and a split tariff on the other.

I used the data in Tables 17 and 18 to calculate the percentage difference between the measured periods in kWh consumption shown in Table 19 and the percentage difference in cost and savings between using a single or split tariff shown in Table 20. The percentage difference is determined by the difference of the two values divided by the average of the two values.

Table 19: Percentage difference of usage calculations between periods

Between periods	Existing usage kWh	Existing usage kWh/day	Estimated usage kWh/day	Estimated savings kWh/year
Tariff	**Both***	**Both***	**Both***	**Both***
3-5 months	50.72%	2.04%	2.09%	7.42%
1-3 months	52.57%	1.64%	1.59%	11.77%
1-5 months	132.37%	0.40%	0.50%	19.15%
*Single and Split				

In Table 19 the first data column depicts the percentage difference between the three periods of existing usage in kWh, where 1 month has the lowest amount and 5 months have the highest amount of kWh used. The second column shows the difference based on existing usage per day. Here 5 months have the lowest usage and 3 months the highest per day. In the final two columns the scheduling calculations (chapter 4.6) have been applied. The third data column shows the difference in usage between the periods, where 5 months have the lowest estimated usage and 3 months the highest. In the final column, which depicts estimated savings in kWh per year, 5 months have the highest amount of estimated savings and 1 month has the lowest.

Table 20: Percentage difference of cost calculations between single and split tariffs

Between tariffs	Existing cost €	Estimated existing cost €/year	Estimated savings €/year
5 months	1.31%	1.31%	148.10%
3 months	1.31%	1.30%	151.56%
1 month	1.40%	1.40%	157.65%

The first two data columns in Table 20 are showing the percentage difference between using single or split tariff based on existing usage. In all periods the split tariff shows a higher cost than single tariff. The third and final data column depicts the percentage difference in predicted savings between the two tariffs after the scheduling calculation (Chapter 4.6) has been applied, where again the split tariff shows higher savings than single tariff.

6.5 Requirement verification

A set of functional requirements were determined in order to capture the desired functionalities of HEP. Table 20 depicts the verification of each of the requirements.

Table 21: Requirement verification

ID	Functional Requirement	Verification
	Home Energy Planner (HEP)	
FR 1	The HEP shall find standby values of end-user defined appliances when applicable.	Satisfied by standby algorithm defined in chapter 4.5
FR 2	The HEP shall provide a schedule with proposed running times of end-user defined appliances within a 24 hour period.	Satisfied by scheduling process defined in chapter 4.6
FR 3	The HEP shall provide the existing usage of appliances chosen.	Satisfied by implementation of class AppliancesToUse in chapter 5.2
FR 4	The HEP shall provide analysis information based on single tariff and/or split tariff.	Satisfied by implementation of class AppliancesToUse in chapter 5.2
FR 5	The HEP shall provide existing cost of appliances chosen.	Satisfied by implementation of class AppliancesToUse in chapter 5.2
FR 6	The HEP shall provide proposed usage savings of appliances chosen.	Satisfied by implementation of class AppliancesToUse in chapter 5.2
FR 7	The HEP shall provide proposed cost savings of appliances chosen.	Satisfied by implementation of class AppliancesToUse in chapter 5.2
FR 8	The HEP shall show results lexically and graphically.	Satisfied by implementation of class LayoutCombined in chapter 5.2
FR 9	The HEP shall be easy to use in terms of supplying the end-user with information on input needed in order to complete analysis.	Satisfied by implementing alerts when end-user has not entered all information needed, see Use case 5.3.2
	End-user	
FR 10	The end-user shall have control over which appliances are used in analysis.	Satisfied by appliance consumption data being uploaded by end-user, see Use case 5.3.1
FR 11	The end-user shall have control over which appliances are used in scheduling.	Satisfied by end-user having to classify appliance type as FA, see chapter 4.3
FR 12	The end-user shall have control over which time period is used in analysis.	Satisfied by end-user having the option to change start date of appliance data
FR 13	The end-user shall have control over tariff cost used in analysis.	Satisfied by providing a venue for the end-user to insert the tariffs, see Use case 5.3.2

6.6 Discussion

The following section provides a discussion with interpretations of the evaluation results provided in previous sections of this chapter.

6.1.1 Standby detection

I calculated precision, recall, F-measure, specificity and accuracy in order to evaluate the quality of the algorithm designed for standby detection. Six test cases were identified where test case 1 represents the application of the algorithm in its entirety, in test case 5 the algorithm is not applied at all but the standby value is based on the lowest reading found. The four test cases (2, 3, 4a and 4b) represent different rules not being applied in running of the algorithm. Test case 1 scored the highest average value as well as having the highest value in F-measure (0.91) and accuracy (0.95), where the highest value is 1.0 and lowest 0, as seen in Table 6. The F-measure is a weighted average of precision and recall and accuracy is the proportion of true positive (tp) and true negative (tn) measurements. These results provide a conclusion; that test case 1, or the designed algorithm works very well and should not be implemented without the use of the rules defined in chapter 4.5. With an F-measure of 0.91 and accuracy of 0.95 I can conclude that it provides over 90% validity.

6.1.2 Flattening of peaks and reduction of peak periods

In order to examine the flattening of the peaks I constructed the graphs which resulted in HEP from the evaluation performed on 1, 3 and 5 moths of data. In all three time periods I constructed one graph for existing usage, one for proposed usage with a single tariff and one for proposed usage with a split tariff. Then I proceeded to calculate the average absolute deviation from the mean power on the resulting readings. The magnitude of the deviation quantifies the variation in power consumption and allows me to quantify the flattening of peak periods. I also examined the reduction of peak periods, which is defined as the periods where the consumption data goes above the mean.

- **Existing versus proposed split tariff:** When comparing the existing usage with proposed split tariff usage the split tariff usage yields a greater reduction of peaks in all three time periods by 24.96%, 18% and 17.26% (1, 3 and 5 months respectively) differences in average absolute deviation from the mean power. These results are consistent with the reduction of peak periods of the graphs in Figures 9-11. In the 3 and 5 months data analysis we can see that the existing graphs show the time period 9:00-23:00 as a 14 hour peak compared to three 2 hour peaks in the graphs showing the proposed split tariff. This yields a reduction from 14 hours in peak periods to 6 hours. The 1 month graph shows a slightly different outcome, where the existing graph has two peaks, one 4 hour peak and one 7 hour peak and the proposed split tariff has two 2 hour peaks and one 1 hour peak. This yields a reduction from 11 hours to 5 hours in peak periods.
- **Existing versus proposed single tariff:** When comparing the existing usage with proposed single tariff usage the single tariff usage yields a greater increase in average absolute deviation from the mean power in all three time periods by 6.12%, 0.00009% and 7.26% (1, 3 and 5 months respectively). When I examine the reduction of peak periods in the graphs in Figures 9-11, I see that the existing 3 and 5 months data analysis has a continuous 14 hour peak period compared to two peaks in the proposed single tariff 5 month analysis; one 2 hour and one 4 hour peak, and

three peaks in the proposed single tariff 3 month analysis; one 1 hour and two 2 hour peaks. The 1 month analysis shows two peaks in existing usage; one 4 hour and one 7 hour, and two peaks in the proposed single tariff 1 month analysis; one 2 hour and one 4 hour peak. Even though this means a reduction of peak periods by 5, 9 and 8 hours (1, 3 and 5 months respectively) by using the proposed single tariff, the increase in the average absolute deviation is caused by the magnitude of the two 4 hour peaks and one 2 hour peak in the three different time periods of the proposed single tariff.

All three time periods for both tariffs show a decrease in peak time periods when compared with existing usage, which allows us to conclude that HEP does reduce peak time periods. Calculating the average absolute deviation from the mean results in flattening of peaks for split tariff compared with existing usage but an increase of peaks for single tariff compared with existing usage. Based on this I could conclude that HEP does only optimize consumption usage when a split tariff is being used, but in the following section I will examine further the reasons behind this.

