Small or medium-scale focused research project (STREP)

Energy Demand-Aware Open Services for Smart Grid Intelligent Automation

SmartHG

EU FP7 Project #317761

Deliverable D5.2.1
Second Year Evaluation

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Objective	**ICT-2011.6.1** *Smart Energy Grids*
Target Outcome	**d**) Home energy controlling hubs that will collect real-time or near real-time data on energy consumption data from smart household appliances and enable intelligent automation.

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To make this deliverable suitable for public dissemination, test-bed data have been anonymized.

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List of Acronyms

API Application Programming Interface

BOP Balance of Plant

COP Coefficient of Performance

DAPP Demand Aware Price Policies

DAPP-H Demand Aware Price Policies for Homes

DAPP-K Demand Aware Price Policies for Substation-Level Energy Storage Control

DB DataBase

DB&A Database and Analytics

DSO Distribution System Operator

EBR Energy Bill Reduction

EDN Electric Distribution Network

ESC Energy Storage Capacity

ESS Energy Storage System

EUMF Energy Usage Modelling and Forecasting

EUMF-H Energy Usage Modelling and Forecasting for Homes

EUMF-K Energy Usage Modelling and Forecasting for Control

EUR Energy Usage Reduction

EUR-H Energy Usage Reduction for Homes

EUR-K Energy Usage Reduction for Control

EVT EDN Virtual Tomography

GIAS Grid Intelligent Automation Service

HECH Home Energy Controlling Hub

HIAS Home Intelligent Automation Service

IAS Intelligent Automation Service

IBR Inclining Block Rate

IQR InterQuartile Range

LV Low Voltage

MV Medium Voltage

OM Operation and Maintenance

PCS Power Conversion System

PEV Plug-in Electric Vehicle

PPSV Price Policy Safety Verification

RESTful REpresentational State Transfer

RMS Root Mean Square

SEIL Smart Energy Integration Lab

T&D Transmission and Distribution

ToU Time of Usage

Executive Summary

Objectives This deliverable describes the evaluation of all Intelligent Automation Service (IAS) developed during the second year of the SmartHG project. They are:

- DAPP, computing a demand-aware price policy for each home with the aim of reducing aggregate demand peaks (Deliverable D4.2.1);
- PPSV, verifying safety of DAPP price policies (D4.2.1);
- EVT, estimating the internal state of the EDN (D4.2.1);
- EBR, computing a control strategy for home energy storage devices (D3.2.1);
- EUMF, forecasting home electricity consumption (D3.2.1);
- EUR, supporting residential users in reducing electric energy usage (D3.2.1).
- DB&A, supporting communication among all SmartHG services (D4.2.1).

Retrospect In the first year iteration of WP5 we evaluated all SmartHG IASs, running them on workstations. We focused on evaluating economic viability of the *control loop* services, i.e., DAPP, PPSV, EBR. This met our goals, as all the other IASs are used by the control loop services to provide their functionalities.

Our first year evaluation was based on historical data from SEAS-NVE on a subset of the homes in Kalundborg test-bed, as SmartHG sensors were not yet installed.

Such an evaluation showed that both residential users and DSOs were able to obtain economic savings when using DAPP, PPSV and EBR. In particular, residential users were able to reduce their bill, and DSOs were able to defer Transmission and Distribution (T&D) investments. Moreover, thanks to the peak shaving achieved, the need of turning on peak power plants is also reduced, thereby reducing CO_2 emissions from them.

Achievements This year we set up two *reference scenarios*, one from Kalundborg test-bed and one from Central District (Israel) test-bed. The latter was not present in the first year. Data from such test-beds are provided by sensors deployed in the homes and historical data on Plug-in Electric Vehicle (PEV) charging, acquired from our networking with the "Test-an-EV" Danish project. All our services have been run on their intended hardware platforms, namely a Raspberry Pi for EBR and workstations for all the others.

