BaaS

Building as a Service

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Reporting Period in Pilot Buildings

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Deliverable Summary Sheet

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Deliverable D6.3.3: Short Description

This document contains the description of the reporting period and the evaluation of the energy savings achieved in the three pilot buildings with the implementation of BaaS solution, applying the energy models that were adjusted and validated in D6.3.2 following the guidelines defined in the IPMVP-Option C.

Keywords: Energy savings, IPMVP, baseline period, reporting period

Deliverable D6.3.3: Revision History

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0.4	25/04/2016	Draft	DALKIA: Energy savings analyses in CAR
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0.6	27/04/2016	Under review	CARTIF and DALKIA: General review and last changes
1.0	28/04/2016	Final	DALKIA and CARTIF: Final version

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Abbreviations and Acronyms

ABE	Adjusted Baseline Energy
BaaS	Building as a Service
ECM	Energy Conservation Measure
ESCO	Energy Services Company
HVAC	Heating, Ventilation and Air Conditioning
IPMVP	International Performance Measurement and Verification Protocol
M&V	Measurement & Verification
RAD	Solar Radiation
SES	Sierra Elvira School
WP	Work Package

Executive Summary

The aim of this report is the evaluation of the energy savings in the three pilot buildings (i.e. CARTIF, ZUB and Sierra Elvira School) achieved with the implementation of the BaaS solution. This assessment is undertaken through a comparison between a reference period (adjusted baseline) and the period understudy (reporting), through the energy models that have been previously developed and included in the previous document *D6.3.2 "Baseline period"*. All these studies are framed in the International Performance Measurement and Verification Protocol (IPMVP), where, after a comprehensive analysis, *"Option C: Whole Facility*" was selected for the three pilot buildings.

The results obtained in the three pilot buildings in terms of performance, energy savings and comfort level after the implementation and testing of the BaaS solution are satisfactory considering the expectations and quite successful bearing in mind that this is a demonstrative project.

This report is a very important outcome within BaaS project as it depicts the final results derived from all the previous tasks and activities related to data acquisition, data analysis and modelling, control and optimization strategies, etc. in terms of energy savings and comfort increase.

In the framework of Energy Services Companies (ESCO) and utilities, the achievements made so far within the BaaS project could serve as a basis for new projects or cases studies, as it can complement the business models based on energy savings obtained with methodologies and algorithms that can be replicated.

1 Introduction

1.1 Purpose

The objective of the reporting is to define a reference period to study and develop an accurate mathematical model valid to evaluate the energy savings achieved with the BaaS solution in the three pilot buildings, applying the methodology defined in the IPMVP.

First of all, after this introductory section, a brief description on how the evaluation of the energy savings is conducted has been included. Then the energy data, evaluation periods and results obtained in the three pilot buildings are specified. Finally, the main conclusions drawn are presented.

1.2 Relationship with other activities in the project

This deliverable continues with the work in the demonstration activities in the project (started in D6.1), and also the Research and Technological Development activities, which aims to the BaaS solution validation and standardization.

Deliverable	Relationship
D1.2	D1.2 established the M&V methodology in order to validate the BaaS solution and the requirements of metering and monitoring for the demonstration buildings
D4.4	D4.4 provided the information and description of the control strategies implemented in ZUB and CAR pilot buildings
D5.1.2	D5.1 identified the Uses Cases and the KPI associated
D5.4	D5.4 provided the information and description of the control strategies implemented in SES pilot building
D6.1	D6.1 selected and provided the information of the demonstration buildings to be adapted in this task
D6.2	D6.2 will be in charge of the analysis of the operation inefficiencies of the demonstration buildings, in order to deploy the M&V plan, baselining and reporting
D6.3.1	D6.3.1 provides the description of the IPMVP Plan.
D6.3.2	D6.3.2 describes the baseline and includes the mathematical models developed to evaluate the energy savings

Table 1: Relationship with other activities

1.3 Contribution from partners

This task is headed by DALKIA, who is supported and monitored by CARTIF and Fraunhofer and the rest of research partners.

Deliverable	Relationship
DALKIA	Carry out the data collection for SES pilot building. Process all the data in the three pilot buildings. Evaluate the BaaS results in the three pilot buildings following the IPMVP methodology.
CARTIF	Support Dalkia in the data collection and the discussion of the BaaS control strategies and results in CARTIF pilot building.

FHG	Support Dalkia in the data collection and the discussion of BaaS control strategies results in ZUB pilot building.
TUC	Support Dalkia in the discussion of the BaaS control strategies and results in ZUB pilot building.
HON, NEC	Support in the description of the control strategies for SES.

Table 2: Contributions from partners

2 Energy savings evaluation based on IPMVP

Once the energy models have been developed and validated during the baseline period, the next step is to apply them in order to evaluate the energy savings that BaaS solution provides.

The first point is to establish well the period in which this assessment will be done, i.e. the reporting period. The length of the reporting period should be at least the same of the baseline period and it should cover at least one normal operating cycle of the building, in order to estimate the energy savings in all normal operating modes. As showed in 6.2.3 "*Baseline: Period, Energy and Conditions*", CARTIF and ZUB pilot buildings have an operating cycle of 12-months, while SES pilot building has an operating cycle of 8-months.

In order to define the specific start and end dates of the reporting period, it is necessary to take into account not only the duration of the baseline period but also the time required for the correct implementation of the BaaS solution.

This period should be carefully defined and must be comparable to the baseline period, in order to be able to use the energy models. As these models were adjusted under certain conditions and assumptions, their correct application will enable to obtain more accurate and realistic estimations of the energy savings achieved during the reporting period.

Once the reporting period is clearly identified, the evaluation methodology is the following one:

- Collecting the required data from the databases, weather stations, energy meters, and temperature sensors deployed in the three pilot buildings.
- Processing the data.
- Checking possible errors and identifying inconsistencies.
- Obtaining the same variables (independent and dependent) and representing the data in the same frequency than for the energy model developed in the baseline period.
- Calculate/determine the energy consumption that the mathematical model predicts for the values that the independent variables (outdoor temperature, solar radiation, indoor temperature…) take during the reporting period.
- Comparing this modelled energy consumption with the real energy consumption of the building provided/registered by the energy meter, in order to see if they have the same temporal profile and evaluate the energy savings obtained with the implementation of the BaaS solution.
- Checking if the energy savings achieved with the BaaS solution meets the specifications required by the Option C of IPMVP.

3 CARTIF Pilot Building

3.1 CARTIF building Use Case 1: Winter

3.1.1 *Background from the baseline period*

According to the IPMVP-Option C guidelines, the next energy model was obtained in *D6.3.2: "Baseline period in the pilot buildings"*, representing the natural gas consumption in CARTIF pilot building for use case 1 (Uc1), as a linear function of the outdoor temperature (daily average) and the solar radiation (total accumulated from the day before). The model includes a correction in the intercept when it is applied to evaluate the consumption during a Monday, as there is a systematic overconsumption on this day of the week.

$$G[m^3] = 10.82 - 0.54 \cdot T_{out}[^{\circ}C] - 0.42 \cdot Rad_{previous}[kWh/m^2]$$

Equation 1: Adjusted Baseline Energy for CARTIF_Uc1 (normal days)

$$G[m^3] = 14.35 - 0.54 \cdot T_{out}[^{\circ}C] - 0.42 \cdot Rad_{previous}[kWh/m^2]$$

Equation 2: Adjusted Baseline Energy CARTIF_Uc1 (Mondays)

In addition, next figure shows how well the energy model developed in the winter baseline period adjusted to the real profile of the energy consumption (represented in kWh of final energy, considering a high calorific value of 11.98 kWh/Nm^3 extracted from the technical guide for designing efficient heating centrals) in CARTIF pilot building.

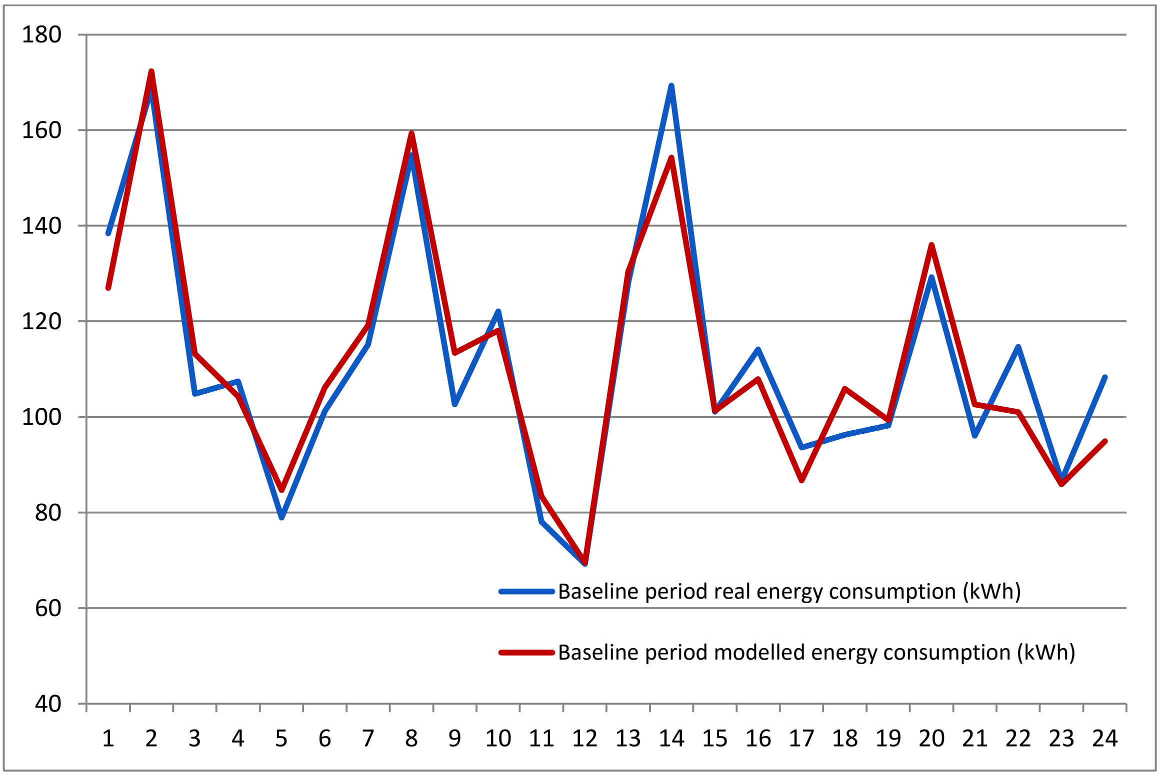

Figure 1: Baseline energy profiles comparison in CARTIF_Uc1

3.1.2 *Static factors during the winter reporting period in CARTIF*

First of all, it should be remarked that the control strategy during winter, which is a knowledge-model-based control whose objective is to operate the HVAC system in CARTIF during the winter season. In this way, this use case aims at finding the optimal parameters (controllable inputs) in the whole HVAC system which allows the reduction of thermal energy consumption and, in consequence, the operational costs, holding or even improving the comfort conditions.

The reporting period that has been defined in CARTIF Pilot Building Uc1 to evaluate the results of the BaaS solution is presented in the table below:

Start of the reporting period	End of the reporting period
4th February, 2016	1st April, 2016

Table 3: Reporting period for the winter season in CARTIF pilot building

Within this evaluation period, several days were not including in the final analyses to evaluate the energy savings due to different problems:

- Data errors in weather station installed in CARTIF building.
- Data errors in the natural gas meter.
- Day in which BaaS did not work correctly (in terms of operating time, setpoints temperatures...).

Besides, it should be also remarked that in some data points, the gas consumption had to be corrected due to maintenance operations (16th, 17th and 18th of February and 17th and 18th of March). During these days, the boiler was operating in the afternoon due to maintenance issues, therefore, these consumptions must not be taken into consideration.

Last but not least, from 13th of March, some of the individual circuits of the radiant floor were unlocked, therefore, the total heated area by this system was increased. In particular, 304.15 m^2 represent the new area from the total area heated by the radiant floor that is 1472.82 m^2. In terms of percentage, the area is out of 20.65%. This is a non-routine adjustment required because the static condition has changed from baseline (even from some span of the reporting period). Additionally, in consequence, the average temperature of these “unlocked” zones has also been incremented. For instance, in the zone 14 (innovation), the average temperature is increased in 1.6 ºC owing to this issue. In fact, Figure 2 displays the temperature of the zone during the reporting period. In blue, it is highlighted the period before unlocking the circuits, whereas red line indicates the days after unlocking. As it is remarked, the temperature of the zones has been also incremented, which also justifies the need of including the non-routing adjustments.

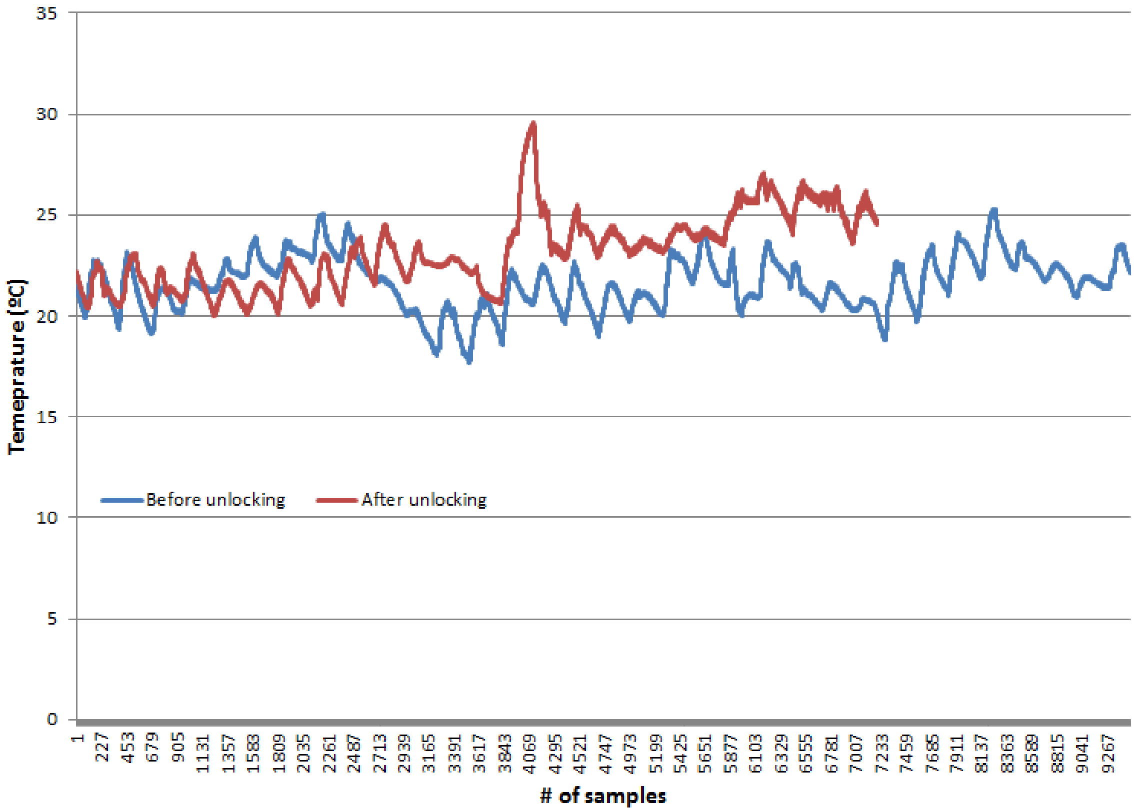

Figure 2: Comparison between locked and unlocked circuits

3.1.3 Data points

Next table includes the summary of the data processed for the evaluation period in CARTIF_Uc1, including dates, natural gas consumption (daily total), outdoor temperature (daily average) and solar radiation (daily total accumulated).

Point	Date	T_{out} [°C]	Rad [kW/m^2]	G real [m^3]
1	04/02/2016	3.09	2.05	7.24
2	05/02/2016	1.58	4.11	8.31
3	08/02/2016	7.64	2.67	8.39
4	11/02/2016	10.44	1.49	5.92
5	12/02/2016	10.08	1.70	5.24
6	14/02/2016	4.98	1.36	5.44
7	15/02/2016	2.19	2.53	11.42
8	18/02/2016	2.65	4.32	7.36
9	19/02/2016	1.37	2.62	8.28
10	21/02/2016	4.31	5.04	6.34
11	22/02/2016	5.09	3.88	10.89
12	23/02/2016	4.31	3.98	7.89

13	24/02/2016	4.54	4.25	4.98
14	25/02/2016	5.92	1.81	5.84
15	26/02/2016	4.06	3.26	6.84
16	01/03/2016	2.87	5.46	6.87
17	02/03/2016	6.00	5.43	6.67
18	03/03/2016	5.75	4.75	6.04
19	04/03/2016	4.45	5.52	5.58
20	13/03/2016	4.11	5.98	5.85
21	14/03/2016	3.38	6.17	12.43

Table 4: Data summary of the reporting period for CARTIF_Uc1

3.1.4 Evaluation of the BaaS Solution in CARTIF Pilot Building_Uc1

Applying the model to the external conditions that occurred during this evaluation period, the ABE for CARTIF_Uc1 can be determined. Table below presents the real and the modelled energy consumptions during this evaluation period.