6.1.2.1 Reasoning for high magnitude peaks

When examining the graphs of proposed single and split tariffs it was noted that they all yield one peak with a great magnitude. The reason for this peak is that the graphs are displaying 24 hours of consumption usage based on an average of the whole usage during the time periods. This means that in both cases I am displaying one session of each flexible appliance at the same hour every day it is scheduled, compared to different times during the day for each day of existing usage. To explain this further; both tariffs schedule the clothes dryer as the first appliance in their schedule, since this is the appliance which has the highest consumption. The clothes dryer's total consumption data ranges from 2.5-2.9 kWh and takes 2 hours to run each session. This means that the first 2 hours in a schedule will enclose 2500-2900 kWh (x0.001) each time the clothes dryer ran for one session (which was on average every two to three days). This consumption is added to the existing usage of the Strict Appliances. This resulted in the highest peak in the range 902-969 for the single tariff and 778-847 for the split tariff. The positioning of these highest peaks is consistent with the scheduling times of the clothes dryer; 20:00, 21:00 and 19:00 for single tariff and 23:00 for split tariff.

Similarly, when I examine the reason for the different results in average absolute deviation from the mean, where the split tariff results in flattening of peaks but the single tariff increases them, I need to take a closer look at why they differ. Both tariffs yield the same appliance order in their schedules; clothes dryer, washing machine, dishwasher and fan on a timer, but different time schedules; 20:00-9:00, 21:00-10:00, 19:00-8:00 on the single tariff and 23:00-12:00 on the split tariff. The schedule is created by moving one session of a Flexible Appliance to the assigned time slot. If there are additional sessions of the Flexible Appliance in one day, they are added to the Strict Appliance's existing usage when the graph is displayed. As an example; one day which is included in all appliances has the clothes dryer running one session at 18:00 and another session at 21:00. This means that the session running at 18:00 will be schedules in the first time slot of each schedule, which is 20:00, 21:00 and 19:00 for the single tariff and 23:00 for the split tariff, and the session running at 21:00 will be added to the Strict Appliance's existing usage when the graph is displayed. This occurs in all data sets for the clothes dryer, washing machine and dish washer several times, and can explain the difference in results between the single and split tariffs.

Based on this information, since the split tariff schedules all start at 23:00 and there were no occurrences of Flexible Appliances running a session at that time, I can conclude that the proposed split tariff does provide a flattening of peaks. On the other hand, I am not able to formulate a conclusion regarding the proposed single tariff, since the data set used has several occurrences of Flexible Appliances running a second or third session at the same time as the proposed schedule is defined.

6.1.3 Calculation results

When examining the outcomes of the calculations performed by HEP I see that there is not a significant difference in existing usage based on 1, 3 and 5 month analysis. 3 months analysis yields the highest kWh usage per day, or 2.04% higher than 5 months and 1.64% higher than 1 month, while the difference between 1 and 5 months is only 0.40%. Similarly, the estimated usage in kWh per day, after applying the schedules for single and split tariffs, is highest for 3 months analysis and lowest for 5 months analysis. The percentage difference is very similar; 3 months is 2.09% higher than 5 months and 1.59% higher than 1 month, while the difference between 1 and 5 months is only 0.50%. The explanation for this is different amounts of existing usage in different time periods.

By applying the scheduling of Flexible Appliances, single and split tariffs result in a decrease by 0.44%, 0.49% and 0.54% in kWh per day (1, 3 and 5 months respectively). This yields estimated savings of 8.442, 9.498 and 10.23 kWh per year. The difference of 19.15% between 1 month analysis and 5 months analysis is caused mainly by one appliance, the coffee maker, not being detected as having a standby value in the 1 month analysis, because when calculating the estimated savings in kWh the only difference between existing usage and usage after applying the schedules is that standby power values have been removed from the appliances. For the same reason; standby values for the coffee maker are not removed, the 1 month analysis (8.442) results in the lowest amount of savings in kWh per year but not the 3 months (9.498), which one could assume since 3 months yield the highest estimated usage in kWh per day.

When examining the outcome of the cost of existing usage, between single or split tariffs the percentage difference is very similar for all three time periods; the split tariff is 1.31% higher than the single tariff in 3 and 5 months analysis and 1.40% higher in 1 month analysis. The reason for this is that the single tariff is the same, or €0.2241 per kWh, during all hours of the week but the split tariff is slightly more expensive, or €0.2387 (peak), Monday through Friday from 7:00-23:00 and slightly less expensive, or €0.2125 (off-peak), Monday through Friday from 23:00-7:00 and on Saturdays and Sundays. The refrigerator and central heating system were the only appliances which ran 24 hours. The appliances which were highest in consumption readings (see Table 8); the oven, the dishwasher, the washing machine and the clothes dryer, all ran their sessions on Mondays-Fridays during the peak period, with the exception of the dishwasher ending two sessions between 23:00-0:00 (both sessions are only included in the 5 months analysis). All other appliances ran in the time period from 8:00-23:00, with the exception of the TV, the set-top box and the router which would often run until 1:00. Thus one can see that the majority of the electricity consumption took place between 8:00 and 23:00 during all days of the week. Since the tariff is higher during this period on five days out of seven, it is clear that the existing cost using a split tariff will result in a higher total price.

On the other hand, when I examine the difference in estimated savings per year after applying the scheduling and using a single or split tariff the outcome is the opposite. The percentage difference results in a higher outcome for the split tariff in all three time periods; the split tariff saves 157.65% more than the single tariff in 1 month analysis, 151.56% more in 3 months analysis and 148.10% more in 5 months analysis.

Based on the above information it can be concluded that there is not a significant difference in the amount of data used in the analysis, however, if the data included does not detect a standby value of an appliance the difference can be as high as 19%. In addition it can be concluded that without scheduling the appliances there is slightly less potential (at least 1.30% less) for cost savings if you use a split tariff, but with scheduling the appliances there is a potential of 148% or more savings by using a split tariff rather than a single tariff.

6.1.4 Requirements verification

Finally, the functional requirements were verified by means of stating design decisions, implementation classes and use cases. All requirements defined have been verified as having been satisfied, which allows me to say that the HEP provides the functionality it was designed to provide.

7. Conclusion and further work

I have researched existing solutions such as Smart Appliances and labeling. I also researched other solutions documented, which resulted in a selection of three Smart Home solutions. All of these solutions aim for the same outcome; to optimize electricity usage in a residence. Two of the three solutions allowed the use of existing appliances, while one required Smart Appliances. One solution required a Smart meter and put a restriction on the type of appliances, while another required the use of sensors in addition to the external power measuring device. The main differences in HEP and these three existing solutions are that HEP has standby power detection, you can see the difference in usage and saving of single and split tariffs and you can see savings in kWh and Euros if you exclude an appliance (such as if you stop using clothes dryer). A summary of the existing solutions and HEP can be seen in Table 22 below.

Table 22: Summary of existing solutions and HEP

	Solution I	Solution II	Solution III	HEP
Existing appliances	X		X	X
Smart appliances		X		
Smart Meter			X	
External measuring device	X		X	X
Sensors	X			
Appliance type restriction	Yes	No	Yes	No
End-user classification of appliance type		X		X
Automatic control	X			
Show potential savings (euro and/or kWh)		X	X	X
Show potential difference in pricing plans				X
Standby power detection/removal				X
Reduction of electricity consumption peaks	X	X	X	X

In order to answer the research question:

Can optimization of electricity and automation of appliances provide a solution which aids a resident in reducing electricity consumption in an existing residence with existing appliances today?

a set of sub questions were researched in order to gain a better understanding and provide a solution.

- What is the state of the art in Smart appliances?
  Smart appliances are just emerging on the public market as of 2012-2013. So far they are limited in types and functions, where some require a connection with a smart meter in order to utilize the energy optimization functions. This puts an emphasis on alternate solutions where the end-user is able to measure and schedule existing appliances.
- What types of energy measurement solutions are available for existing appliances today?
  The European Union and individual countries are actively implementing regulations and directives where the main goal is to reduce energy consumption in all sectors which has led to a great improvement in energy efficient appliances. Several companies are providing Home

Automation Systems which allow the end-user to measure the energy consumption at individual appliance level and provide the end-user with the means to be aware of their own consumption.

I have designed, implemented and evaluated the Home Energy Planner, the main purpose of which is to aid the end-user in creating schedules and detecting standby power on existing appliances measured with Plugwise. This enables me to answer the remaining sub questions which relate to HEP:

- Can we create effective standby power detection on the appliances measured?
  I designed and implement an algorithm which detects standby values on the measured appliances. In my evaluation of the algorithm I was able to prove that it produces 95% accuracy, 100% specificity and an F-measure of 0.91. This is a highly effective standby power detection algorithm which can be used on the appliances measured.
- Can we reduce peak periods and flatten peaks using the optimization application?
  In my evaluation I concluded that peak periods could be reduced if appliances where scheduled according to provided suggestions. In regards to flattening the peaks, I calculated the average absolute deviation from the mean power, based on the graphs produced. This resulted in flattening of peaks if a split tariff was used in the calculations, but not if a single tariff was used. Since this was based on the graphs produced in the HEP, which show the average usage for 24 hours over a selected period, I found that I could possibly flatten the peaks, but this method of using average consumption data is not effective enough.
- Can we provide a means to see if different types of tariffs are adding to monetary savings?
  In the design and implementation of HEP I included a venue for the end-user to provide a single or a split tariff. The end user can see the difference in cost when applying both tariffs. When I evaluated this solution I found that based on existing usage, a split tariff would not be cost efficient if the appliances where not scheduled. On the other hand there was a potential for a 148% saving or higher if the appliances where scheduled and a split tariff was used.

I believe I can now proceed to answer the research question positively. The application HEP has been shown to be an effective solution to optimizing electricity. It is designed to work with existing appliances, by using a Home Automation System, such as Plugwise and it does not require any additional equipment. The evaluations proved that the application works very well on standby power detection and reduction of peak periods. In addition, it provides suggestions to the end-user on how to schedule their appliances and assign standby killers which reduce electricity consumption. Finally, the end-user is in control of which appliances to use in the analysis which provides the end-user with a way of seeing how the usage would change if an individual appliance was not included.

HEP will benefit from further work involving more extensive analysis in order to produce more efficient schedules for appliances. One approach could be to use a database with consumption information from appliance producers. The end-user would then be able to identify the appliance by make and model and that would allow for better detection regarding the standby values, as well as more accurate estimates of average running times of appliances. In the case of a particular appliance not being available in the database, the end-user could classify it by type and purchase year. Then the database would be searched for appliances with similar properties and estimate the consumption and running times.

Another approach could be to re-define the timeslots into smaller intervals. The HEP timeslots are one hour each, which can in some cases be very inefficient. Looking at the example given in chapter 7 where the appliance needs 70 minutes to run one session, but is started at 5 minutes before the hour, it is evident that the HEP determines that the appliance needs 180 minutes to run instead of 70. If the timeslots were divided into 15 minute intervals, the maximum reading the previous appliance would get is 90 minutes. This would result in much tighter schedules for high consuming appliances.

A great benefit for the application would be to add the ability to use real time pricing of energy, since this is one of the promised features of the smart grid (10). This means that a component would have to be added that could collect price information from electricity providers in real time, determine which provider to use and give suggestions on schedules based on dynamic pricing. This would involve a prediction algorithm to determine what the price will be in the next twenty four hours based on current price information and trends.

I found that the current graphical display of consumption did not produce true flattening of peaks. It could be more effective if we produced a graph with one day of consumption for the purpose of flattening of peaks. This does not however interfere with the proposed scheduling and standby power detection, since I also display these in words and provide calculations showing potential savings and usage.

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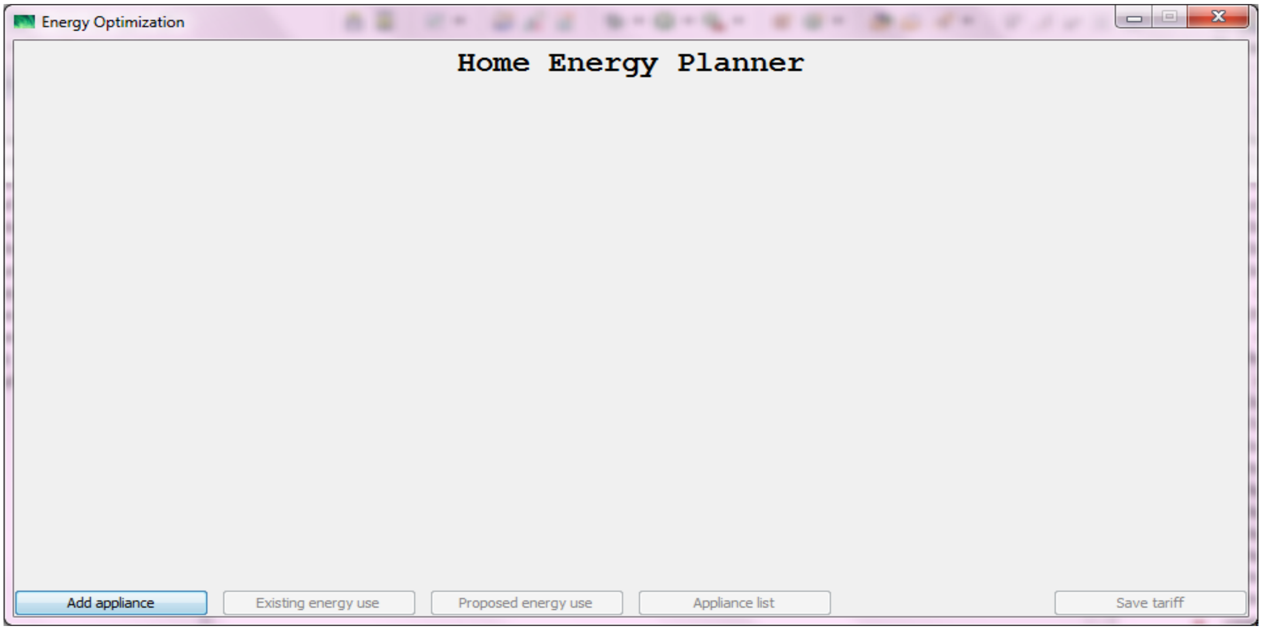
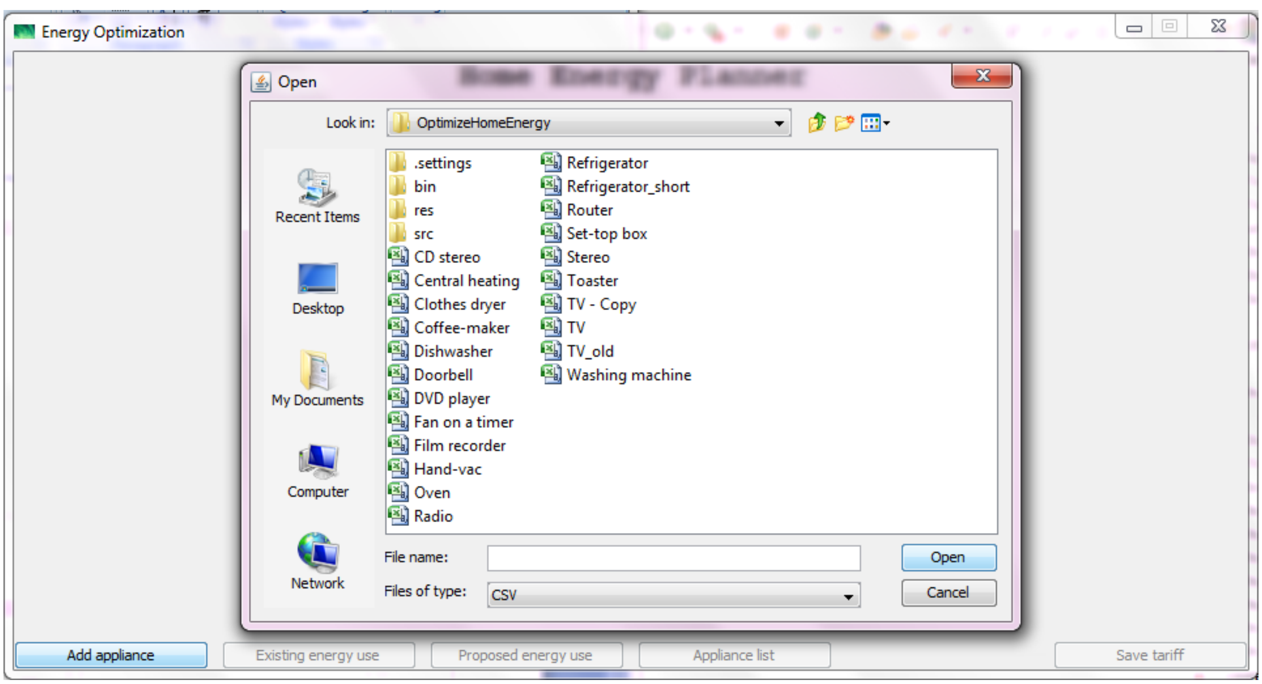
Appendix I – Images explaining the Graphical User Interface of HEP