Datapoint	Adjusted Baseline Energy [kWh]	Reporting period energy [kWh]
1	99	87
2	98	100
3	109	101
4	54	71
5	55	63
6	90	65
7	145	137
8	90	88
9	107	99
10	76	76
11	119	130
12	81	95
13	78	60
14	82	70
15	87	82
16	83	82
17	63	80
18	68	72
19	73	67

20	91	70
21	149	149
TOTAL	**3,186 kWh**	**2,908 kWh**

Table 5: Data for the energy consumptions evaluation in CARTIF_Uc1

Next graph shows a comparison between the real energy profile in the reporting period after the implementation of the ECM related to the BaaS solution and the theoretic energy profile predicted by the ABE model in the same weather conditions if the BaaS solution had not been applied.

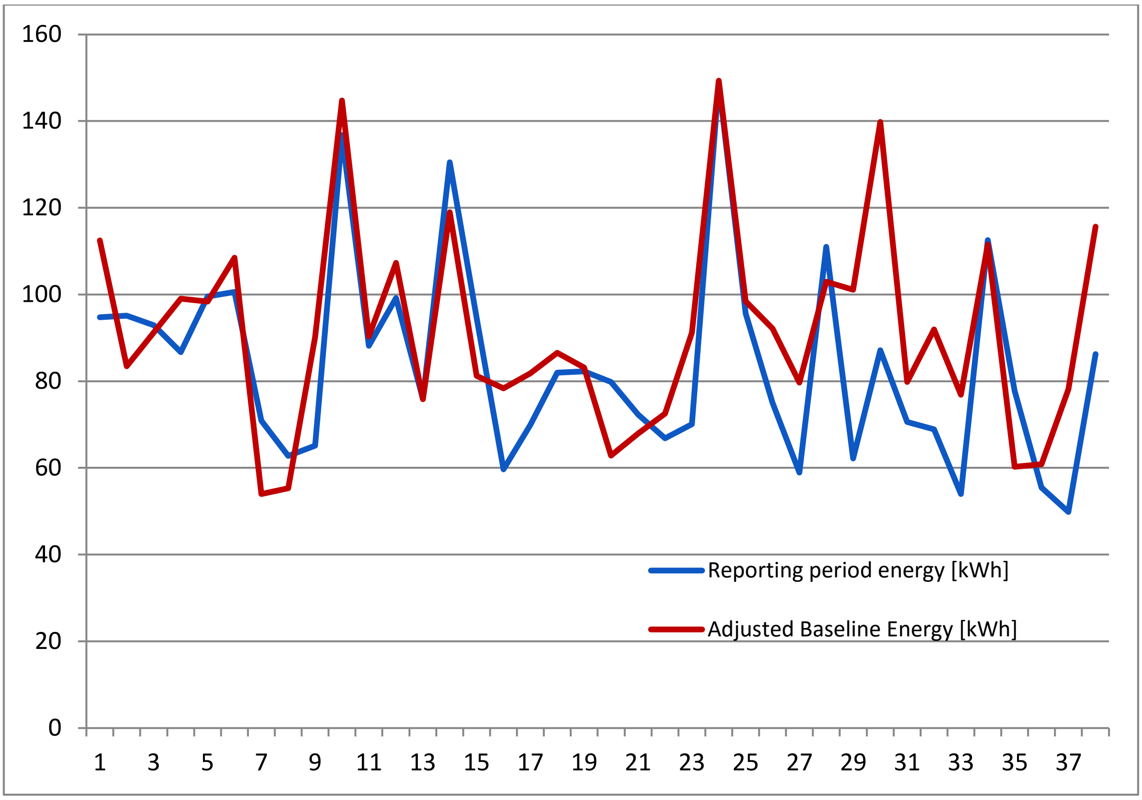

Figure 3: Comparison between the real and modelled profiles in CARTIF Uc1

Adding up these daily energy consumptions, the total energy consumption during this evaluation period can be calculated and, thus, the energy savings achieved with the BaaS solution operating in CARTIF pilot building during evaluation period of the winter season (Uc1) can be estimated.

Considering the whole period, BaaS results give an estimation of 9% in energy savings, which does not meet the IPMVP recommendations for Option C (savings > 10%). However, it should be remarked that the days with higher consumptions compared to the ABE were first days of the period, which were devoted to calibrating and carrying out different tests (schedules, set points, etc.). Not including those preparation days, the energy savings achieved with BaaS achieve the 10% recommended by the IPMVP.

Pilot Building	Use Case	Evaluation period	Energy savings	
CAR	Uc1	14/02/2016 – 01/04/2016	**284 kWh**	**10%**

Table 6: BaaS project results in the reporting period CARTIF_Uc1

3.2 CARTIF building Use Case 2: Summer

3.2.1 *Background from the baseline period*

Regarding CARTIF_Uc2, after numerous analyses, a power-based model (an energy-based model was not possible as the energy meter has a very low sensibility that made impossible adjusting the baseline data) was obtained for the baseline period, in the framework of IPMVP-Option C. This model represented the cooling power [W] as a quadratic function of the outdoor temperature, indoor temperature and solar radiation. The model includes a correction in the intercept when it is applied to evaluate the consumption during a Monday, as there is a systematic overconsumption on this day of the week. Next equation represented the aforementioned model:

$$P[W] = 355{,}458{,}065 + 1{,}057{,}195 \cdot T_{out}[^{\circ}C] + \text{-}26{,}729{,}48\,8 \cdot T_{indoor}[^{\circ}C] + \text{-}81{,}230 \cdot Rad[W/m^2] + 2{,}119 \cdot Day + \text{-}19{,}396 \cdot T_{out} x T_{in} + 306 \cdot T_{out} x Rad + 3{,}294 \cdot T_{out}^{\ 2} + \text{-}19{,}374 \cdot T_{in}^{\ 2} + 492{,}642 \cdot Rad^2$$

Equation 3: Adjusted Baseline Energy for CARTIF_Uc2

Next chart shows the model adjustment to real energy consumption data. As it can be observed, the real and modelled power profiles and ranges of values are similar.

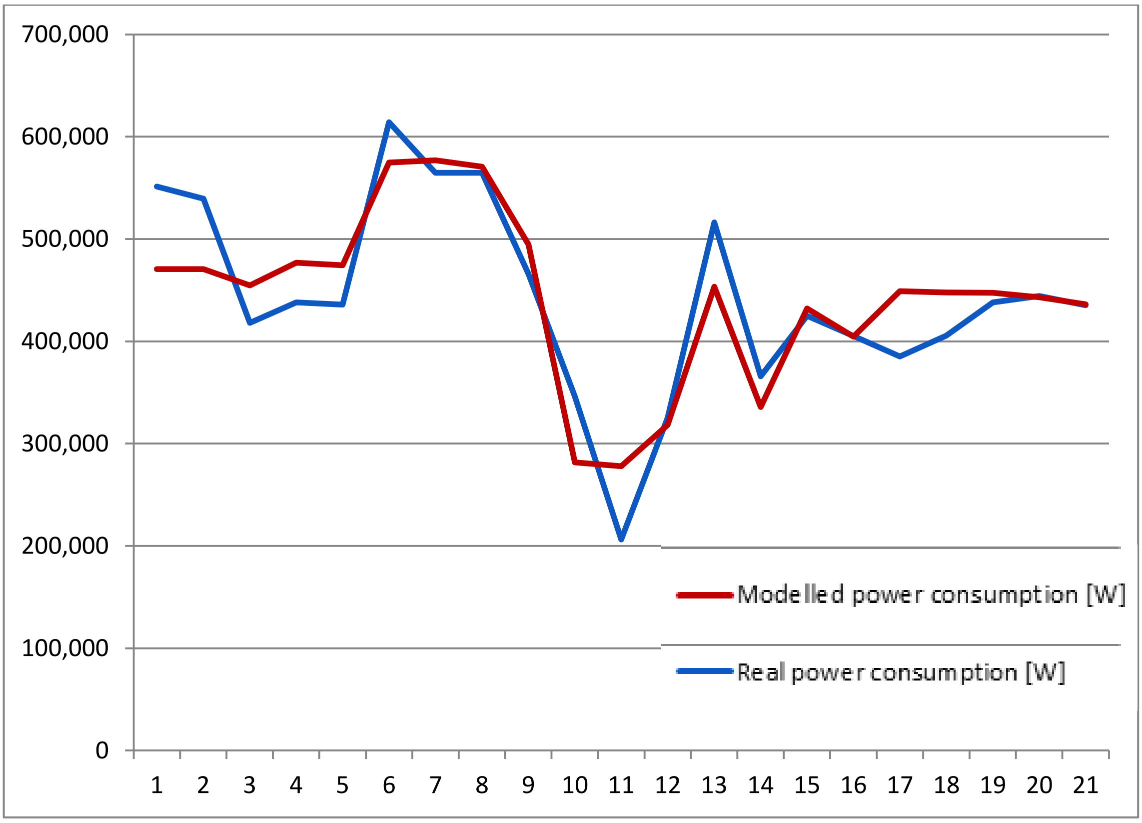

Figure 4: Baseline power profiles comparison in CARTIF_Uc2

3.2.2 *Static factors during the summer reporting period*

The reporting period considered for the evaluation of the BaaS solution in CARTIF pilot building, use case 2 was from 17th of August to 11th of September.

Start of reporting period	End of reporting period
17th August 2015	11th September 2015

Table 7: CARTIF Building reporting period for the summer use case

These periods were selected taking into account that the start date for the operation of the BaaS control strategies was in August 2015 and also that CARTIF building was closed in 2015 during the first 2 weeks of August. Moreover, the summer mode was officially stopped in 11th of September when the maintenance staff decided to step to the inter-season period.

3.2.3 Data points

Next table includes a summary of data points (from the middle of August to the middle of September 2015) that are representative of the period under study in CARTIF_Uc2, in order to test the power model:

Date	Day	T_{out}[ºC]	T_{ind} [ºC]	RAD [W/m^2]	Power [W]
17/08/2015	Monday	19.41	24.58	537.72	71,100
18/08/2015	Tuesday	18.61	24.96	670.56	232,800
19/08/2015	Wednesday	19.81	25.44	685.22	217,500
20/08/2015	Thursday	21.42	25.40	676.60	385,200
21/08/2015	Friday	23.47	25.81	604.52	723,400
24/08/2015	Monday	13.23	25.85	497.18	453,500
25/08/2015	Tuesday	15.51	25.32	675.95	347,500
26/08/2015	Wednesday	18.98	25.26	620.48	363,300
27/08/2015	Thursday	19.69	25.70	640.42	359,200
28/08/2015	Friday	20.62	26.48	669.38	260,100
31/08/2015	Monday	21.05	27.97	354.86	834,900
01/09/2015	Tuesday	18.28	26.07	559.25	564,700
02/09/2015	Wednesday	18.70	25.94	590.22	84,300
03/09/2015	Thursday	16.48	25.12	553.03	87,500
04/09/2015	Friday	15.35	25.39	631.84	289,400
07/09/2015	Monday	16.53	25.64	471.81	153,000
08/09/2015	Tuesday	15.00	25.45	652.08	191,700
09/09/2015	Wednesday	16.26	25.72	397.19	153,000
10/09/2015	Thursday	18.00	26.06	598.26	325,400
11/09/2015	Friday	15.83	25.90	641.16	297,100

Table 8: Data summary of the reporting period for CARTIF_Uc2

3.2.4 Evaluation of the BaaS Solution in CARTIF Pilot Building_Uc2

3.2.4.1 Evaluation with the energy model

By applying the model to the independent variables considered in the model the adjusted baseline power can be determined. Table below presents the real and the modelled power consumptions.

Datapoint	Adjusted Baseline Power [W]	Reporting period power [W]
1	1,055,141	71,100
2	447,704	232,800
3	439,689	217,500
4	397,621	385,200
5	173,739	723,400
6	-134,763	453,500
7	51,796	347,500
8	493,165	363,300
9	526,048	359,200
10	1,128,111	260,100
11	749,450	834,900
12	553,811	564,700
13	564,184	84,300
14	463,903	87,500
15	133,146	289,400
16	272,956	153,000
17	41,474	191,700
18	66,959	153,000
19	620,676	325,400
20	365,850	297,100

Table 9: Data for the energy consumptions evaluation in CARTIF_Uc2

Representing the real and modelled cooling thermal power profiles during the considered evaluation period in Figure 5, it can be observed as the model developed for the baseline do not adjust at all with the real data in the reporting period as it gives aleatory results. Hence, it is not correct to apply it in the energy savings evaluation (point with extreme under-consumptions, points with extreme over-consumptions, points with negative power…).

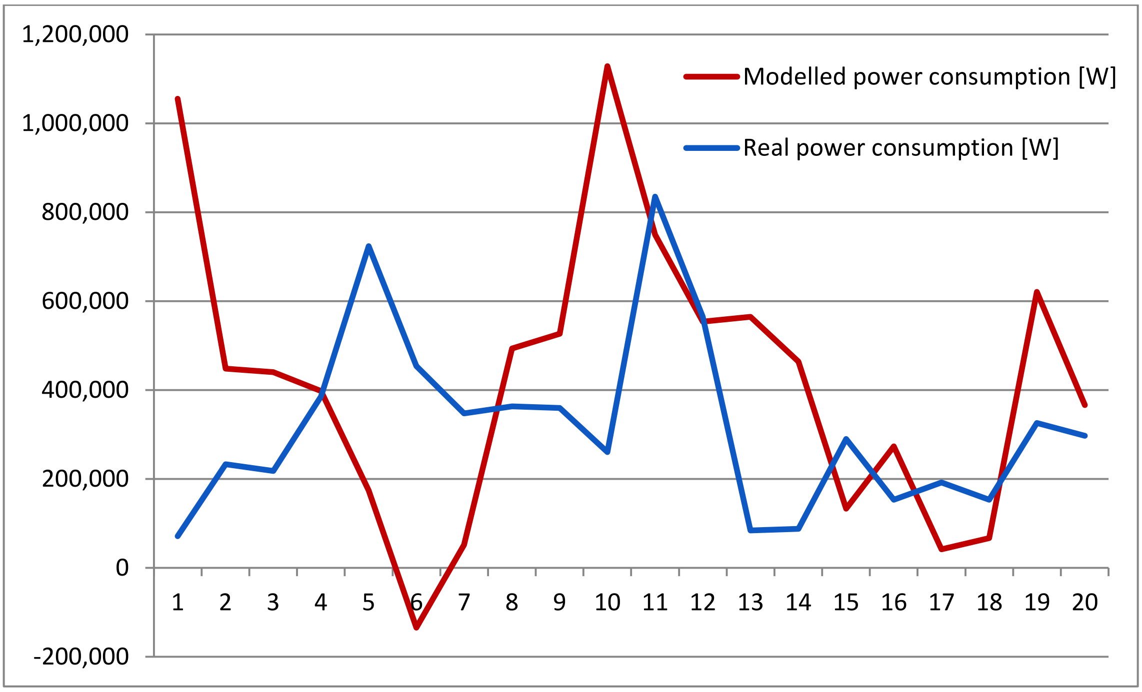

Figure 5: Reporting power profiles comparison in CARTIF_Uc2

This issue can be due to an over-adjustment of the model (too many variables involved for the data sample, some variables were not significant, etc.). In order to correct this maladjustment, it is proposed to analyse the operation of those heat pumps of the cooling system over which BaaS acted, taking advantage of the analyses already undertaken in the framework of D4.4, as it is described in the next subsection.

3.2.4.2 Evaluation with the kWh_e and CDD

As it has been mentioned before, once it has been proved that the energy model developed is not valid to apply in the reporting period, another possibility to carry out the assessment of the energy savings achieved during the summer reporting period is to study the heat pumps over which BaaS acted.

By knowing their power output and the number of hours in which they have operated, an estimation of the electric energy consumption can be obtained. This electric energy could give an idea of the cooling consumption in CARTIF pilot building during summer (Uc2).