When the application is started the end user adds the appliances to use in the analysis by selecting the Add appliance button on the start-up page:



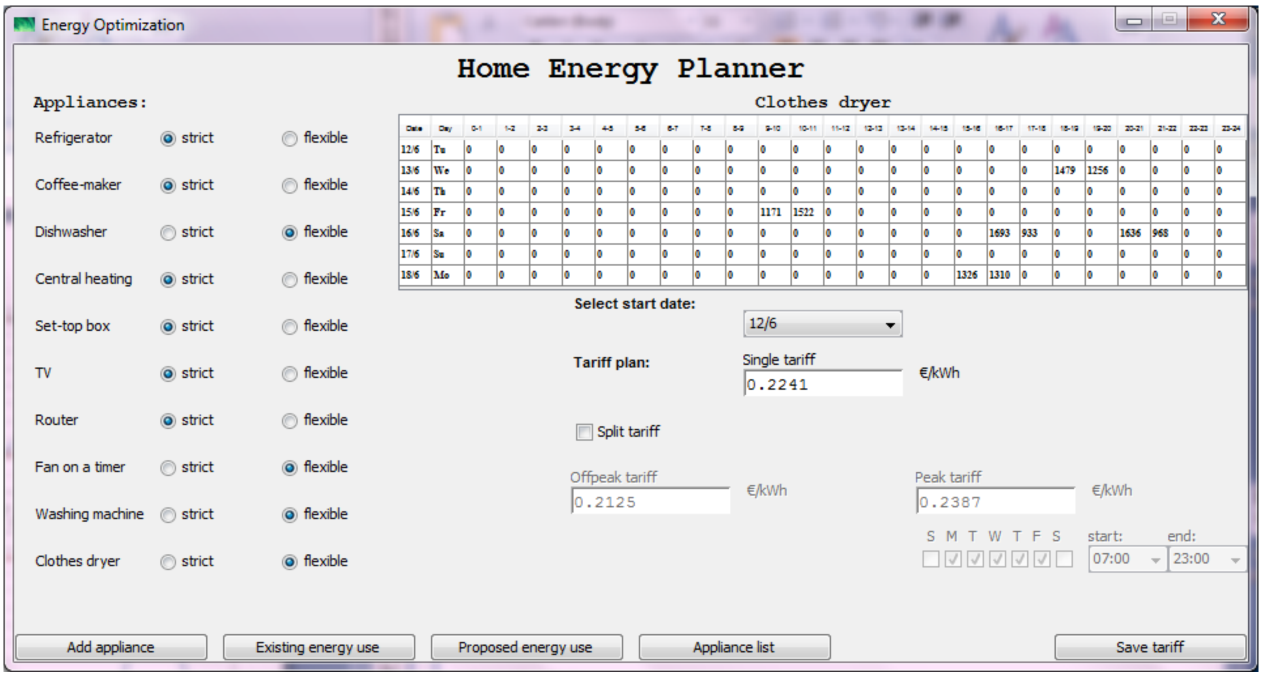
Start-up

The end user is able to choose which appliances to include in the analysis and uploads the csv file:



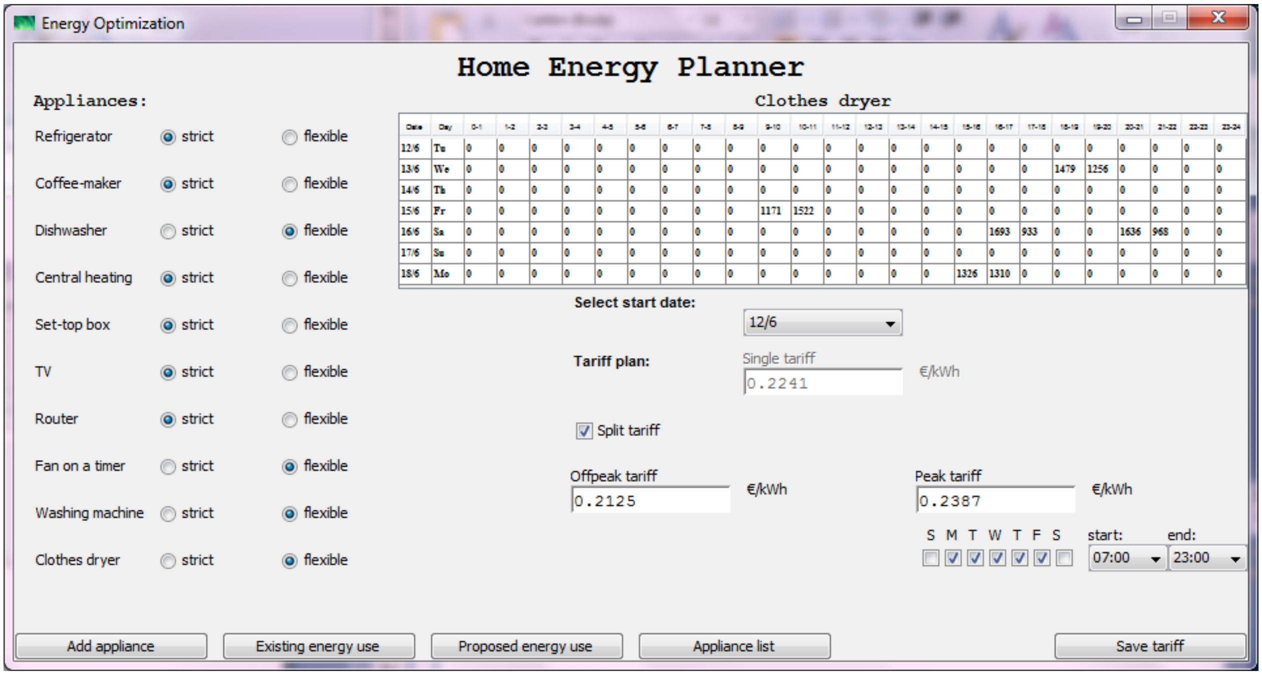
Select appliance to upload file

When the appliances have been uploaded they are listed on the left. Immediately following the name of each appliance are two radio buttons where each appliance is classified either as strict or flexible. The table displays one week consumption for one appliance. The appliance chosen can by changed by clicking on the name in the appliance list. In addition the end user chooses the date to start the analysis on below the table, which in turn determines the start of the week displayed in the table above. The final input needed from the end user is the tariff information. The screenshot below shows how the end user has inserted the tariff for a single tariff as well as for the split tariff. By not having the check box Split tariff selected, the information for the split tariff is dimmed and no included in the calculation.



Single tariff

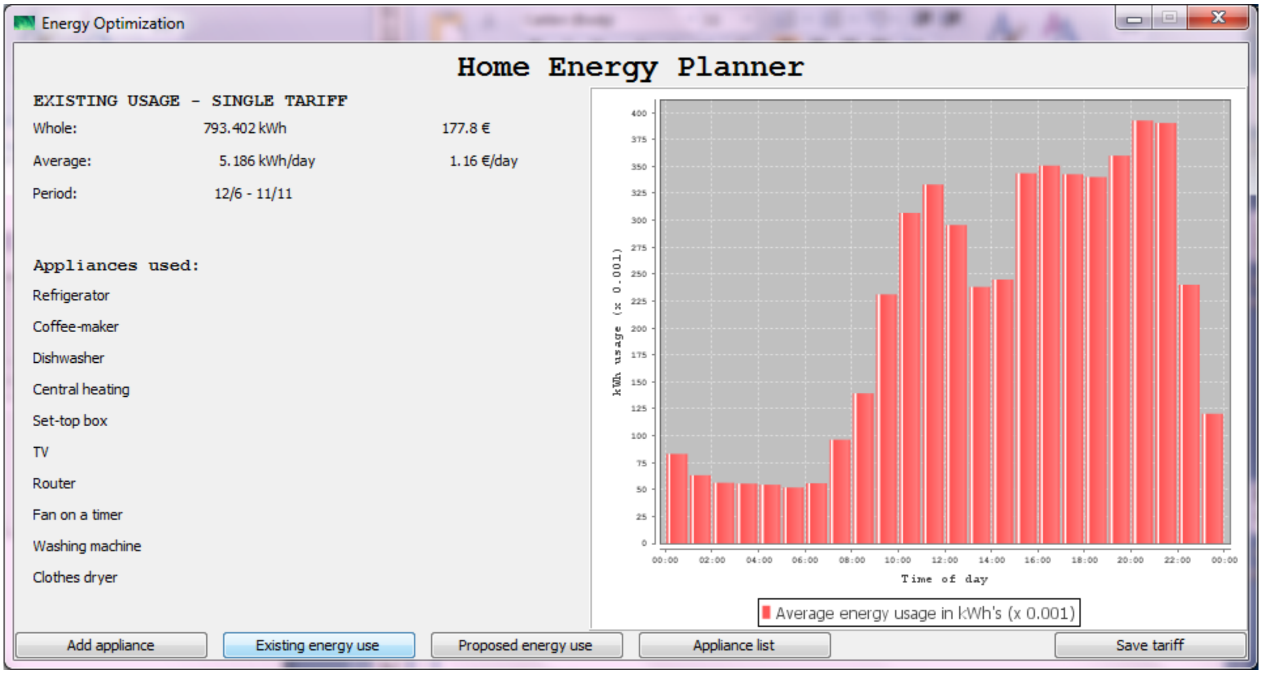
The final screen shot below shows how the end user has selected the check box Split tariff, and thus the information needed for a split tariff is visible and editable, and the single tariff text box is dimmed and disabled. Finally when the end user has given all information needed and selects the buttons Existing energy use or Proposed energy use, the calculations are performed and the results are shown as can be seen in the screen shots in Appendix II.