Moreover, comparing this energy consumption in the baseline and reporting periods, and referring these consumptions to the outdoor conditions, the energy savings achieved with the implementation of the BaaS solution can be estimated.

In this way, it is important to highlight that the analysis of all the heat pumps have not been considered, but the main important ones (i.e. covering the most of the cooled area). These are UCB5 (vision 2D), UBC6 (robotics), UBC7 (energy 1), UBC8 (energy 2) and UBC14 (innovation). Also, it is remarkable that the control of the BaaS system in UBC6 and UBC14 was applied later than the others. However, in order to consider a homogeneous reporting period, their analysis is included, which provides an estimated value for the electricity energy consumed during reporting period.

In order to undertake these comparisons, the electric energy consumption has been calculated in kWh_e and the external conditions are considered by the cooling degree days with base temperature 23 ºC (CDD_{23}).

Option 1: High improvement of the ratio kWh/CDD

Period	IPMVP	E (kWh_e)	CDD_{23}	Ratio (kWh_e / CDD_{23})
Summer 2014	Baseline	2,392	72.1	33.17
Summer 2015	Reporting	1,962	94.9	20.67

Table 10: Reduction of the ratio kWh/CDD

The amount of relative cooling energy (represented by the electrical consumption of most representative heat pumps) needed to cool CARTIF pilot building during the summer time has been significantly reduced comparing the baseline with the reporting period: 12.50 kWh_e/CDD_{23} which represents a 38% of improvement, as described in D4.4 "*Evaluation of the WP5 results under different KPIs*".

Option 2: Estimation of the cooling energy savings through an "IPMVP" evaluation

Another possible analysis is trying to estimate the adjusted baseline energy.

According to its definition, ABE is the energy that would be consumed by the building in the reporting period with those outdoor conditions if it kept operating as in the baseline period. On the one hand, if the cooling system operates as in the baseline period, the value of the ratio kWh/CDD should keep constant. On the other hand, the outdoor conditions in the reporting period are represented by the cooling degree days.

Therefore, the ABE could be estimated as the product of the baseline kWh/CDD ratio and the reporting CDD:

$$ABE^* = ratio_{baseline} \times CDD_{reporting}$$

Equation 4: Estimated ABE for CARTIF_Uc2

Applying this method, the energy savings achieved in the reporting period due to the implementation of the BaaS solution are estimated in 756 kWh_e which represents a 24% of the reference consumption.

Pilot building	Use Case	Period	Reporting	ABE *	Energy savings
CARTIF	Uc2	Summer 2015	2,392 kWh_e	3,148 kWh_e	**756 kWh_e (24%)**

Table 11: Energy savings estimation in CARTIF_Uc2

The results achieved with this estimation are aligned with the reduction of the hours of operation that the heat pumps had with BaaS (30%), whose study is detailed in deliverable D4.4 "*Evaluation of the WP5 results under different KPIs*".

4 ZUB Pilot Building

4.1 Background from the baseline period in ZUB pilot building

Following the IPMVP-Option C guidelines, the next energy model was obtained in *D6.3.2: "Baseline period in the pilot buildings"*, representing the heat consumption in ZUB pilot building for Uc1, as a linear function of the outdoor temperature (daily average) and the solar radiation (total accumulated).

$$H[kWh] = 370.08 - 23.82 \cdot T_{out}[^{\circ}C] - 25.32 \cdot Rad[kWh/m^2]$$

Equation 5: Adjusted Baseline Energy for ZUB_Uc1

In addition, next figure shows how well the energy model developed in the baseline period adjusted to the real profile of the energy consumption.

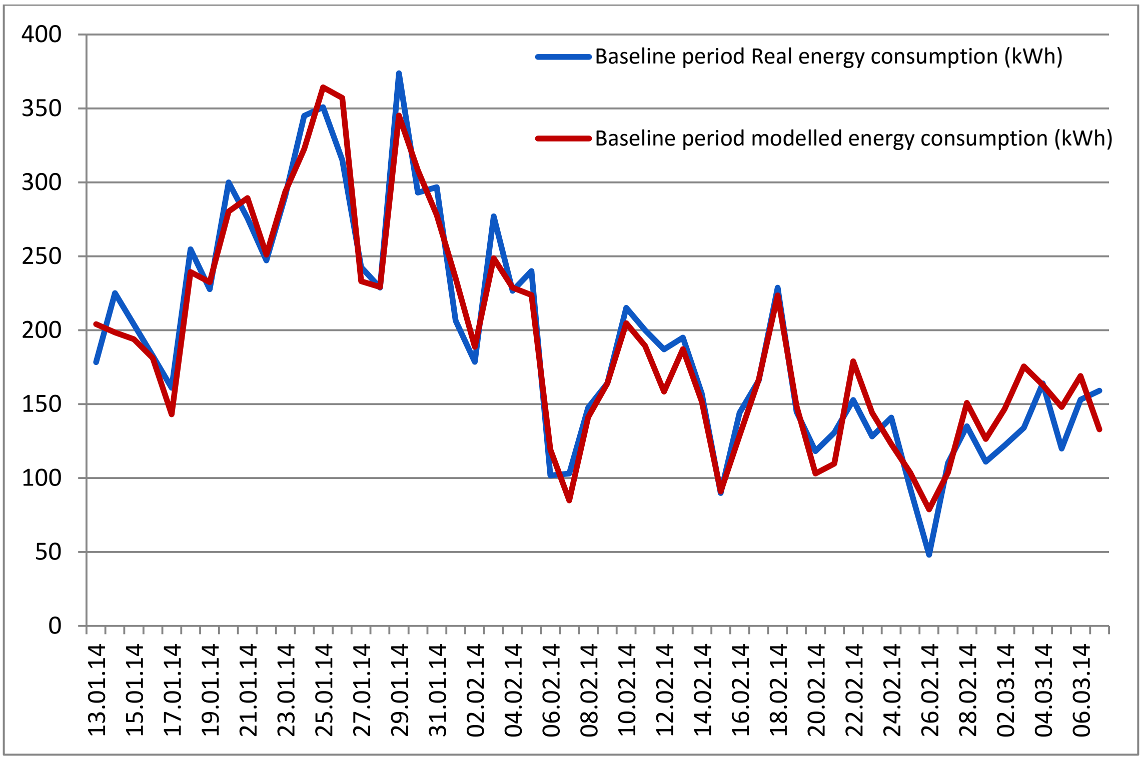

Figure 6: Baseline energy profiles comparison in ZUB_Uc1

4.2 Static factors during the reporting period in ZUB

The configuration of the control services of the ZUB building initiated at December 9th, 2015, in order to improve the software entities of Module Manager. The initial implementation had been enriched with more functional methods to support more complex services and enhance the stability of the complex deployment process. Therefore, the reporting period that has been defined in ZUB Pilot Building Uc1 to evaluate the results of the BaaS solution is presented in the table below:

Start of the reporting period	End of the reporting period
10th December, 2015	15th March, 2016

Table 12: Reporting period for the winter season in ZUB pilot building

In ZUB Pilot Building, different tests have been conducted in order to assess the performance of the BaaS solution. For the winter control experiments, two different configurations were used for the Use Case 1 of ZUB pilot building:

i) a **knowledge-based** control solution, designed based on the understanding of the building dynamics and the baseline control and applied in the period 10/12/2015 – 21/02/2016; and

ii) a **simulation model-based** control design solution as described in Deliverable D5.3, applied in the period 22/02/2016 – 15/03/2016.

On the one hand, the **knowledge-based** control solution alters the baseline control strategy, favouring a more energy-efficient control of the building. The baseline controller uses a heating curve to generate a new water temperature set-point every one hour, and maintains the building set-point at 21°C constantly, while the input of the heating curve is the 24-h running mean of the outside air temperature. From reviewing the building inefficiencies (see Deliverables 5.1a, 5.1b and 5.4) we know that this strategy can lead to overheating of the first floor, especially for cold, sunny winter days. Thus, we have designed a different heating curve that generates lower water temperatures for higher outside air temperatures compared to the baseline strategy, while also setting the building set-point to a lower value (19.8°C) in order to save energy.

On the other hand, the **simulation model-based** control solution utilizes the algorithms presented in Deliverable D5.3 and leads to a different control strategy, compared to the baseline and knowledge-based control solutions. Here, the building is systematically pre-heated on Sunday evening up until Monday morning and then it free-floats for the rest of the week (or some additional heating is provided for a small period of time if necessary), using the internal gains from the equipment and the occupants, as well as solar gains for preserving comfortable interiors and thus leading to energy savings. This strategy is not manually programmed to the system using a set of pre-defined rules, but is designed automatically utilizing the weather predictions and the simplified thermal simulation model of ZUB building described in Deliverable D4.3.

According to the description above, within the reporting period in ZUB pilot building, two evaluation periods should be distinguished before conducting the energy savings evaluation, as it is reflected in the table below:

Control strategy	Evaluation period
Knowledge-based control solution	10/12/2015 – 21/02/2016
Simulation model-based control design solution	22/02/2016 – 15/03/2016

Table 13: ZUB_Uc1 control strategies and evaluation periods

During the last weeks of winter, 16/03/2016 – 01/04/2016, there was a problem that did not allow continuing the experiment and, thus, those days were not included in the analysis. As it has been already explained in other related reports, ZUB pilot building has a complex automation installation. Three PLCs are interconnected with a low-level protocol named S-Bus for sharing the actual values of the signals and for feeding the inputs of the PID controllers. One of these is responsible to control the hot water temperature entering the TABS, as well as the general set-point of the building. Several software components have active connection with this specific device (MW, third-party data-loggers, etc.) and it is not clear from the manufacturer what is the maximum number allowed for active clients. Thus, sometimes the device needs a cold reset from the supervisor of the BMS in order to be again functional. Within BaaS, we can ensure the stability of the devices with the maximum number of two simultaneously connections. During the model-based control design experiment, in the middle of March 2016, several third-party clients were connected simultaneously to the device and this forced the earlier termination of the experiment.

4.3 ZUB_Uc1 control strategy 1: Knowledge-based solution

As it has been described above, the **knowledge-based** control solution modifies the control strategy that was implemented during the baseline period, favoring a more energy-efficient control of the ZUB Pilot Building during the Uc1. This strategy has been designed with a different heating curve that generates lower water temperatures for higher outside air temperatures compared to the baseline strategy, while also setting the building set-point to a lower value (19.8°C) in order to save energy.

The evaluation period for this control strategy is reflected in the next table:

Start of the evaluation period 1	End of the evaluation period 1
10th December, 2015	21st February, 2016

Table 14: ZUB Building evaluation period 1 for the Uc1

It should be remarked that during this first evaluation period, there were some days that could not be included in the final analysis because many errors were identified during the data processing, which leaded to inconsistencies and illogical values in the independent variables (outdoor temperature and solar radiation) and the dependent variable (energy consumption). The days that were taken away from the evaluation were the following ones:

- 10/01/2016 – 21/01/2016 and 29/01/2016 – 01/02/2016: Errors detected in the data from the weather station.
- 17/02/2016 and 18/02/2016: Errors and inconsistencies both in the data registered in the weather station and in the heat meter.

4.3.1 *Data summary*

Next table includes the summary of the data processed for this first evaluation period, including dates, energy consumption (daily total), outdoor temperature (daily average) and solar radiation (daily total accumulated).

Date	Day	Heat consumption [kWh]	T_{out} [°C]	Rad [kWh/m^2]
10/12/2015	Thursday	143.0	4.76	1.04
11/12/2015	Friday	206.0	4.90	0.13
12/12/2015	Saturday	113.0	7.24	0.13
13/12/2015	Sunday	76.3	7.81	0.14
14/12/2015	Monday	218.2	6.16	0.42
15/12/2015	Tuesday	135.0	8.16	0.14
16/12/2015	Wednesday	119.0	9.55	0.10
17/12/2015	Thursday	46.0	13.14	0.42
18/12/2015	Friday	44.0	13.18	0.16
19/12/2015	Saturday	35.0	12.15	0.57
20/12/2015	Sunday	49.0	10.60	1.27
21/12/2015	Monday	70.0	11.13	1.05
22/12/2015	Tuesday	71.0	12.10	0.98

23/12/2015	Wednesday	70.0	11.30	0.32
24/12/2015	Thursday	86.0	10.86	0.46
25/12/2015	Friday	84.0	10.99	0.68
26/12/2015	Saturday	49.0	12.48	0.57
27/12/2015	Sunday	50.0	10.51	0.60
28/12/2015	Monday	112.0	7.17	1.58
29/12/2015	Tuesday	248.9	4.93	0.38
30/12/2015	Wednesday	170.9	6.42	0.93
31/12/2015	Thursday	281.0	4.96	0.32
01/01/2016	Friday	217.0	6.65	0.17
02/01/2016	Saturday	212.0	3.92	1.70
03/01/2016	Sunday	247.5	2.98	0.73
04/01/2016	Monday	261.0	2.41	0.43
05/01/2016	Tuesday	245.0	5.73	0.37
06/01/2016	Wednesday	265.8	3.49	0.41
07/01/2016	Thursday	287.7	4.95	1.26
08/01/2016	Friday	182.9	5.94	1.45
09/01/2016	Saturday	221.6	2.78	2.41
22/01/2016	Friday	387.5	-4.23	0.55
23/01/2016	Saturday	336.7	3.01	0.28
24/01/2016	Sunday	222.0	5.31	1.38
25/01/2016	Monday	208.0	8.41	1.38
26/01/2016	Tuesday	165.0	9.58	0.27
27/01/2016	Wednesday	88.0	11.11	0.51
28/01/2016	Thursday	36.0	9.06	1.04
02/02/2016	Tuesday	62.0	10.28	0.13
03/02/2016	Wednesday	164.3	6.52	0.13
04/02/2016	Thursday	239.1	5.03	0.14
05/02/2016	Friday	250.0	6.48	0.42
06/02/2016	Saturday	142.4	10.14	0.14
07/02/2016	Sunday	151.0	9.29	0.10
08/02/2016	Monday	215.0	8.80	0.42
09/02/2016	Tuesday	94.0	8.34	0.16

10/02/2016	Wednesday	198.9	5.56	0.57
11/02/2016	Thursday	170.6	5.99	1.27
12/02/2016	Friday	162.0	4.91	1.05
13/02/2016	Saturday	198.6	3.20	0.98
14/02/2016	Sunday	178.0	6.15	0.32
15/02/2016	Monday	221.0	3.41	0.46
16/02/2016	Tuesday	311.1	0.93	0.68
19/02/2016	Friday	255.9	3.03	0.57
20/02/2016	Saturday	237.8	5.26	0.60
21/02/2016	Sunday	75.0	11.47	1.58

Table 15: Data summary of the reporting period in ZUB (control 1)

4.3.2 Evaluation of the BaaS Solution in ZUB Pilot Building_Uc1 (control strategy 1)

Applying the model to the external conditions that occurred during this evaluation period under control strategy (1), the ABE can be determined. Table below presents the real and the modelled energy consumptions during this first evaluation period.

Datapoint	Adjusted Baseline Energy [kWh]	Reporting period energy [kWh]
1	246.9	143.0
2	252.6	206.0
3	171.0	113.0
4	177.5	76.3
5	217.2	218.2
6	172.8	135.0
7	137.6	119.0
8	49.4	46.0
9	45.5	44.0
10	67.3	35.0
11	108.8	49.0
12	89.6	70.0
13	77.5	71.0
14	83.2	70.0
15	97.1	86.0
16	104.1	84.0
17	44.4	49.0
18	103.5	50.0

19	177.3	112.0
20	226.3	248.9
21	214.0	170.9
22	248.7	281.0
23	208.2	217.0
24	266.1	212.0
25	295.5	247.5
26	310.4	261.0
27	223.0	245.0
28	282.9	265.8
29	237.6	287.7
30	196.5	182.9
31	277.2	221.6
32	445.9	387.5
33	290.4	336.7
34	232.0	222.0
35	152.6	208.0
36	127.5	165.0
37	90.1	88.0
38	114.2	36.0
39	115.6	62.0
40	191.3	164.3
41	242.1	239.1
42	211.6	250.0
43	85.5	142.4
44	130.1	151.0
45	149.6	215.0
46	162.1	94.0
47	227.3	198.9
48	195.4	170.6
49	216.5	162.0
50	232.8	198.6
51	209.7	178.0
52	281.7	221.0

53	312.9	311.1
54	263.0	255.9
55	238.0	237.8
56	83.9	75.0
TOTAL	**10,412 kWh**	**9,388 kWh**

Table 16: Energy consumptions comparison in ZUB with control strategy 1

Next graph shows a comparison between the real energy profile in the reporting period after the implementation of the ECM related to the BaaS solution and the theoretic energy profile that would have been consumed in the same weather conditions if the BaaS solution had not been applied.

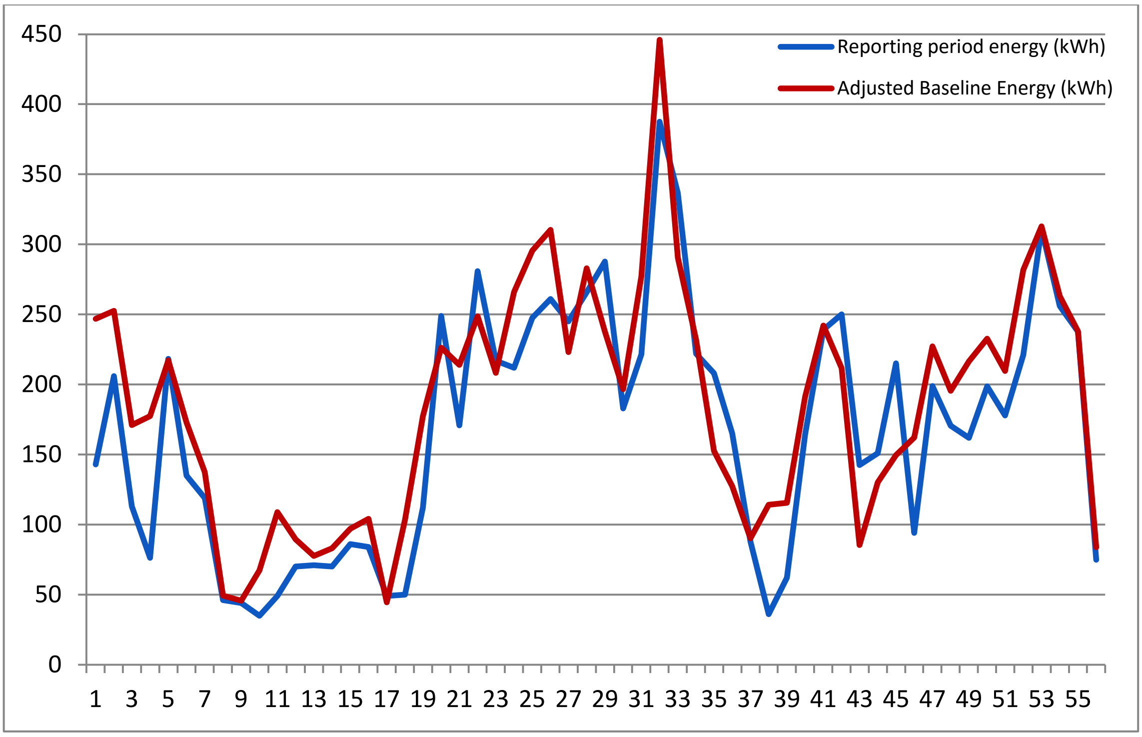

Figure 7: Reporting energy profiles comparison in ZUB_Uc1 (Control 1)

Adding up these daily energy consumptions, the total energy consumption during this evaluation period can be calculated and, thus, the energy savings achieved with the BaaS solution operating under this control strategy can be estimated. As it can be seen in the next table, the energy savings meet the IPMVP guideline of a minimum 10% established for the Option C.

Pilot Building	Evaluation period	Control strategy	Energy savings	
ZUB	10/12/2015 – 21/02/2016	Knowledge-based	**1,024 kWh**	**10 %**

Table 17: BaaS results in ZUB_Uc1 (Control 1)

4.4 ZUB_Uc1 control strategy 2: Simulation model-based solution

The **simulation model-based** control solution utilizes several algorithms that lead to a different control strategy, compared to the baseline and knowledge-based control solutions, as it was previously explained (for more details see D5.3 and D4.3). This strategy is designed automatically utilizing the weather predictions and the simplified thermal simulation model of ZUB Pilot Building.

The period considered to evaluate this control strategy is presented in the next table:

Start of the evaluation period 2	End of the evaluation period 2
21st February, 2016	15th March, 2016

Table 18: ZUB Building evaluation period 2 for the Uc1

4.4.1 *Data summary*

Next table includes the summary of the data processed for this second evaluation period, including dates, energy consumption (daily total), outdoor temperature (daily average) and solar radiation (daily total accumulated).

Date	Day	Heat consumption [kWh]	T_{out} [°C]	Rad [kWh/m^2]
22/02/2016	Monday	52.0	9.88	0.91
23/02/2016	Tuesday	71.0	5.78	1.68
24/02/2016	Wednesday	210.0	5.01	1.26
25/02/2016	Thursday	93.4	2.86	2.10
26/02/2016	Friday	167.0	3.55	1.78
27/02/2016	Saturday	203.0	2.65	3.34
28/02/2016	Sunday	114.4	2.61	2.26
29/02/2016	Monday	235.1	3.39	2.78
01/03/2016	Tuesday	152.3	2.95	2.35
02/03/2016	Wednesday	230.2	6.00	1.12
03/03/2016	Thursday	279.0	6.18	2.05
04/03/2016	Friday	42.0	5.67	1.91
05/03/2016	Saturday	30.0	7.04	0.60
06/03/2016	Sunday	280.4	5.26	1.12
07/03/2016	Monday	314.4	4.08	1.45
08/03/2016	Tuesday	171.0	3.18	2.17
09/03/2016	Wednesday	145.3	4.90	4.02
10/03/2016	Thursday	24.0	4.74	2.05
11/03/2016	Friday	34.0	6.21	3.31
12/03/2016	Saturday	43.0	5.12	0.55
13/03/2016	Sunday	57.0	5.04	2.08

14/03/2016	Monday	63.0	5.70	4.44
15/03/2016	Tuesday	63.0	5.75	1.69

Table 19: Data summary of the reporting period in ZUB (control 2)

4.4.2 Evaluation of the BaaS Solution in ZUB Pilot Building_Uc1 (Control strategy 2)

In order to evaluate the energy savings achieved due to the implementation of the BaaS solution in ZUB Pilot Building operating under the control strategy (2), the energy model designed for the baseline period is used to calculate the ABE, applying the equation presented at the beginning of this section.

Datapoint	Adjusted Baseline Energy [kWh]	Reporting period energy [kWh]
1	111.8	52.0
2	189.7	71.0
3	218.7	210.0
4	248.6	93.4
5	240.3	167.0
6	222.5	203.0
7	250.5	114.4
8	218.9	235.1
9	240.3	152.3
10	198.8	230.2
11	171.2	279.0
12	186.5	42.0
13	187.1	30.0
14	216.5	280.4
15	236.3	314.4
16	239.5	171.0
17	151.5	145.3
18	205.2	24.0
19	138.4	34.0
20	234.2	43.0
21	197.2	57.0
22	121.9	63.0
23	190.3	63.0
TOTAL	**4,616 kWh**	**3,075 kWh**

Table 20: Energy consumptions comparison in ZUB with control strategy 2

Next graph shows a comparison between the real energy profile in the reporting period after the implementation of the ECM related to the BaaS solution and the theoretic energy profile that would have been consumed in the same weather conditions if the BaaS solution (control strategy 2) had not been applied.

As also reported in deliverables D4.4 and D5.4, it is obvious that the control strategy designed automatically using the algorithms presented in deliverable D5.3 is significantly different compared to baseline control and the BaaS knowledge-based controller. The building is systematically pre-heated on Sunday evening up until Monday morning and then it free-floats for the rest of the week (or some heating is provided if required). This allows for preserving comfortable interiors while saving energy at the same time through a strategy that exploits the high thermal mass of the building by utilizing the internal gains from the equipment and the occupants, as well as solar gains. Therefore, this is why the energy profiles that are represented in the graph (BaaS and ABE) are quite different.

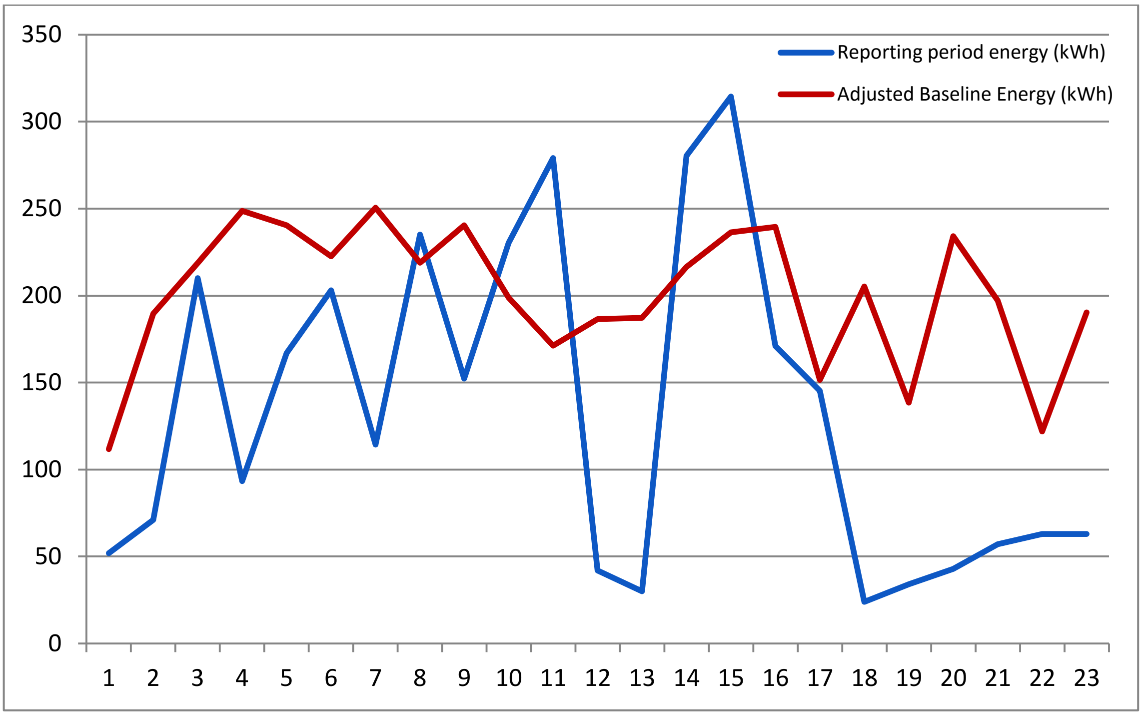

Figure 8: Energy profiles comparison in ZUB_Uc1 (Control 2)

Finally, adding up the daily energy consumptions, the total energy consumption during this evaluation period can be calculated and, thus, the energy savings achieved with the BaaS solution operating under this control strategy can be estimated. As it can be seen in the next table, the energy savings far overcome the IPMVP guideline of a minimum 10% established for the Option C.

Pilot Building	Evaluation period	Control strategy	Energy savings	
ZUB	22/02/2016 – 15/03/2016	Simulation-based	**1,541 kWh**	**33%**

Table 21: BaaS project results in ZUB_Uc1 (Control 2)

4.5 Overall reporting period in ZUB_Uc1

Once the two control solutions have been implemented in ZUB_Uc1 and the yielded results have been analysed applying the IPMVP methodology, in terms of consumptions, profiles and energy savings, it is also interesting to get an overall depiction of the BaaS solution in the whole reporting period under study, by combining the results obtained with the two control solutions individually.

Adding up the total energy consumptions in the two evaluation periods, the total energy consumption during the reporting period can be calculated and, thus, the total energy savings achieved with the BaaS solution can be estimated.

Pilot Building	Reporting period	Energy consumed	Energy savings	
ZUB	10/12/2016 – 15/03/2016	12,462 kWh	**2,566 kWh**	**17%**

Table 22: Overall BaaS project results in ZUB_Uc1

The overall energy savings achieved in ZUB_Uc1 during the reporting period under study are estimated on a 17%, which clearly overcomes the minimum established by the IPMVP for the Option C (10%).

5 Sierra Elvira School Pilot Building

5.1 Background from the baseline period in SES

Sierra Elvira School pilot building Use Case 1 (SES_Uc1) is aimed to reduce the energy consumption associated to the distribution system according to demand installation and comfort constraints balancing the thermal comfort levels and the energy consumption of the complete system (see more details in Deliverable D5.1 *"Building Services: Functional and interoperability requirements"*).

Therefore, two different models were designed aimed to evaluate this double objective: achieving energy savings while improving the comfort level. The models were adjusted using data from the beginning of January to the end of March of 2015, when BaaS solution was not implemented yet.

It is important to note that, in order to obtain a more specific and precise analysis, the model is customized distinguishing between the two main zones of SES pilot building (corresponding to the two circuits of the heating system).

5.1.1 *Energy consumption model*

Equations below represent the energy consumption model (in MWh), divided in the two main zones of SES Pilot Building.

$$E = -0.10 - 0.01 \cdot T_{out} + 0.01 \cdot T_{ret} - 0.02 \cdot T_{in-1} + 0.01 \cdot T_{in} + 0.12 \cdot Day_{Monday} - 0.13 \cdot Month_{March}$$

Equation 6: Adjusted Baseline Energy for SES_Uc1 (Zone 1)

$$E = 0.06 - 0.01 \cdot T_{out} + 0.01 \cdot T_{ret} - 0.02 \cdot T_{in-1} + 0.01 \cdot T_{in} + 0.10 \cdot Day_{Monday} - 0.16 \cdot Month_{March}$$

Equation 7: Adjusted Baseline Energy for SES_Uc1 (Zone 2)

Next charts show the model adjustment to real energy consumption data (in kWh) in SES pilot building during the baseline period. As it can be observed, the energy profiles and ranges of values are very similar as they represent the energy consumption in the two main circuits of the heating system.

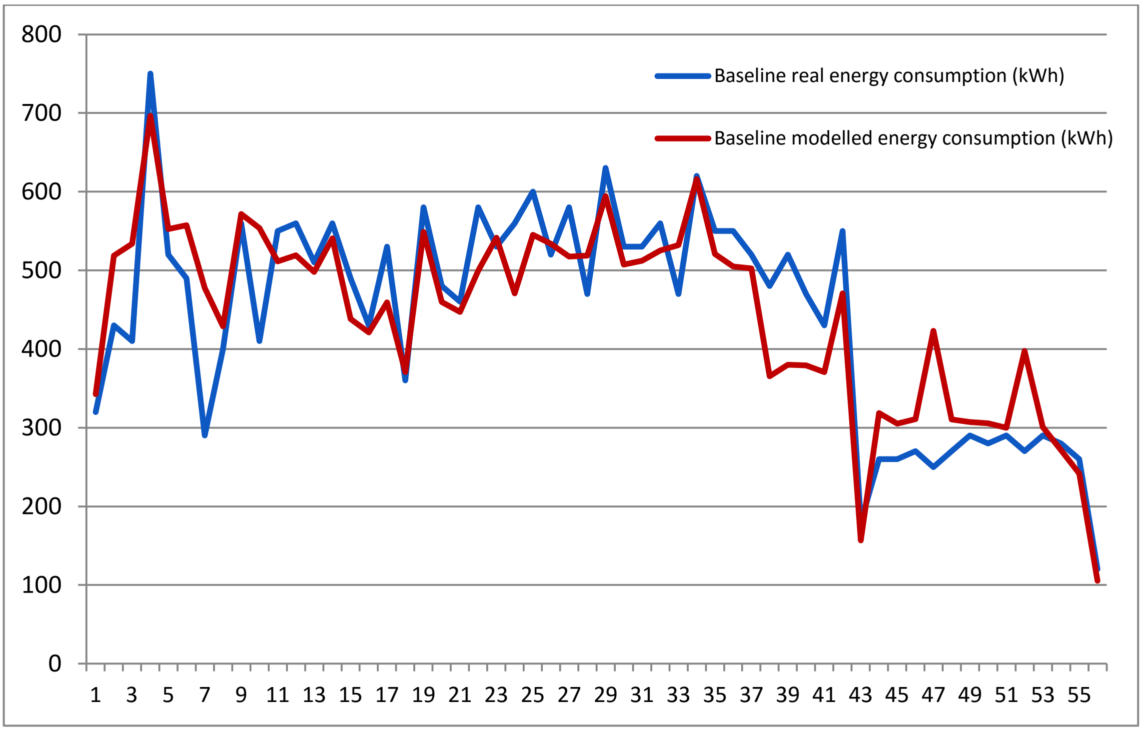

Figure 9: Energy model adjustment in SES_Uc1 (Zone 1)