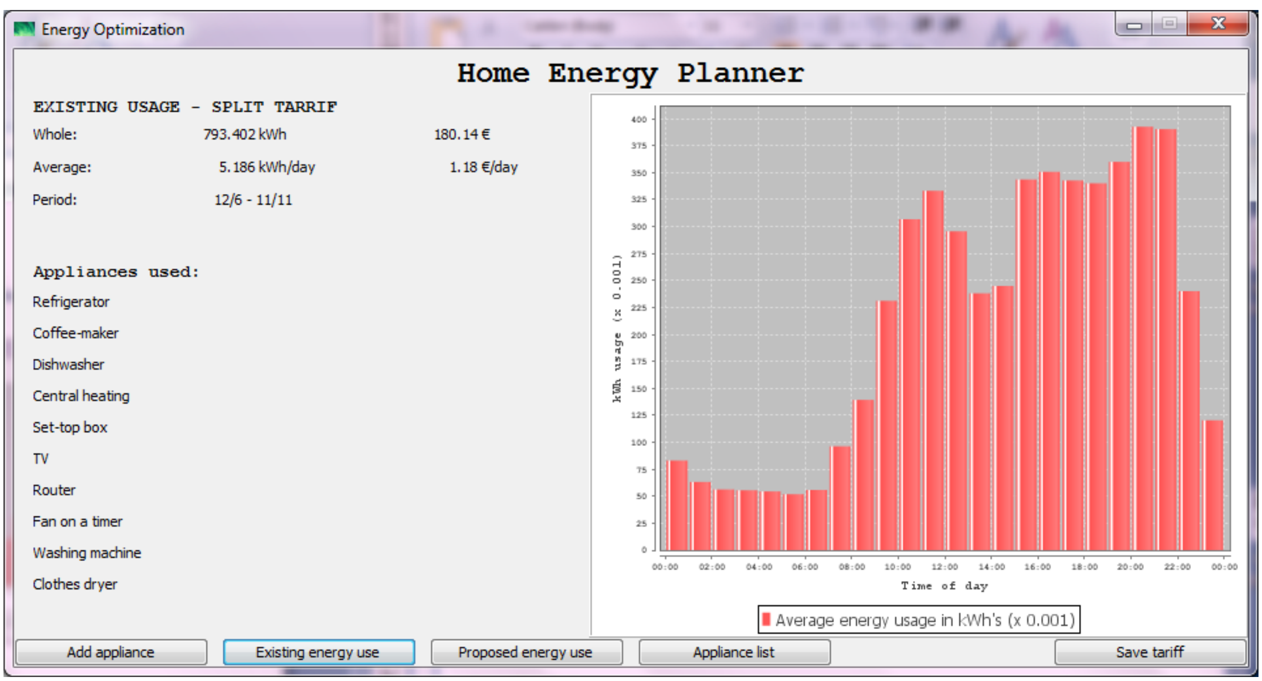
Split tariff

Appendix II – Screenshots from HEP of optimization evaluation

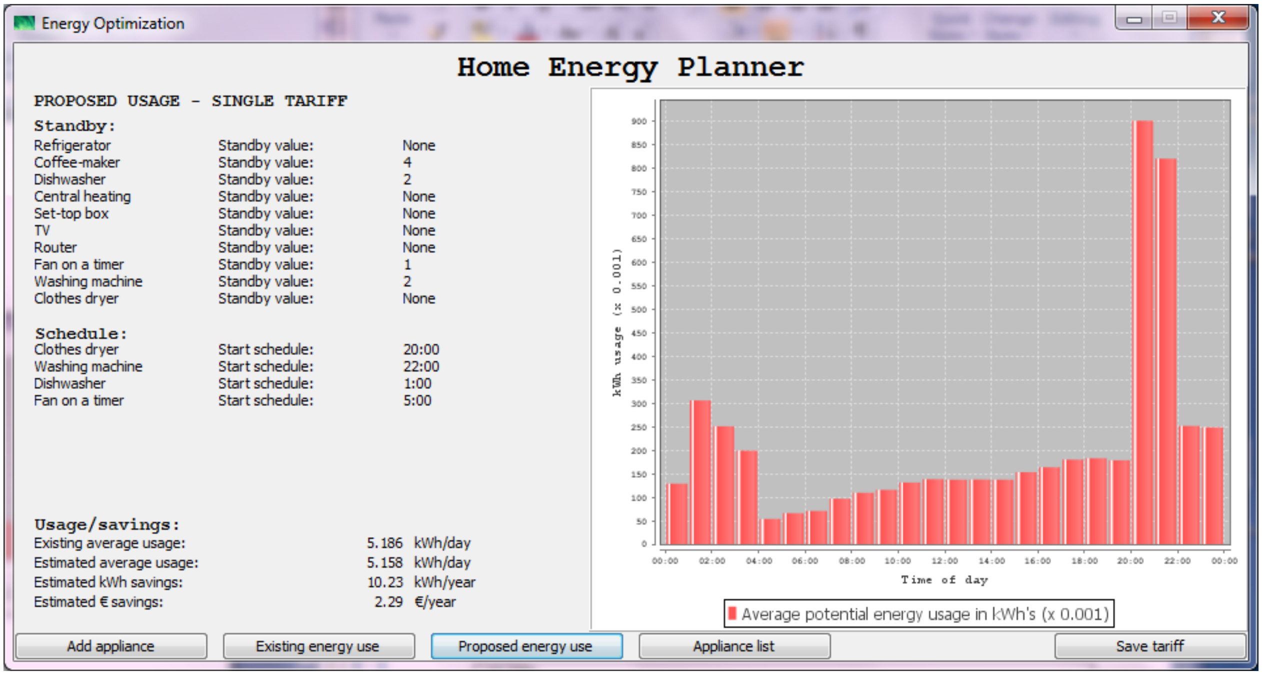
Below are provided screenshots of the actual data used in the evaluations obtained from HEP.