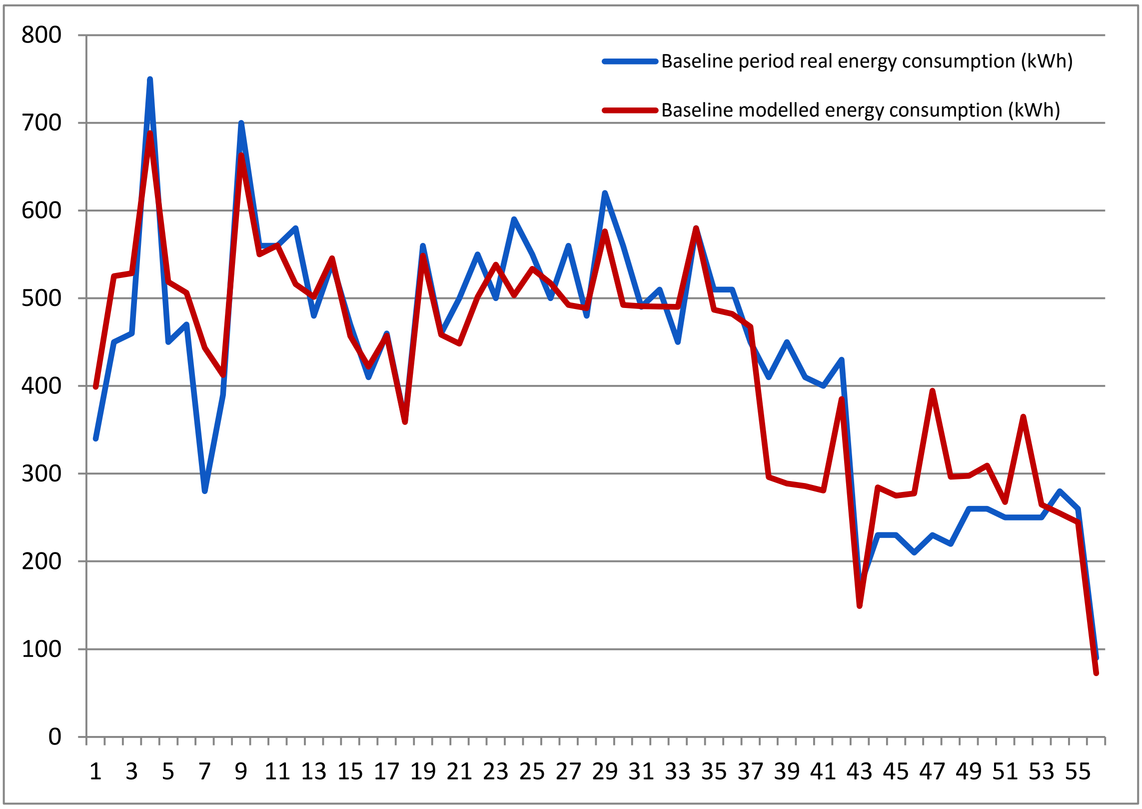

Figure 10: Energy model adjustment in SES_Uc1 (Zone 2)

5.1.2 *Indoor comfort level model*

The following equations show the indoor comfort level model (represented by the maximum indoor temperature achieved during the operation hours ºC) in the two main zones of SES pilot building:

$$T_{ind}[^{\circ}C] = 6.41 + 2.19 \cdot E[MWh] + 0.19 \cdot T_{out}[^{\circ}C] + 0.67 \cdot T_{ind\_prev}[^{\circ}C]$$

Equation 8: Indoor comfort level model for SES_Uc1 (Zone 1)

$$T_{ind}[^{\circ}C] = 5.42 + 2.94 \cdot E[MWh] + 0.19 \cdot T_{out}[^{\circ}C] + 0.75 \cdot T_{ind\_prev}[^{\circ}C]$$

Equation 9: Indoor comfort model for SES_Uc1 (Zone 2)

Next charts show the model adjustment to real indoor temperature data in the two main areas of SES pilot building during the baseline period. It can be observed that the indoor temperature profiles and the ranges of values are quite similar in both zones.

It can be noticed in the graphs that the comfort level in both main zones of SES building, i.e. zone 1 and zone 2, the maximum indoor temperatures reached many of the days did not reach 18ºC, which is a very low level taking into account that the national regulation establish a reference of 21ºC during winter time.

Therefore, one of the main initial goals of the implementation of BaaS was to improve the comfort conditions in SES while maintaining the energy consumption. This basically means that the indoor temperature should reach comfort range conditions through different control strategies applied on the heating system (schedules, boiler set-points…) that are designed to optimize the energy consumption of the building.

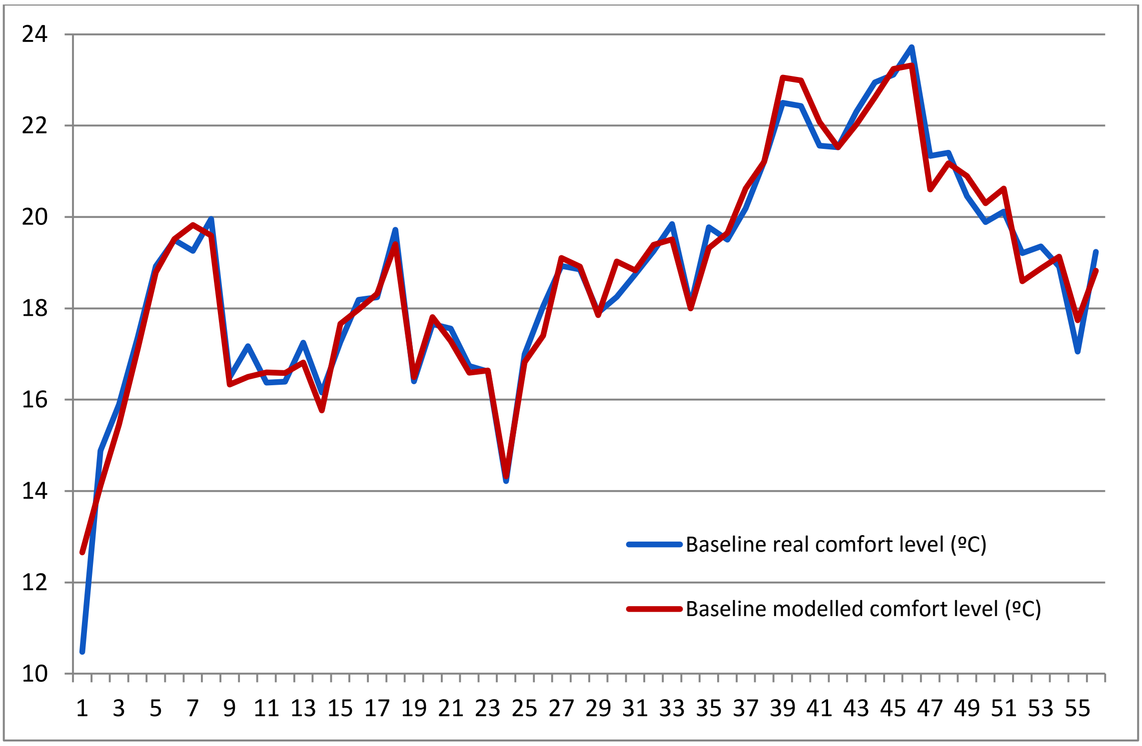

Figure 11: Comfort model adjustment in SES_Uc1 (Zone 1)

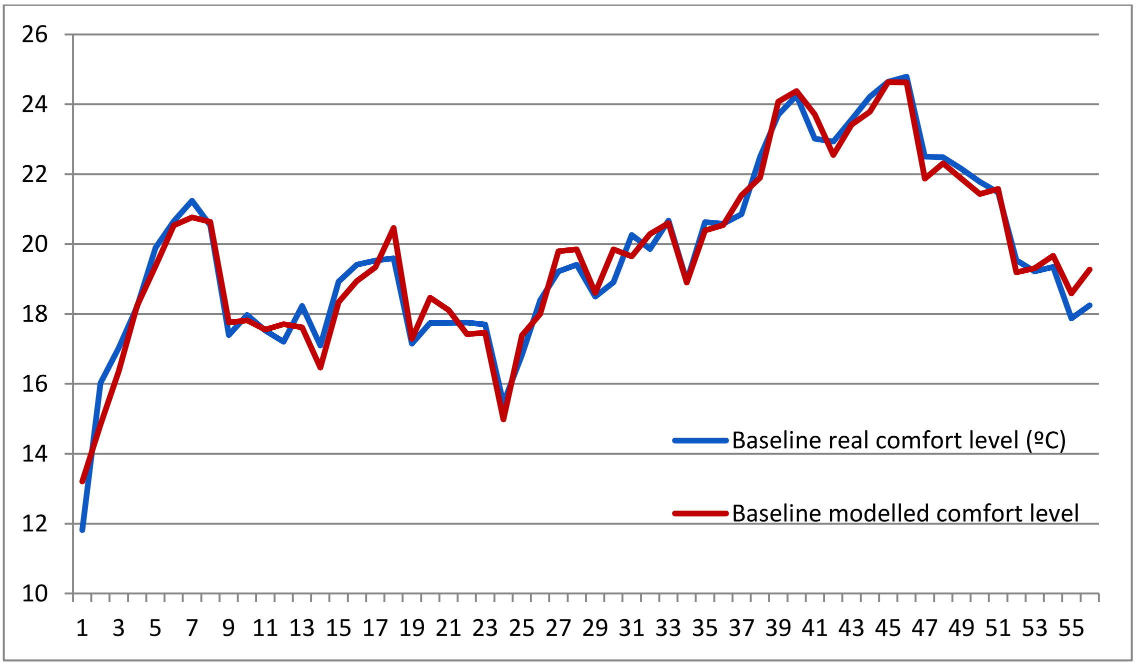

Figure 12: Comfort model adjustment in SES_Uc1 (Zone 2)

5.2 Static factors during the reporting period in SES

The analysis and tests of the BaaS solution started in November 2015 and finished in March 2016, corresponding to the beginning and ending of the heating season in SES pilot building. Therefore, the specific reporting period is the following one:

Start of the reporting period	End of the reporting period
11th November, 2015	21st March, 2016

Table 23: Reporting period for the winter season in SES pilot building

It is important to remark that, during this period, two different control strategies have been swapped from NEC to HON. They have differed and the main objective of them is stated below.

- **NEC control strategy: *Data-driven optimization***

From data gathered during the baseline period (winter season 2014-2015), predictive models have been developed in WP5 in order to implement control and optimization strategies in the heating system of SES pilot building. Taking predicted outdoor conditions as well as the heating system's set points into account it is possible to predict classroom temperatures over a school-day and the associated energy use per heating circuit. Genetic optimization has been applied in order to schedule the set points for both circuits over the coming school-day. For more details, see: D5.3 and D5.4 and the corresponding references therein.

Each circuit's optimization problem focuses on minimizing consumed energy subject while meeting the comfort requirements related to the indoor temperature. Using the WP3 middleware, the application layer then communicates the scheduled set points to the SES Building Management System for actuation. Over the execution of the experiments, it was detected that data outages and, occasionally, inaccurate weather forecasts caused problems in schedule efficiency. For more details, see D5.4 and the references there included.

The tests and experiments related to this control strategy were carried out in a discontinuous way during the reporting period, due to malfunctioning problems, but at least it could be distinguished to well-differentiated periods or experiments:

- **Experiment 1** which was carried out in November 2015, during the first weeks of the winter season in SES pilot building: 11/11/2015 – 30/11/2015.
- **Experiment 2** which was carried out during three days of middle February (10/02/2016 – 12/02/2016) and then from the end of February to the end of March 2016 (24/02/2016 – 07/03/2016 and 15/03/2016 – 21/03/2016), coinciding with the end of the reporting period in SES pilot building.

The gaps and days missing within this evaluation period either correspond to bank holidays or to weekends or they are due to malfunctioning or configuration problems, in some cases unrelated to BaaS system.

- **HONEYWELL control strategy: *Reinforcement Learning***

On the other hand, Honeywell applied an alternative approach to the very same system. This strategy consists on a holistic optimization of HVAC systems via distributed data-driven control and it is based on the principles of reinforcement learning with the following specification:

1. The cost function (negative reward) was defined as a combination of both discomfort costs and biomass costs.
2. Basic approach was strongly data-driven, calculating the Q functions[1], namely the Fitted Q Iteration (FQI) which was acknowledge also in may engineering applications.
3. Finally, the FQI was tailored so it is able to cope with a variable size of the state vector. The variable size is motivated by the fact that the considered weather forecasts are shorter at the end of the occupancy period than at its beginning.

The details of this strategy are described in D5.3, D5.4 and the references therein.

The evaluation of this control solution has conducted from middle January to the beginning of February 2016: 20/01/2016 – 09/02/2016. This control strategy could be performed continuously in the time, with no malfunctioning or missing days. The only days not included in the analyses correspond to weekends when the heating system, and hence, BaaS are off. This fact makes the analysis and evaluations easier and more reliable.

In order to assess the energy savings achieved as well as the comfort level improvements within the reporting period in SES pilot building, it is proposed to study the results obtained with these two control strategies in terms of energy consumption and indoor temperature independently. The table below summarizes this information. After that, an overall analysis encompassing the whole reporting period could be also provided.

Control strategy	Evaluation period
NEC: Data driven optimization	11/11/2015 – 30/11/2015
	10/02/2016 – 12/02/2016 24/02/2016 – 07/03/2016 15/03/2016 – 21/03/2016
HONEYWELL: Reinforcement Learning	20/01/2016 – 09/02/2016

Table 24: SES_Uc1 control strategies and evaluation periods

[1] A Q function is a mapping that has as input (i) quantities characterizing states – e.g. zone temperatures and (ii) quantities representing actions – e.g. hot water set-points. The output is the expected reward till the end of the prediction horizon. When minimizing the Q function for fixed states over actions, we obtain the optimal the optimal decision.

Finally, it should be remarked that the results of the energy evaluations will be presented total energy consumptions in SES pilot building (zone 1 + zone 2), which is aligned with the IPMVP guidelines defined for the evaluation as Option C of the protocol. It was already described the energy model is customized by the two heating circuits into which the building is divided.

For the comfort level evaluation, it results more useful to evaluate the indoor temperature in the different areas of the building (represented by the average of the two most representative classrooms of each zone), and thus, the results will be presented and discussed in such way taking in to account that the comfort model previously obtained also enables this distinction.

5.3 SES_Uc1 Honeywell control strategy: *Reinforcement Learning*

As it was stated in the previous section, HONEYWELL control solution is based on reinforcement learning and it is aimed to holistically optimize the HVAC systems via distributed data-driven control. The evaluation period for this control strategy is reflected in the next table:

Start of the evaluation period	End of the evaluation period
20th January, 2016	09th February, 2016

Table 25: SES Pilot Building evaluation period for HONEYWELL strategy

Within this period, the only days not included in the evaluation are the ones in which the thermal energy consumption was null, which corresponds to weekends (Saturdays and Sundays). The rest of the time the control system operated correctly.

5.3.1 Data summary

Next tables include the summary of the data processed for this evaluation period, including dates, outdoor temperature, return temperature, indoor temperatures (at the start and the maximum) and the energy consumption.

Date	Day	T_{out} (ºC)	T_{ret} (ºC)	$T_{in\ start}$ (ºC)	$T_{in\ max}$ (ºC)	E (MWh)
20/01/2016	Wednesday	8.40	44.90	14.80	19.00	0.39
21/01/2016	Thursday	8.86	47.01	15.29	18.87	0.39
22/01/2016	Friday	9.99	53.73	15.74	19.82	0.47
25/01/2016	Monday	10.30	52.48	15.53	20.23	0.55
26/01/2016	Tuesday	11.00	50.99	17.37	21.75	0.43
27/01/2016	Wednesday	8.00	51.03	17.23	20.44	0.43
28/01/2016	Thursday	8.28	51.11	17.08	20.38	0.42
29/01/2016	Friday	9.95	47.19	17.05	20.20	0.35
01/02/2016	Monday	9.59	48.14	14.62	19.55	0.51
02/02/2016	Tuesday	10.81	52.02	16.92	21.47	0.43
03/02/2016	Wednesday	9.95	48.07	17.66	21.02	0.34
04/02/2016	Thursday	10.58	46.56	17.67	20.38	0.35
05/02/2016	Friday	9.86	52.41	17.45	21.43	0.41
08/02/2016	Monday	7.01	50.02	15.62	19.54	0.49

09/02/2016	Tuesday	9.73	54.47	16.33	20.74	0.48

Table 26: Data summary of the reporting period in SES Zone 1 (Honeywell control)

Date	Day	T_{out} (ºC)	T_{ret} (ºC)	$T_{in\ start}$ (ºC)	$T_{in\ max}$ (ºC)	E (MWh)
20/01/2016	Wednesday	8.40	42.45	15.37	18.83	0.45
21/01/2016	Thursday	8.86	44.13	15.83	19.60	0.45
22/01/2016	Friday	9.99	50.84	16.28	20.71	0.51
25/01/2016	Monday	10.30	50.05	16.10	20.32	0.58
26/01/2016	Tuesday	11.00	48.91	17.78	21.09	0.42
27/01/2016	Wednesday	8.00	48.96	17.75	21.07	0.43
28/01/2016	Thursday	8.28	48.91	17.82	21.14	0.41
29/01/2016	Friday	9.95	45.07	17.69	20.35	0.32
01/02/2016	Monday	9.59	46.41	15.23	20.35	0.51
02/02/2016	Tuesday	10.81	49.86	17.41	21.56	0.43
03/02/2016	Wednesday	9.95	45.73	18.18	21.32	0.35
04/02/2016	Thursday	10.58	44.49	18.13	21.60	0.37
05/02/2016	Friday	9.86	50.16	18.09	21.91	0.41
08/02/2016	Monday	7.01	47.85	16.19	20.31	0.51
09/02/2016	Tuesday	9.73	51.80	16.95	20.89	0.48

Table 27: Data summary of the reporting period in SES Zone 2 (Honeywell control)

5.3.2 *Evaluation of the BaaS Solution in SES Building in terms of energy consumption*

Applying the model to the external conditions that occurred during this evaluation period, the ABE for SES pilot building (zone 1 + zone 2) can be determined. Table below presents the real and the modelled energy consumptions during this first evaluation period.

Datapoint	Adjusted Baseline Energy [kWh]	Reporting period energy [kWh]
1	850	840
2	883	840
3	1,052	980
4	1,247	1,130
5	949	850
6	970	860
7	968	830
8	844	670
9	1,172	1,020

10	991	860
11	861	690
12	813	720
13	992	820
14	1,209	1,000
15	1,066	960
TOTAL	**14,867 kWh**	**13,070 kWh**

Table 28: SES total energy consumption in Uc1 with Honeywell control

Charts below show the energy consumption profiles in the two zones of SES pilot building:

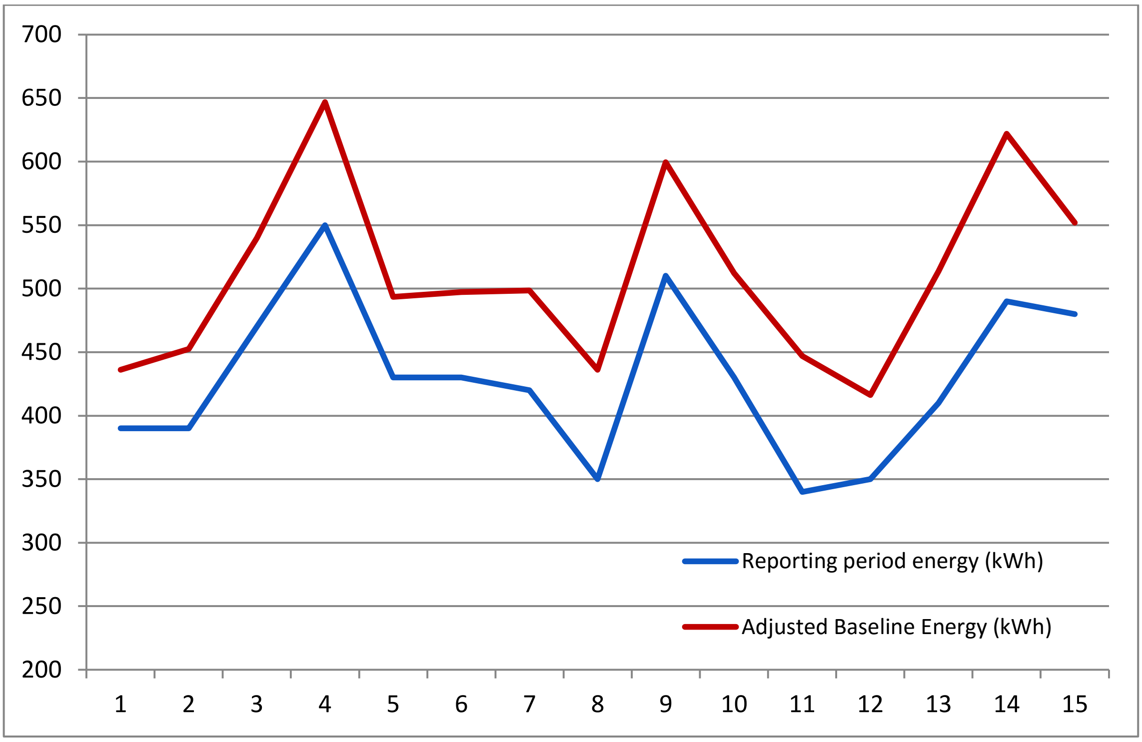

Figure 13: Comparison between the real and modelled energy profiles in SES zone 1

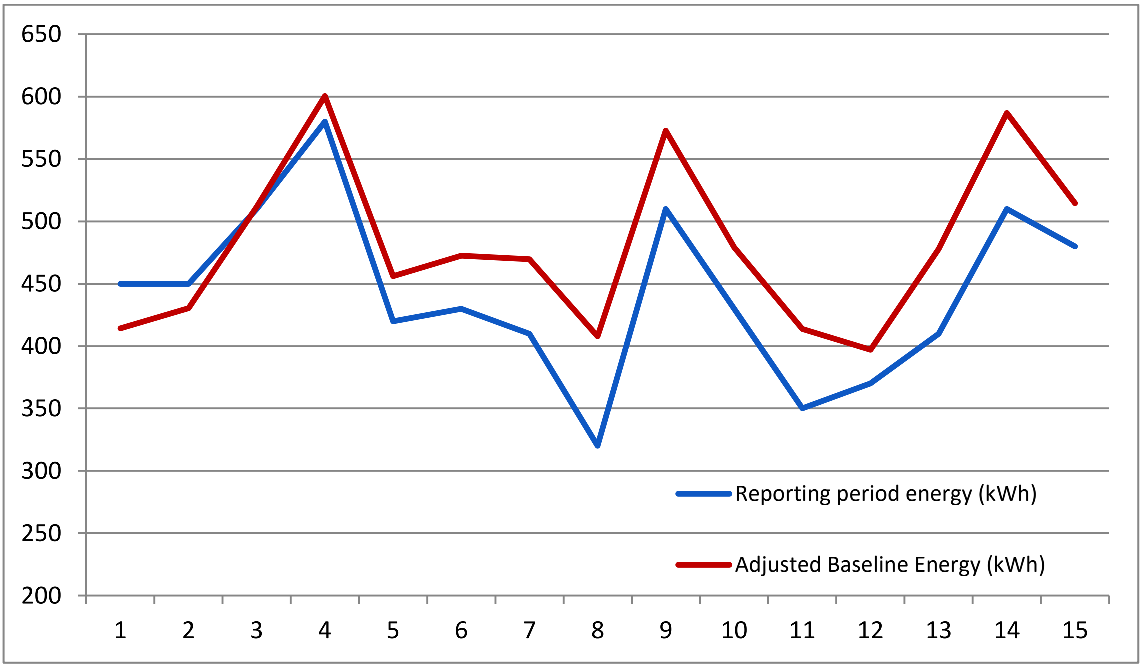

Figure 14: Comparison between the real and modelled energy profiles in SES zone 2

In a nutshell, the total energy savings in SES (zone 1 + zone 2) during this evaluation period under Honeywell control are quite significant (estimated around 1,797 kWh) and BaaS solution meets the IPMVP guidelines for Option C (10%).

Pilot Building	Use Case	Evaluation period	Control strategy	Energy savings	
SES	Uc1	20/01/2016 – 09/02/2016	Honeywell	**1,797 kWh**	**12%**

Table 29: BaaS project results in SES_Uc1 (Honeywell Control)

5.3.3 *Evaluation of the BaaS Solution in SES Building in terms of comfort level*

Next tables include the evaluation of the real indoor temperature in SES pilot building (zones 1 and 2), compared to the comfort model.

Datapoint	Reporting period comfort [ºC]	Adjusted Baseline Comfort [ºC]
1	19.00	18.71
2	18.87	19.13
3	19.82	19.81
4	20.23	19.91
5	21.75	21.01
6	20.44	20.35
7	20.38	20.28
8	20.20	20.42
9	19.55	19.08

10	21.47	20.67
11	21.02	20.81
12	20.38	20.96
13	21.43	20.80
14	19.54	19.22
15	20.74	20.19
Average	**20.32 ºC**	**20.09 ºC**

Table 30: Energy consumptions comparison with HON control in SES zone 1

Datapoint	Reporting period comfort [ºC]	Adjusted Baseline Comfort [ºC]
1	18.83	19.77
2	19.60	20.20
3	20.71	20.92
4	20.32	21.05
5	21.09	21.96
6	21.07	21.41
7	21.14	21.46
8	20.35	21.41
9	20.35	20.06
10	21.56	21.68
11	21.32	21.86
12	21.60	22.00
13	21.91	21.95
14	20.31	20.30
15	20.89	21.29
Average	**20.15**	**20.61**

Table 31: Energy consumptions comparison with HON control in SES zone 2

As it can be observed in the charts below, in this evaluation period of the BaaS solution based on Honeywell's control strategy, the new comfort level in SES pilot building is quite acceptable compared to the original situation. Most of the days, the indoor temperatures reach levels of over 19 ºC (in average 20.61ºC which is very close to the 21ºC-reference) while optimizing the energy consumption.

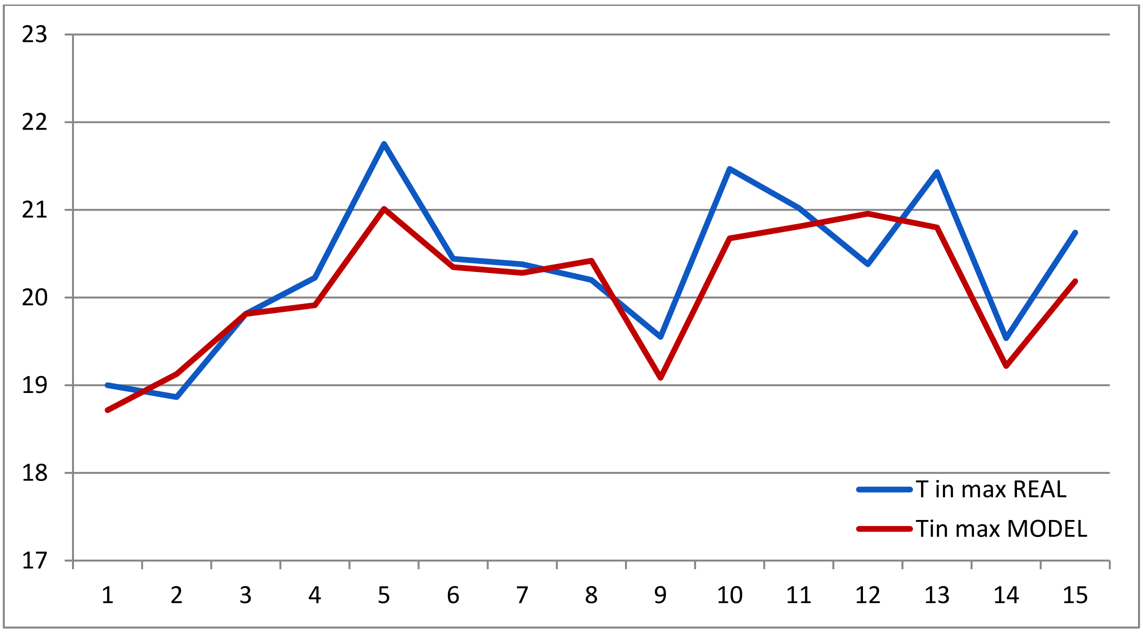

Figure 15: Comparison between the real and modelled comfort level profiles in SES zone 1

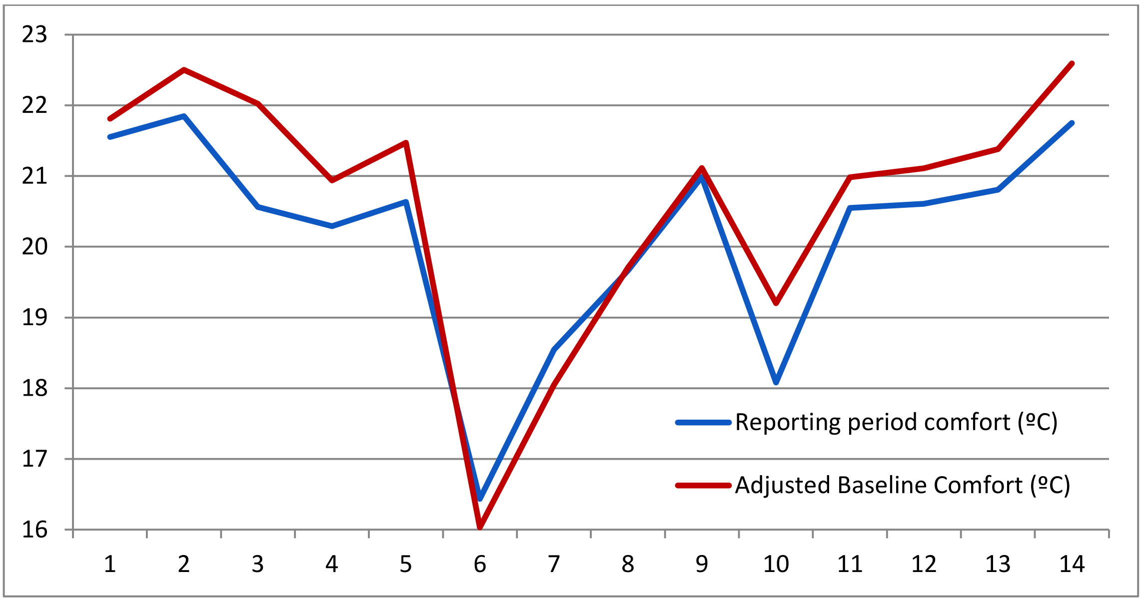

Figure 16: Comparison between the real and modelled comfort level profiles in SES zone 2

5.4 SES_Uc1 NEC control strategy: Data-driven optimization

As it was described before, this control solution includes the predictive models developed in WP5 in order to implement control and optimization strategies in the heating system of SES pilot building. The experiments related to this strategy were undertaken in very different months in terms of outdoor temperatures and solar radiation (November and February-March), and therefore, it could result interesting to evaluate the impact and results separately, although at the end of this section an overall overview will be also provided.

5.4.1 *Experiment 1*

The evaluation period for this first experiment of NEC control solution is depicted in the next table:

Start of the evaluation period	End of the evaluation period
11th November, 2015	30th November, 2015

Table 32: SES Pilot Building evaluation period for NEC control experiment 1

5.4.1.1 Evaluation of the BaaS Solution in SES Building in terms of energy consumption

Next graphs show the comparison between the energy consumption (in kWh) profiles during this period and the ABE in both zones 1 and 2 of SES pilot building.