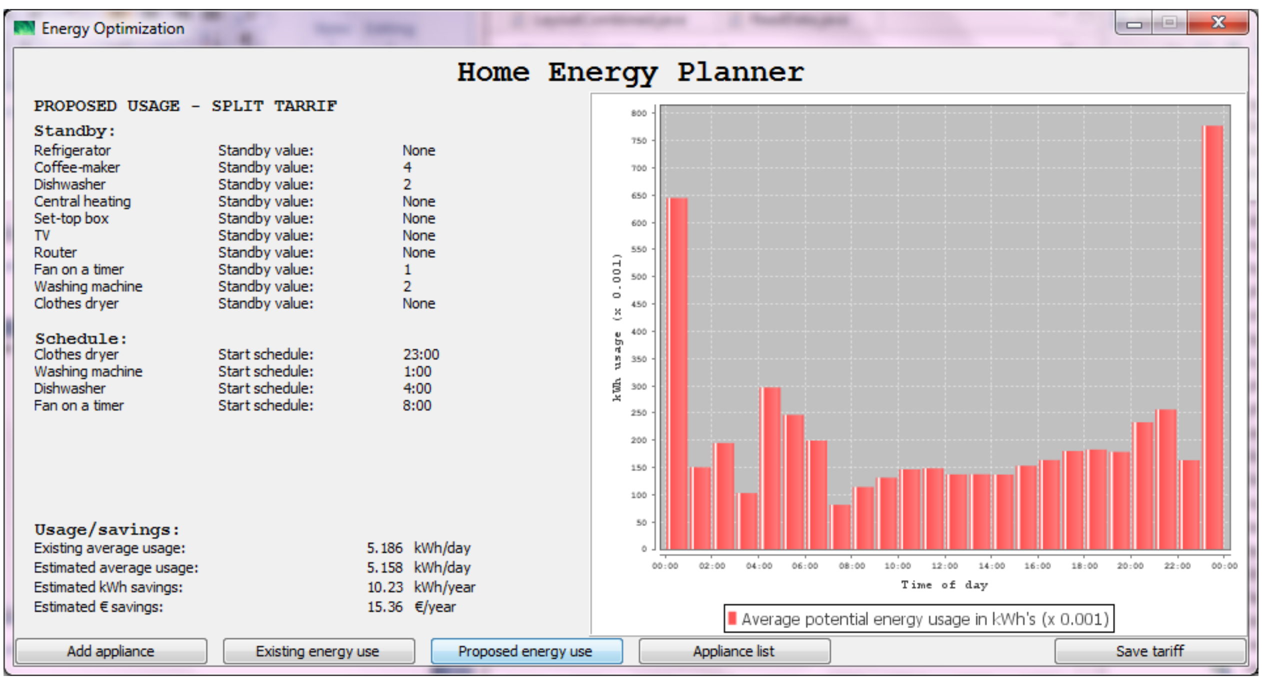
Existing usage with a single tariff – 5 month period



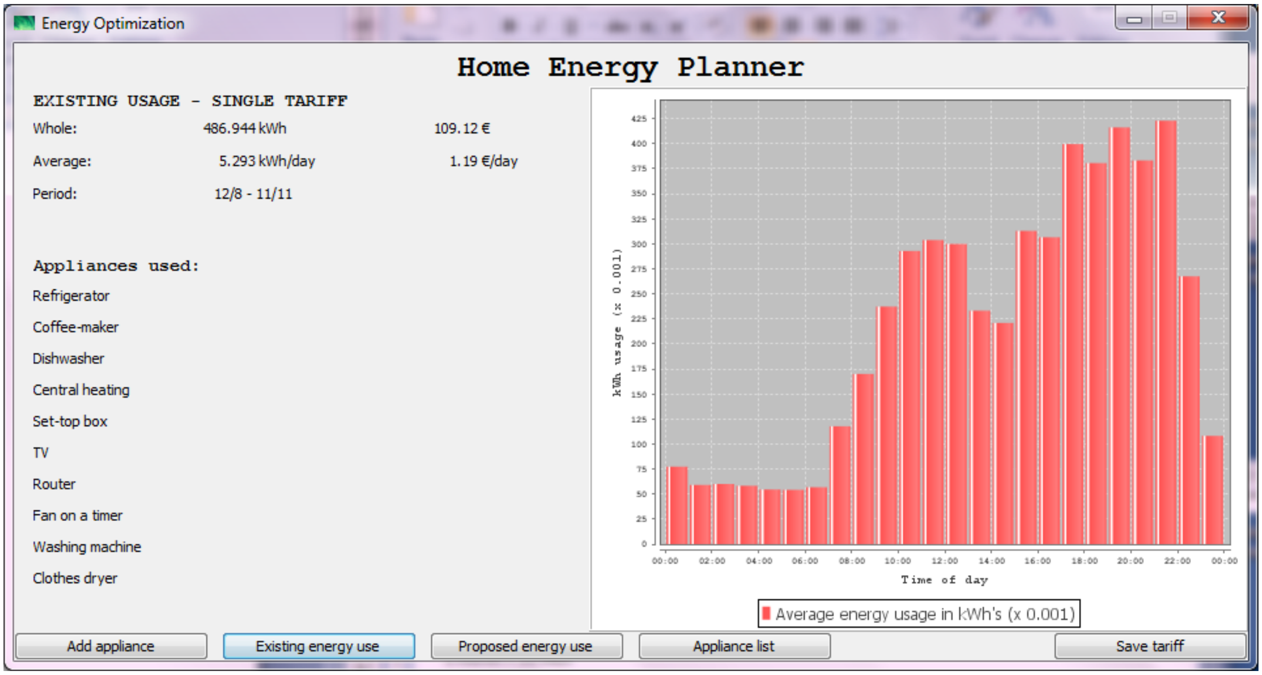
Existing usage with a split tariff – 5 month period



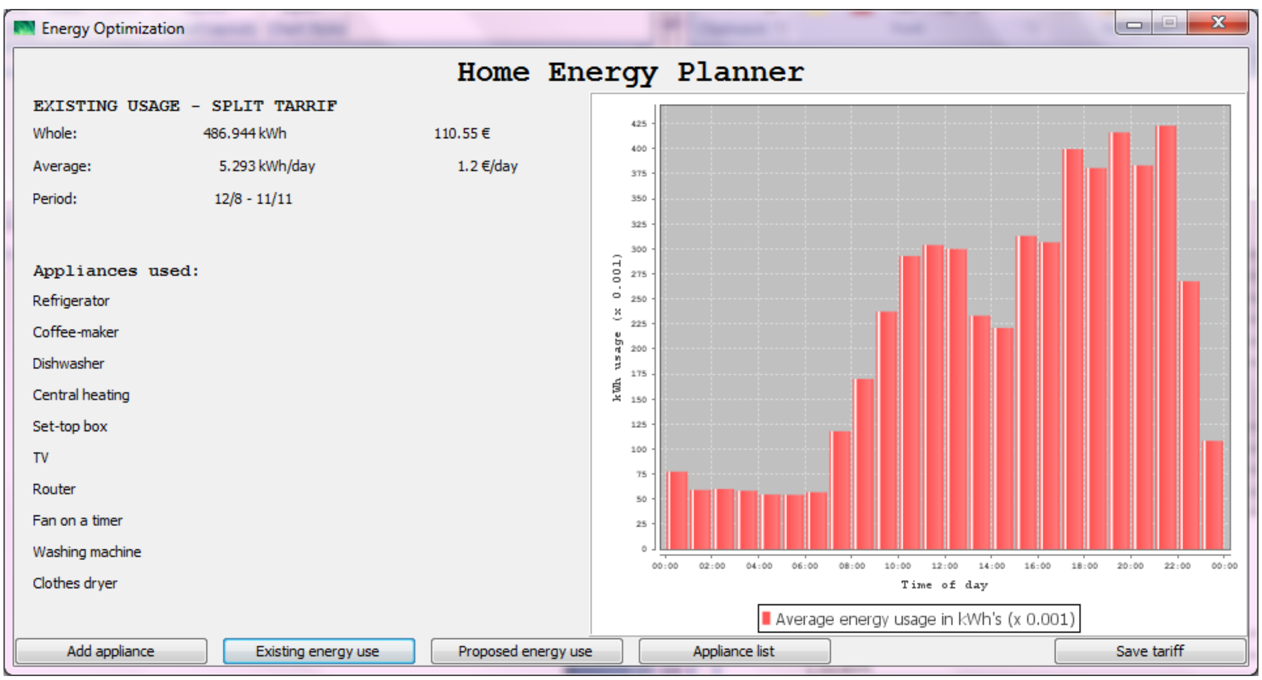
Proposed usage with a single tariff – 5 month period



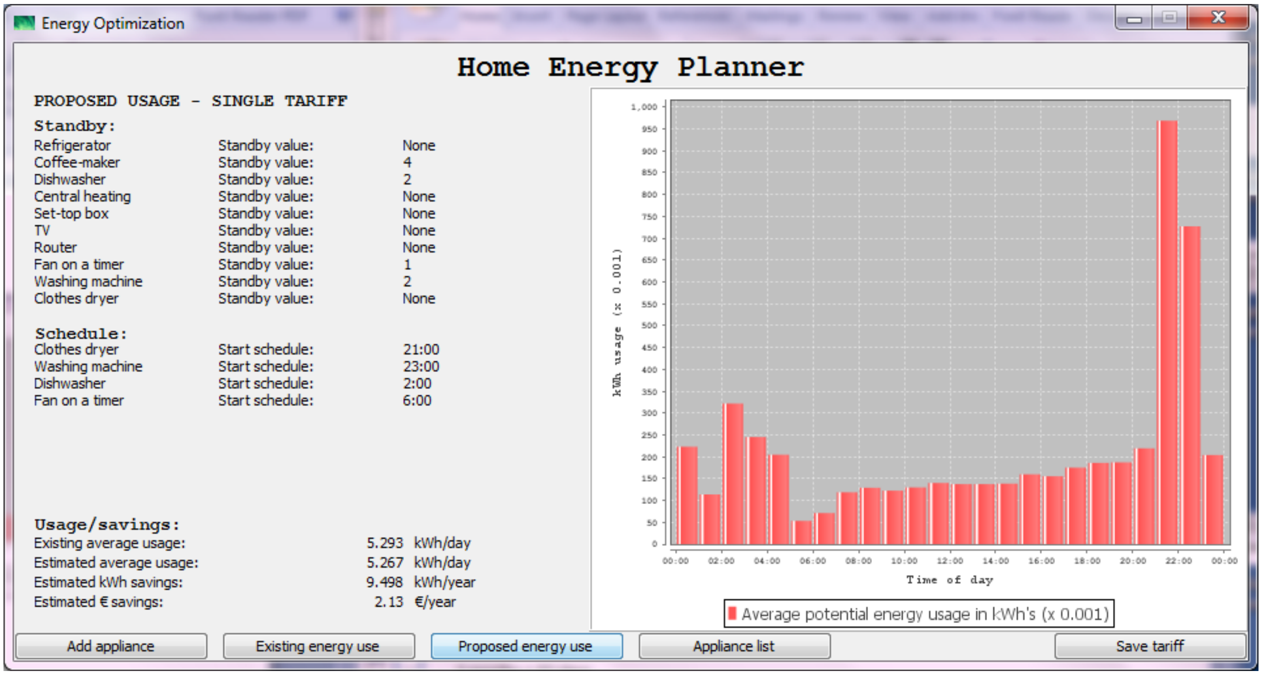
Proposed usage with a split tariff – 5 month period



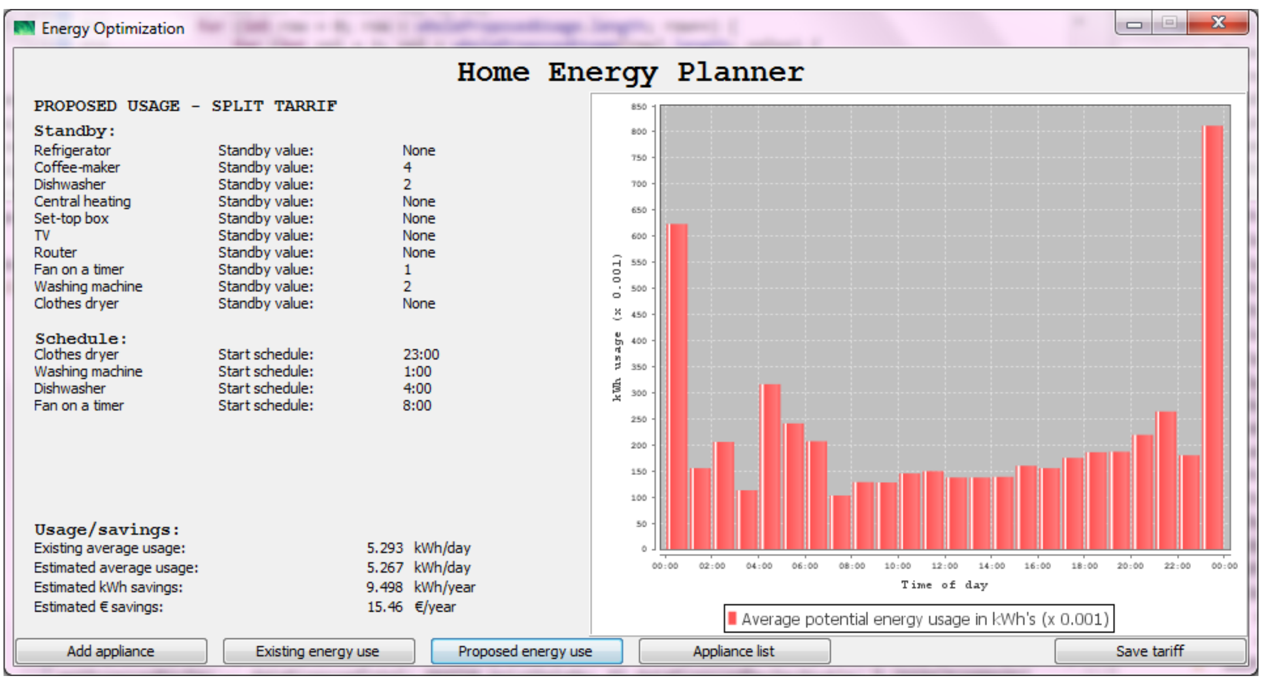
Existing usage with a single tariff – 3 month period



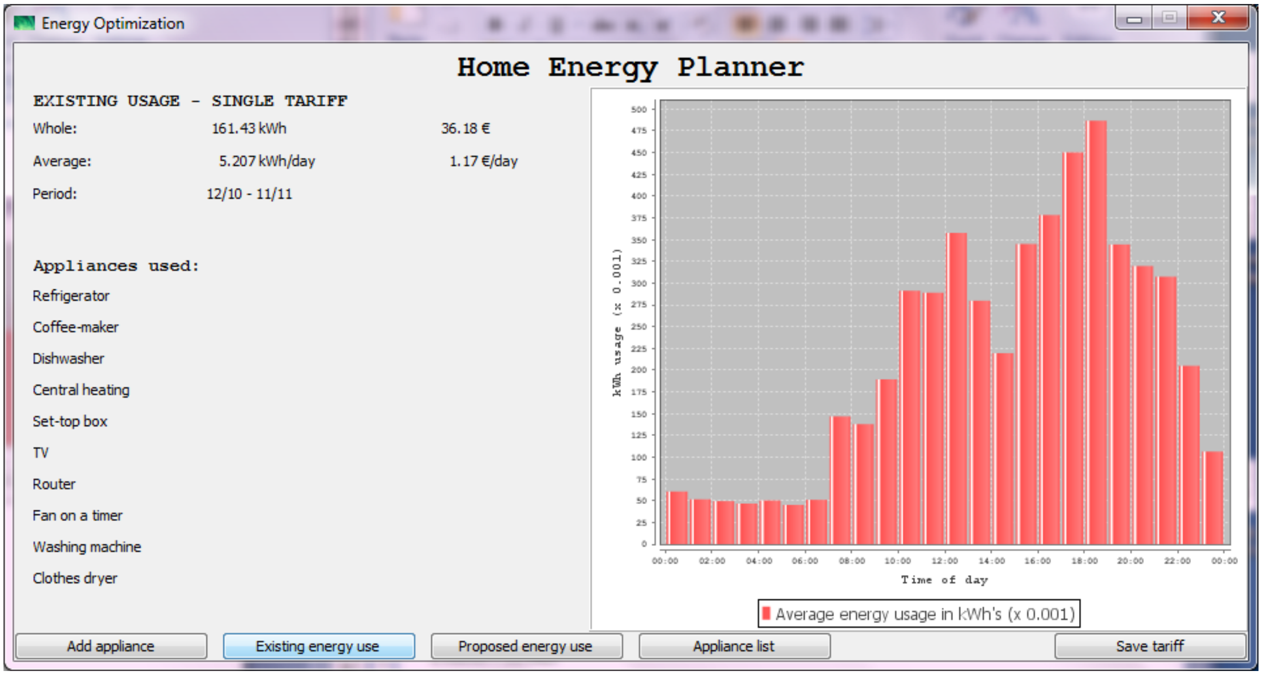
Existing usage with a split tariff – 3 month period