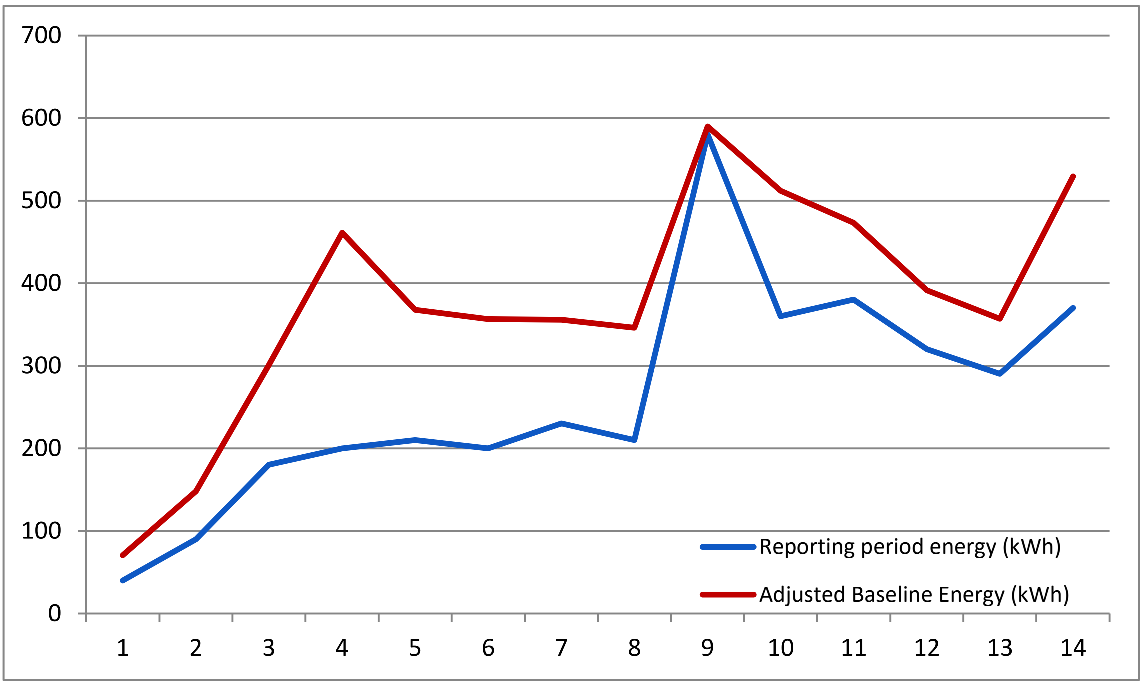

Figure 17: Comparison between the real and modelled energy profiles in SES Uc1 (zone 1)

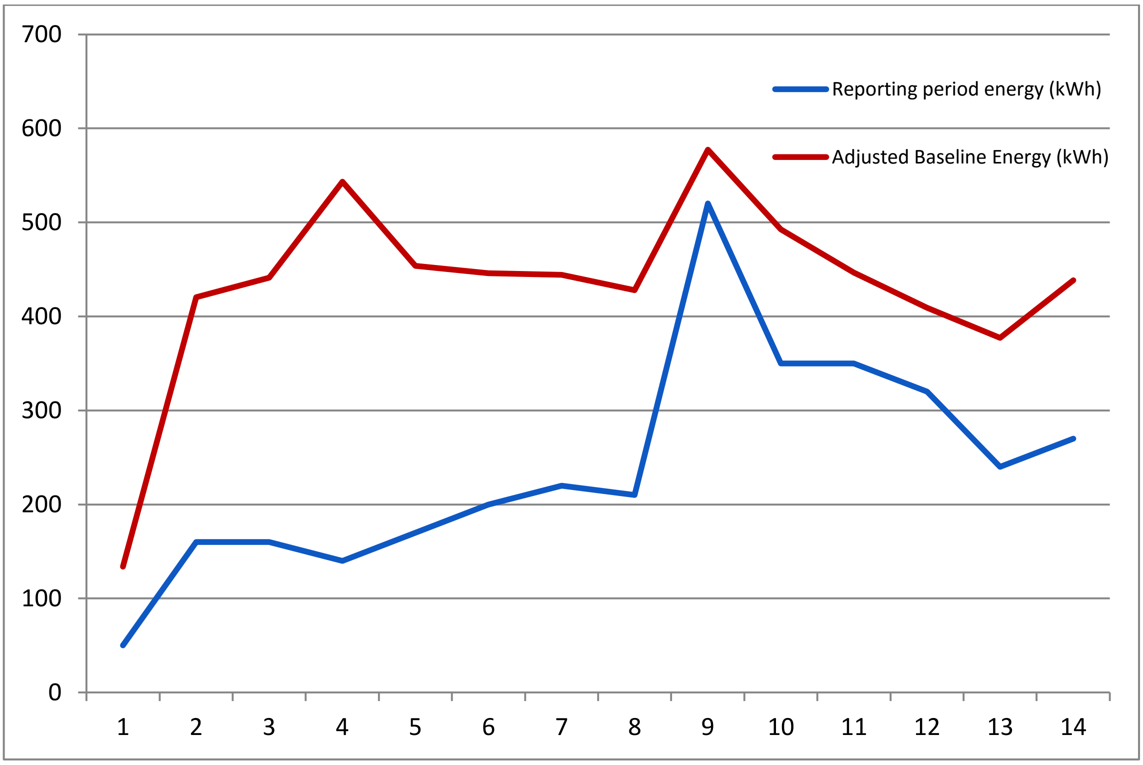

Figure 18: Comparison between the real and modelled energy profiles in SES Uc1 (zone 2)

It can be observed a clear decrease on the consumption, while keeping the same trend. The consumptions predicted by the ABE could be a bit overestimated because the independent variables are in the limits of the ranges of values on which the model was adjusted (the model was based on winter conditions and November 2015 was one of the warmest in the last years in Spain). In particular, during the first 10 days of the period, when the outdoor temperature was quite high (11.2 ºC average), the return temperature was lower than usual (37.4ºC) and the indoor temperatures were also high (it starts on 17.9 ºC and reaches 20.3 ºC, in average).

Moreover, it is important to note that the last days of November when the outdoor temperatures were more normal, the difference between BaaS and the ABE is lower and the profile are even more similar.

Next table summarizes these total daily energy consumptions (zone 1 + zone 2), both for the ABE and the real one (in kWh).

Datapoint	Adjusted Baseline Energy [kWh]	Reporting period energy [kWh]
1	204	90
2	568	250
3	742	340
4	1,004	340
5	822	380
6	802	400
7	800	450
8	774	420

9	1,147	1,100
10	1,005	710
11	920	730
12	800	640
13	734	530
14	967	640
TOTAL	**11,289 kWh**	**7,020 kWh**

Table 33: SES total energy consumption in Uc1 with NEC control (experiment 1)

Finally, adding up the daily energy consumptions, the total energy consumption during this evaluation period can be calculated and, thus, the energy savings achieved with the BaaS solution operating under this control strategy can be estimated.

Pilot Building	Use Case	Evaluation period	Control strategy	Energy savings	
SES	Uc1	11/11/2015 – 30/11/2015	NEC	**4,269 kWh**	**38%**

Table 34: BaaS project results in SES_Uc1 (NEC Control)

As it can be seen in the table above, the energy savings estimated with this experiment are very high compared to other BaaS results and far overcome the IPMVP guideline of a minimum 10% established for the Option C. However, in the same line of the previous explanation for the graphs, if we consider only the lasts days of the experiment, the energy savings are estimated around 19% which is a result more reasonable within BaaS frame.

5.4.1.2 Evaluation of the BaaS Solution in SES Building in terms of comfort level

Regarding the comfort level, it can be observed in the next graph that almost all the days the indoor temperature, for instance in zone 1, reaches at least 18ºC and many days it is around 20ºC. This is an important result because the minimum requirement for the implementation of BaaS to keeping the comfort level at least at 18C while saving energy.

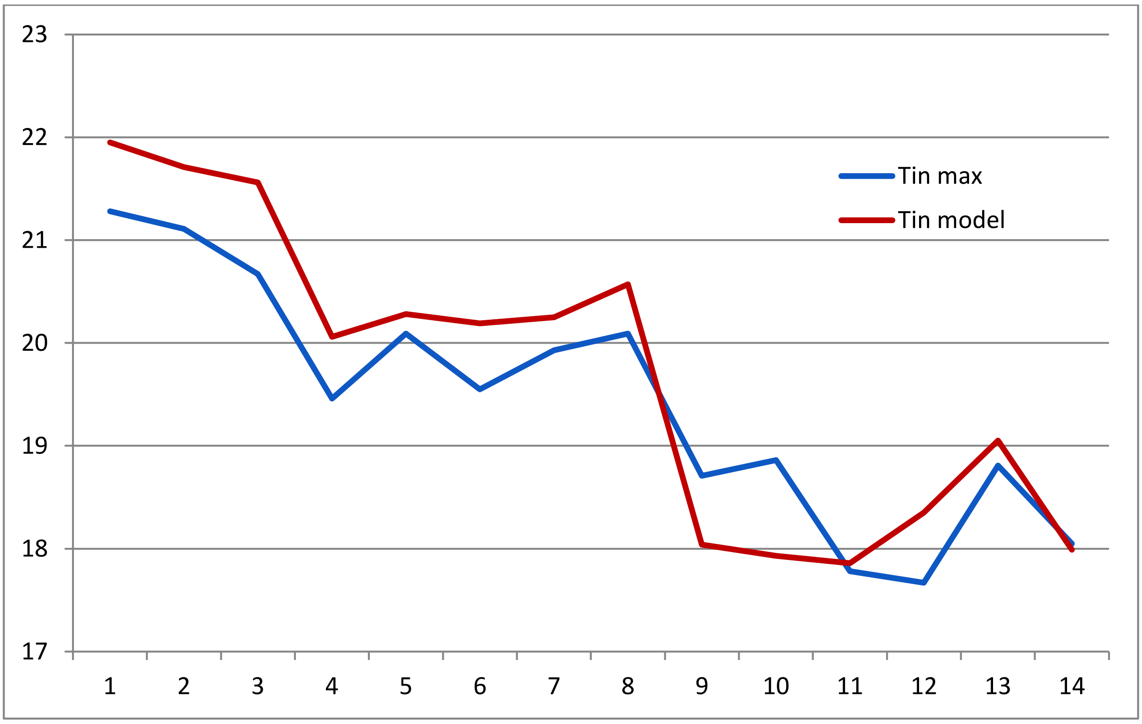

Figure 19: Comparison between real and modelled comfort profiles in SES Uc1 (zone 1)

5.4.2 Experiment 2

The evaluation dates for this second experiment of NEC control solution are included in the next table:

Start of the experiment	End of the experiment
10th February, 2016	12th February, 2016
24th February, 2016	7th March, 2016
15th March, 2016	21st March, 2016

Table 35: SES Pilot Building evaluation dates for NEC control experiment 2

The days 19th, 20th, 21st of March were not included as they are within the Easter school holidays, and thus, the energy consumption in the building was zero.

5.4.2.1 Data summary

Next tables include the summary of the data processed for this evaluation period, including dates, outdoor temperature, return temperature, indoor temperatures (at the start and the maximum) and the energy consumption.

Date	Day	T_{out} (ºC)	T_{ret} (ºC)	$T_{in\ start}$ (ºC)	$T_{in\ max}$ (ºC)	E (MWh)
10/02/2016	Wednesday	11.95	53.16	17.12	20.96	0.5
11/02/2016	Thursday	13.36	51.94	17.72	21.29	0.35
24/02/2016	Wednesday	8.57	53.40	17.07	19.53	0.45

25/02/2016	Thursday	10.54	53.43	17.27	20.45	0.49
01/03/2016	Tuesday	5.58	46.31	10.60	16.82	0.45
02/03/2016	Wednesday	8.20	50.25	12.93	18.37	0.47
03/03/2016	Thursday	9.40	39.94	15.06	18.86	0.38
04/03/2016	Friday	10.65	54.23	16.34	20.81	0.48
07/03/2016	Monday	4.88	49.38	14.52	18.09	0.54
15/03/2016	Tuesday	10.18	48.20	16.38	20.43	0.44
16/03/2016	Wednesday	10.19	38.60	16.79	20.14	0.32
17/03/2016	Thursday	9.02	45.72	17.09	20.01	0.43
18/03/2016	Friday	11.40	46.52	18.31	21.43	0.43

Table 36: Data summary of the reporting period in SES Zone 1 (NEC control)

Date	Day	T_{out} (ºC)	T_{ret} (ºC)	$T_{in\ start}$ (ºC)	$T_{in\ max}$ (ºC)	E (MWh)
10/02/2016	Wednesday	11.95	49.34	17.30	21.55	0.47
11/02/2016	Thursday	13.36	48.97	17.91	21.85	0.45
24/02/2016	Wednesday	8.57	44.86	17.09	20.29	0.42
25/02/2016	Thursday	10.54	42.58	17.51	20.64	0.38
01/03/2016	Tuesday	5.58	43.49	11.06	16.44	0.51
02/03/2016	Wednesday	8.20	47.28	13.03	18.55	0.52
03/03/2016	Thursday	9.40	42.07	15.15	19.66	0.41
04/03/2016	Friday	10.65	49.87	16.73	20.99	0.49
07/03/2016	Monday	4.88	47.15	14.97	18.08	0.60
15/03/2016	Tuesday	10.18	45.80	16.63	20.55	0.44
16/03/2016	Wednesday	10.19	40.80	17.11	20.61	0.36
17/03/2016	Thursday	9.02	42.85	17.53	20.81	0.41
18/03/2016	Friday	11.40	45.33	18.56	21.75	0.41

Table 37: Data summary of the reporting period in SES Zone 2 (NEC control)

5.4.2.2 Evaluation of the BaaS Solution in SES Building in terms of energy consumption

Next graphs show the comparison between the energy consumption (in kWh) profiles during this period and the ABE in both zones 1 and 2 of SES pilot building. It can be observed a decrease on the consumption, while keeping the same trend.

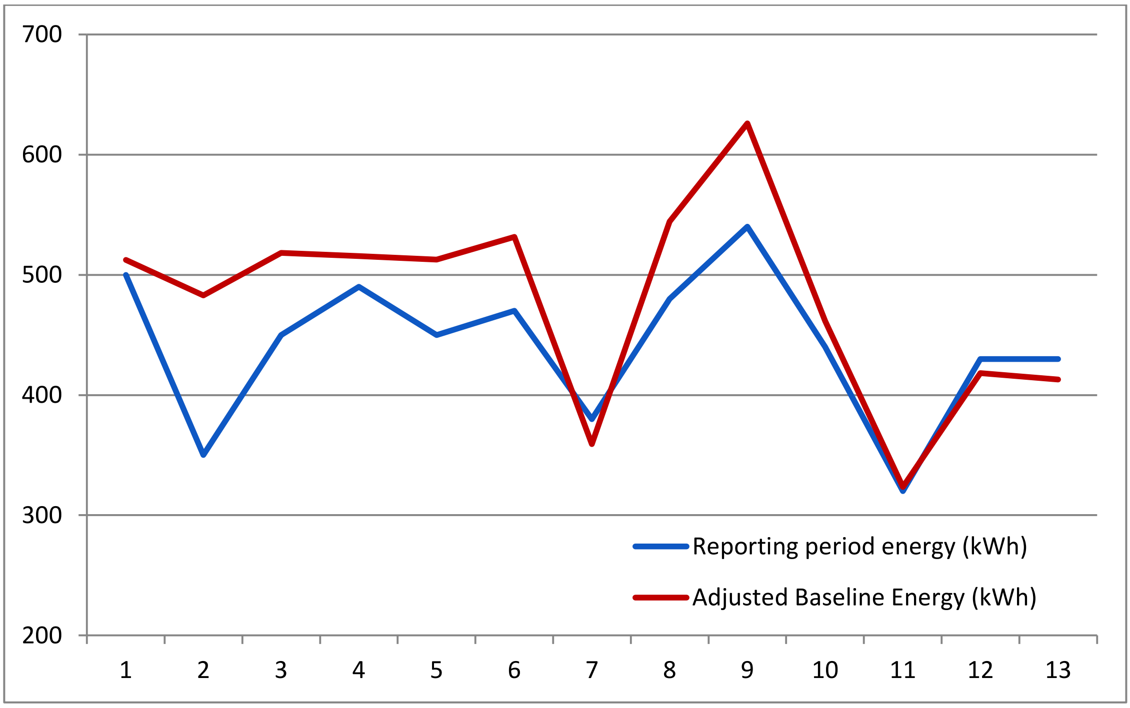

Figure 20: Comparison between the real and modelled energy profiles in SES Uc1 (zone 1)

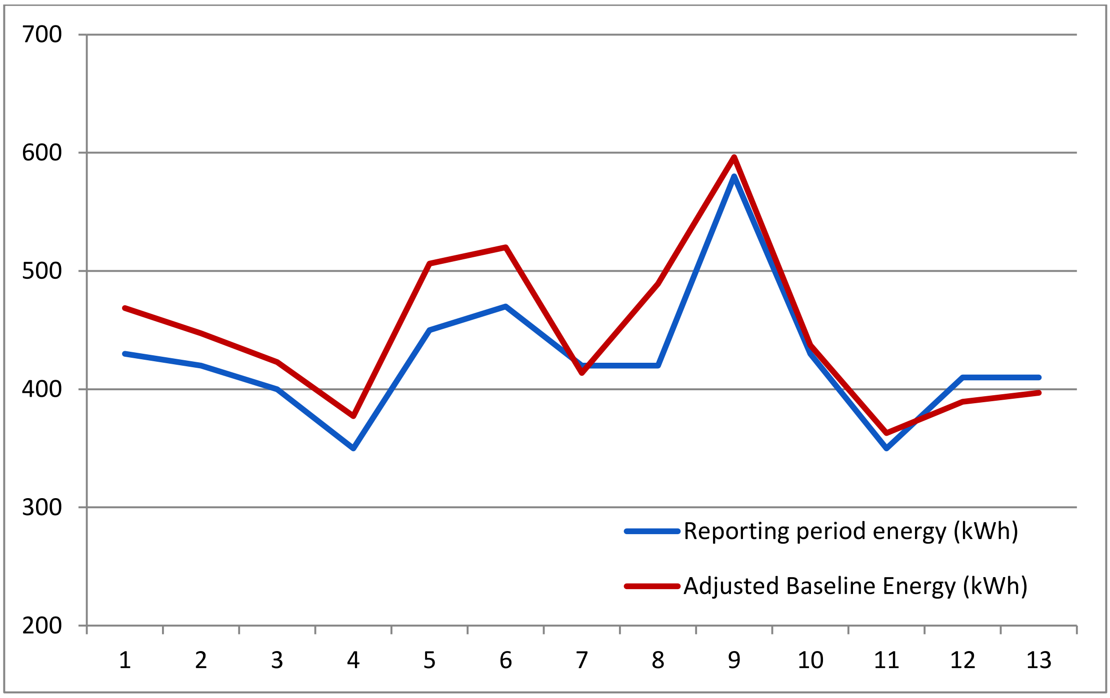

Figure 21: Comparison between the real and modelled energy profiles in SES Uc1 (zone 2)

Next table summarizes these total daily energy consumptions in SES pilot building (zone 1 + zone 2), both for the ABE and the real one (in kWh).

Datapoint	Adjusted Baseline Energy [kWh]	Reporting period energy [kWh]
1	981	930

2	930	770
3	941	850
4	893	840
5	1,019	900
6	1,052	940
7	773	800
8	1,034	900
9	1,222	1,120
10	899	870
11	687	670
12	808	840
13	810	840
TOTAL	**12,047 kWh**	**11,270 kWh**

Table 38: SES total energy consumption in Uc1 with NEC control (experiment 2)

Finally, adding up the daily energy consumptions, the total energy consumption during this evaluation period can be calculated and, thus, the energy savings achieved with the BaaS solution operating under this control strategy can be estimated. As it can be seen in the next table, the energy savings estimated with this experiment are a bit low and they do not reach the IPMVP guideline (minimum 10%) recommended for the Option C.

Pilot Building	Use Case	Experiment period**	Control strategy	Energy savings	
SES	Uc1	10/02/2016 – 21/03/2016	NEC	**777 kWh**	**6%**

** It was interrupted several days, and set into automatic mode **

Table 39: BaaS project results in SES_Uc1 (NEC Control)

5.4.2.3 Evaluation of the BaaS Solution in SES Building in terms of comfort level

Regarding the comfort level, even though trend of the temperature profile is almost maintained compared to the baseline comfort model, it has been observed that the indoor temperature has slightly gotten worse in general terms. However, an important result is that most of the days it is over 19ºC in zone 1 and over 20ºC in zone 2 which is a very good achievement taking into account the poor conditions of the school in terms of thermal comfort before the implementation of BaaS.

Next tables and graphs include the data summary related to the indoor temperatures achieved in zones 1 and 2 of SES pilot building. The comfort level is almost maintained near 20ºC which is very good compared to the discomfort that they experimented in the past.

Datapoint	Adjusted Baseline Comfort [ºC]	Reporting period comfort [ºC]
1	20.96	21.18
2	21.29	21.51

3	20.71	21.22
4	19.53	20.39
5	20.45	20.98
6	16.82	15.51
7	18.37	17.60
8	18.86	19.05
9	20.81	20.36
10	18.09	18.19
11	20.43	20.21
12	20.14	20.22
13	20.01	20.45
AVERAGE	**19.74 ºC**	**19.65 ºC**

Table 40: SES comfort level in zone 1 with NEC control (experiment 2)

Datapoint	Adjusted Baseline Comfort [ºC]	Reporting period comfort [ºC]
1	21.55	21.81
2	21.85	22.50
3	20.56	22.02
4	20.29	20.94
5	20.64	21.47
6	16.44	16.03
7	18.55	18.05
8	19.66	19.70
9	20.99	21.11
10	18.08	19.20
11	20.55	20.98
12	20.61	21.11
13	20.81	21.38
AVERAGE	**20.16 ºC**	**20.64 ºC**

Table 41: SES comfort level in zone 2 with NEC control (experiment 2)

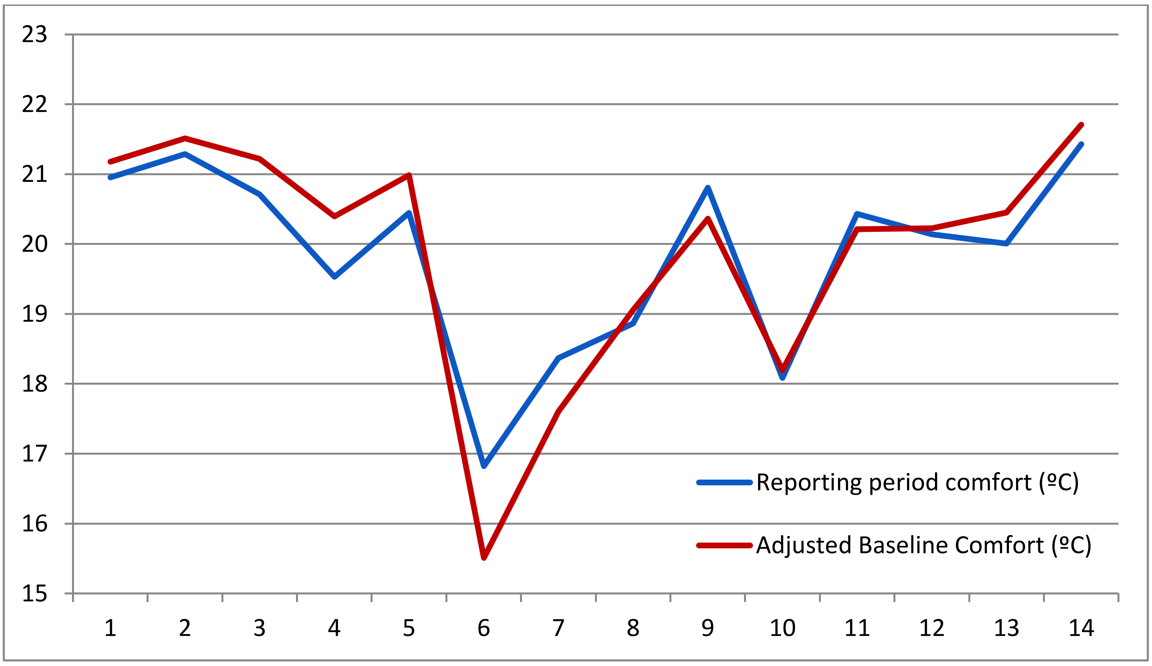

Figure 22: Comfort level in SES Uc1 (zone 1)

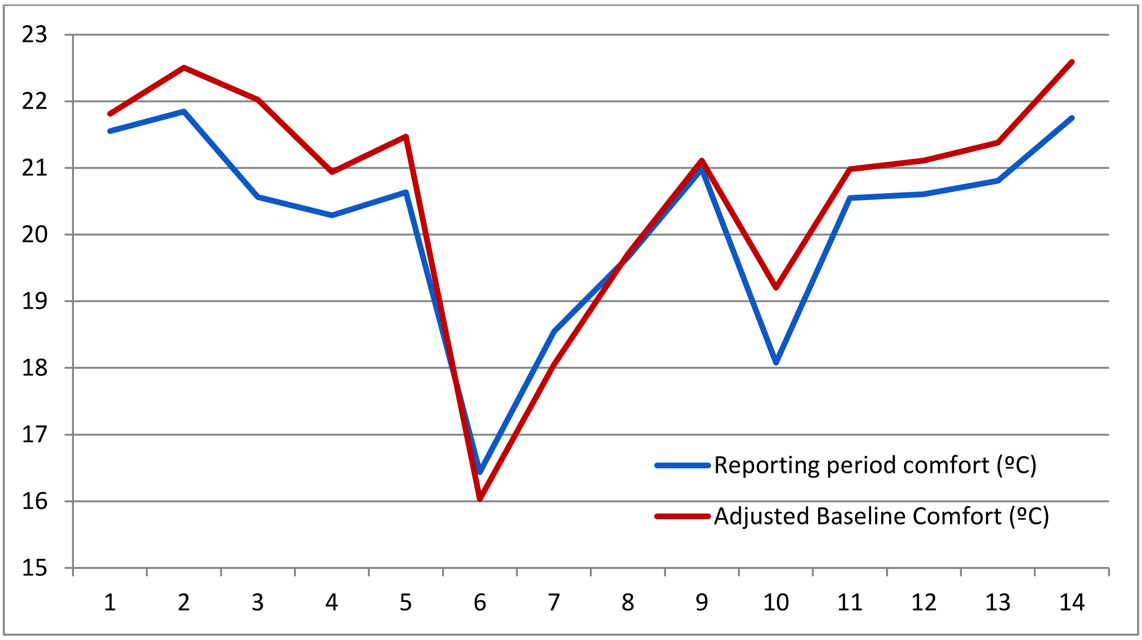

Figure 23: Comfort level in SES Uc1 (zone 2)

5.5 Overall reporting period in SES_Uc1

Once the two control solutions have been implemented in SES_Uc1 and the yielded results have been analysed applying the IPMVP methodology, in terms of consumptions, profiles and energy savings, it is also interesting to get an overall depiction of the BaaS solution in the whole reporting period under study, by combining the results obtained with the two control solutions individually.

Adding up the total energy consumptions in the two evaluation periods, the total energy consumption during the reporting period can be calculated and, thus, the total energy savings achieved with the BaaS solution can be estimated.

Pilot Building	Reporting period	Energy consumed	Energy savings	
SES	11/11/2015 – 21/03/2016	38,203 kWh	6,843 kWh	18%

Table 42: Overall BaaS project results in SES_Uc1

The overall energy savings achieved in SES_Uc1 during the reporting period under study are estimated on 18 %, which clearly overcomes the minimum established by the IPMVP for the Option C (10%).

In terms of comfort level, the implementation of BaaS in SES building has enabled to keep the indoor temperatures in the different classrooms at comfortable levels compared to the previous ones (minimum reference of 18ºC) and in some cases reaching acceptable conditions (over 20-21ºC). Additionally, the fluctuations in the indoor temperature after BaaS have decreased comparing to the baseline period, and also the number of days with discomfort is very low.

The important aspect that should be highlighted is that the control and optimization strategies allow reach a double objective: keeping the classrooms in acceptable comfort levels while obtaining energy savings, although initially, in the use case definition was contrary (i.e. improving the comfort by keeping the energy consumption).

Therefore, in the future, the energy savings obtained with BaaS could be translated into higher comfort improvements: adapting these control strategies in order to improve more the comfort level (21ºC-22ºC) while reducing the share of energy savings or, if necessary, consuming the same energy (zero energy savings).

6 Summary of BaaS results in terms of energy savings

In summary of all the aforementioned analysis of data, the final energy savings achieved for the buildings and use cases is represented in Table 43.

Pilot Building	Use Case	Reporting period	Energy consumed	Energy savings	
CAR	Uc1 (Winter)	14/02/2016 – 01/04/2016	2,908 kWh_{th}	284 kWh_{th}	10%
	Uc2 (Summer)	17/08/2015 – 06/09/2015	1,962 kWh_e	756 kWh_e	24%
ZUB	Uc1 (Winter)	10/12/2016 – 15/03/2016	12,462 kWh_{th}	2,566 kWh_{th}	17%
SES	Uc1 (Winter)	11/11/2015 – 21/03/2016	31,360 kWh_{th}	6,843 kWh_{th}	18%

Table 43: Overall BaaS project results in CAR, ZUB and SES

By extrapolating the savings achieved during BaaS experiments and evaluation periods to the whole winter/summer seasons, it is possible to estimate the potential energy savings, and hence, the potential economic savings that would be achieved with the implementation of the BaaS solution during a complete season. Next table summarizes these potential outcomes of BaaS, considering the following assumptions:

- Average price: natural gas (€/kWh_{gas}), electricity (€/kWh_e) and final thermal energy (€/kWh_f) in the corresponding periods.
- Total (all winter/summer) real consumption in the building during the reporting period.
- Average estimated energy savings share (%) achieved with BaaS related to the real consumption.

Pilot Building	Use Case	Potential Energy savings	Unit price	Potential Economic savings
CAR	Uc1 (Winter)	1.08 MWh_{gas}	0.038643 €/kWh_{gas}	**42 €/season**
	Uc2 (Summer)	1.79 MWh_e	0.069378 €/kWh_e	**124 €/season**
ZUB	Uc1 (Winter)	4.34 MWh_{th}	0.10 €/kWh_{th}	**434 €/season**
SES	Uc1 (Winter)	20.44 MWh_{th}	68.24 €/MWh_{th}	**1,395 €/season**

Table 44: Potential energy and economic savings in the whole winter/summer seasons

An important conclusion that should be remarked in this regard is the different potential that the implementation of BaaS could have depending on the building typology:

- In high-performance buildings (i.e. CAR and ZUB), despite the fact that BaaS solution can be applied, it is more difficult to obtain significant energy and economic savings.
- In low-performance buildings (i.e. SES), where the potential of improvements is higher, BaaS enables a great optimization of the system obtaining very important energy savings and also comfort improvements.

7 Conclusions

This document is a continuation of the deliverable *"D6.3.2: Baseline period in the Pilot Buildings"*, in which the energy savings and comfort improvements achieved with the implementation of the BaaS solution are evaluated in the three pilot buildings (i.e. CARTIF, ZUB and SES) by using the different final models previously obtained in the aforementioned report, following the guidelines and methodology defined in the Option C of the IPMVP protocol.

The first outcome that should be remarked is that all those models are valid and suitable to be applied under the reporting period conditions, as the energy profiles and data ranges observed are reasonable and comparable to the real ones. The only case were the model do not adjusted well to the reporting period data was in CARTIF_Uc2 (summer period), but this issue has been corrected by an estimation of the electric consumption of the heat pumps normalized with the CDD, following the IPMVP methodology. This is aligned with the approach and results and analyses obtained in deliverable D4.4.

Due to the functional simplicity of the models (linear expressions) their application to evaluate the results obtained with BaaS can be carried out in a simple and systematic way. Moreover, it should be kept in mind that the data processing methodology and the independent variables calculation for the reporting period must be exactly the same than in the baseline period, otherwise the results obtained with the model would not be correct.

In CARTIF pilot building, the energy savings estimated on 10% for the Uc1 (winter) and around 24% in Uc2 (summer), which fulfil the IPMVP requirements for Option C (10%).

In ZUB pilot building, two different control strategies have been deployed during the winter reporting period for Uc1: knowledge-based and simulation-based. With both of them, BaaS solution enables achieving energy savings (10% and 33%, respectively).

In SES pilot building, also two different control solutions have been experimented during the winter period for Uc1: data-driven optimization (designed by NEC) and reinforcement learning (defined by HONEYWELL). In the first case the overall energy savings are estimated on 38% and in the second one around 12%, both of them overcoming the IPMVP minimum requirement.

In addition, in the case of SES pilot building, a comfort model was also designed in D6.3.2 in order to evaluate the indoor temperature achieved in some characteristic classroom after the operation hours of the heating system. It has been contrasted that with the implementation of BaaS in SES building has enabled to keep the indoor temperatures in the different classrooms at comfortable levels compared to the previous ones (minimum reference of 18ºC) and in some cases reaching quite acceptable conditions (over 20-21ºC). The fluctuations in the indoor temperature after BaaS have decreased comparing to the baseline period, and also the number of days with discomfort is very low. The important aspect that should be highlighted is that the control and optimization strategies allow reach a double objective: keeping the classrooms in acceptable comfort levels while obtaining energy savings. Therefore, in the future the energy savings obtained with BaaS could be translated into higher comfort improvements: adapting these control strategies in order to improve more the comfort level (21ºC-22ºC) while reducing the share of energy savings or, if necessary, consuming the same energy (zero energy savings).

Therefore, the results obtained in the three pilot buildings (i.e. CAR, ZUB and SES) after the implementation of BaaS are quite satisfactory in terms of performance, energy savings and comfort level. Thus, this solution demonstrates an effectiveness that can be applied in other real case studies.

This report is a very important outcome within BaaS project as it depicts the final results, in terms of energy savings, operation & performance of the systems and comfort increase, derived from all the previous tasks and activities related to data acquisition, data analysis and modelling, control and optimization strategies, etc.

Finally, in the framework of Energy Services Companies (ESCO) and utilities, the achievements made so far within the BaaS project would serve as a basis for new projects or cases studies, as it can complement the business models based on energy savings obtained with methodologies and algorithms that can be replicated. In high-performance buildings the optimization potential in terms of economic savings is less significant, but in the case of low-performance buildings important energy, thus economic, savings can be achieved.

8 References

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