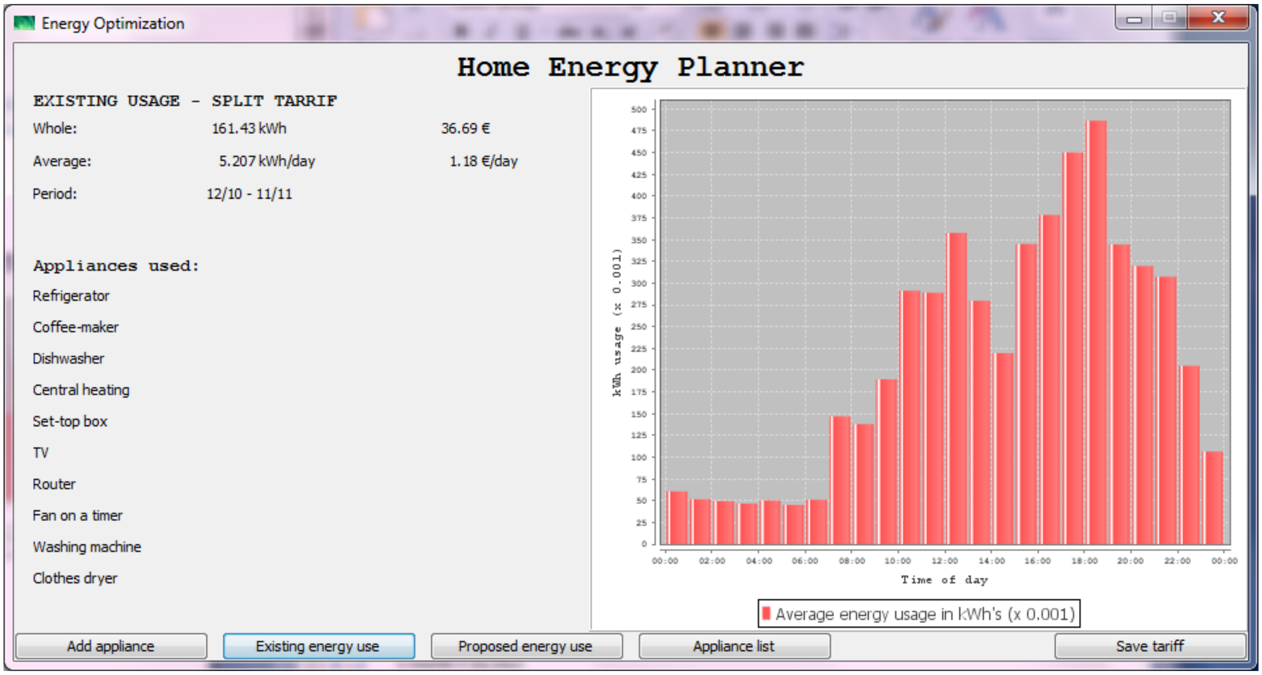
Proposed usage with a single tariff – 3 month period



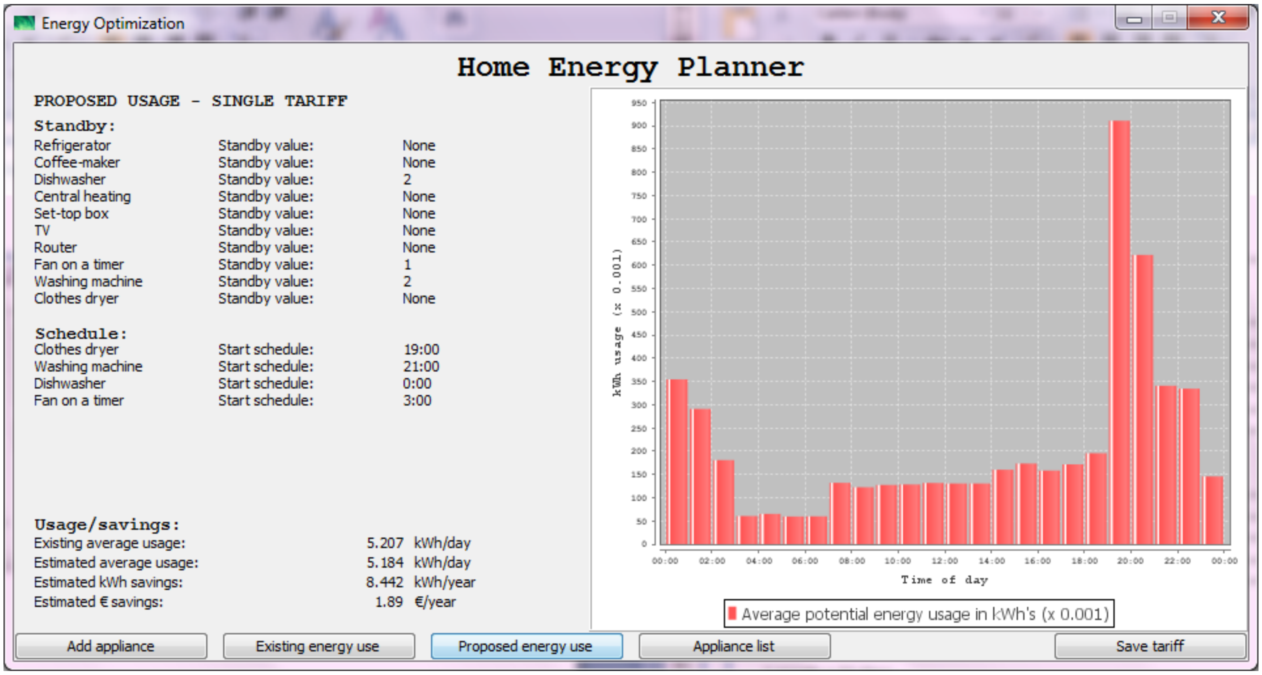
Proposed usage with a split tariff – 3 month period



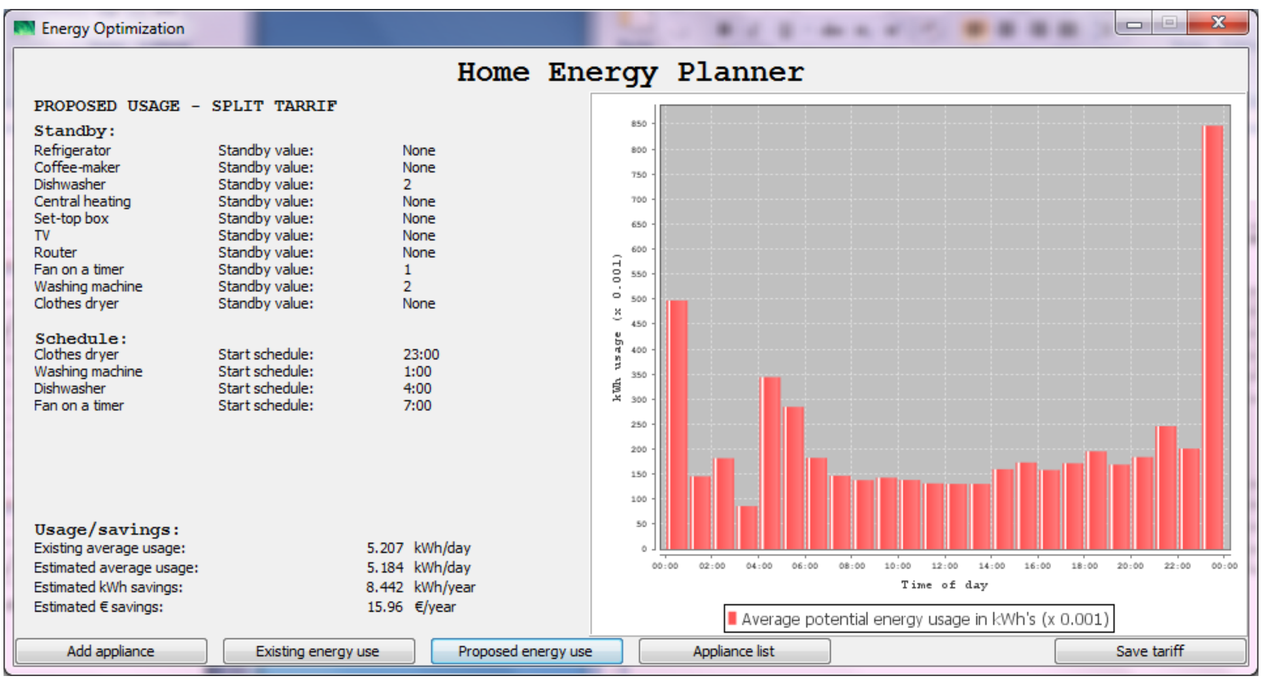
Existing usage with single tariff – 1 month period



Existing usage with split tariff – 1 month period



Proposed usage with a single tariff – 1 month period



Proposed usage with a split tariff – 1 month period