On out test-bed scenarios we perform *technical*, *economic* and *environmental* evaluations. Our technical evaluation shows that computation time and memory usage of all IASs are compatible with their intended use. Our economic evaluation shows that IASs are *economically viable*. Namely, by using our *control loop services*, *both* residential users and DSOs obtain an economic saving. In particular: a) residential users can save about 150.00 EUR per year on average (considering a 10-year hardware amortisation plan); b) if residential users strictly follow DAPP suggested power profiles, then the DSO can save, on average, 0.6 EUR per residential user per year due to T&D investment deferral. Even though peak shaving of aggregated demand does not entail reduction of electrical energy costs (arbitrage), our evaluation on Kalundborg test bed data shows that DAPP allows the energy supplier to save about 0.8 EUR per residential user per year.

When there is no need for peak power plant, our second year scenario, reduction of CO_2 emissions does not follow from peak shaving. Nevertheless, our environmental evaluation shows that, by shifting the user demand with the control loop services, on our reference scenarios, CO_2 emissions in Kalundborg are reduced by 5.05 Kg per year per residential user.

Limitations and Future Work To date, most but not all planned sensors have been installed. Our third year evaluation will exploit the deployment of the full set of SmartHG sensors.

Our current evaluation of EBR at IMDEA micro-grid does not address communication delays. This will be considered in the next year.

Chapter 1

Retrospect

In this section we briefly recall the main achievements obtained (and the main shortcomings identified) in the first year version of the SmartHG services evaluation. The detailed list of all advancements of the second year evaluation (described in this deliverable) w.r.t. the first year evaluation is reported in Section 6.

In the first year iteration of WP5 we evaluated all SmartHG Intelligent Automation Services (IASs), i.e., Demand Aware Price Policies (DAPP), Price Policy Safety Verification (PPSV), EDN Virtual Tomography (EVT), Database and Analytics (DB&A), Energy Bill Reduction (EBR), Energy Usage Reduction (EUR) and Energy Usage Modelling and Forecasting (EUMF). The preliminary results showed that first year SmartHG IASs were very promising. Namely, in the reference scenario used for the evaluation (mainly based on data from Kalundborg test-bed, integrated with data from the literature), both residential users and Distribution System Operators (DSOs) were able to obtain significant economic gains, when using the control loop services (namely DAPP, PPSV and EBR). In fact, users were able to reduce their bill, and DSOs to defer investments in Transmission and Distribution (T&D). Moreover, by using such services on the reference scenario, DSOs were also able to significantly reduce the CO_2 emissions. Finally, since the other services DB&A, EVT, EUR and EUMF were needed by the control loop services in order to obtain the results discussed above, the first year evaluation final outcome was that the first year versions of all SmartHG services were economically viable.

Finally, the following main limitations for the first year evaluation were identified, which we address in this year evaluation: i) evaluation was performed on data coming from only one test-bed (namely Kalundborg); ii) only a limited number of homes from the Kalundborg test-bed were used for the evaluation; iii) there were very few smart meters deployed, thus they were not exploited; iv) the evaluation of control loop home services like EBR lacked an evaluation on real hardware.

Chapter 2

Introduction

The main objective of the SmartHG project is to develop Intelligent Automation Services (IASs) that are *economically viable* for both residential homes and Distribution System Operators (DSOs). This is achieved using a hierarchical control approach (see Figure 2.1) where the high level control loop (steered by the DSO) sets price policies for the electrical energy for each residential user, and the low level control loop (steered by residential users) manage home devices in order to minimise home energy bill. Grid Intelligent Automation Service (GIAS) support the DSO in computing price policies whereas Home Intelligent Automation Service (HIAS) supports residential users in managing home devices. IAS (i.e., GIAS + HIAS) communicate via the Database and Analytics (DB&A) service with the architecture summarised in Figure 2.2.

HIASs comprise the following services: Energy Usage Reduction for Homes (EUR-H), Energy Usage Modelling and Forecasting for Homes (EUMF-H), Energy Usage Reduction for Control (EUR-K), Energy Usage Modelling and Forecasting for Control (EUMF-K), Energy Bill Reduction (EBR). Note that, both in the SmartHG proposal and in the first year deliverables, EUR-H and EUR-K (respectively, EUMF-H and EUMF-K) were

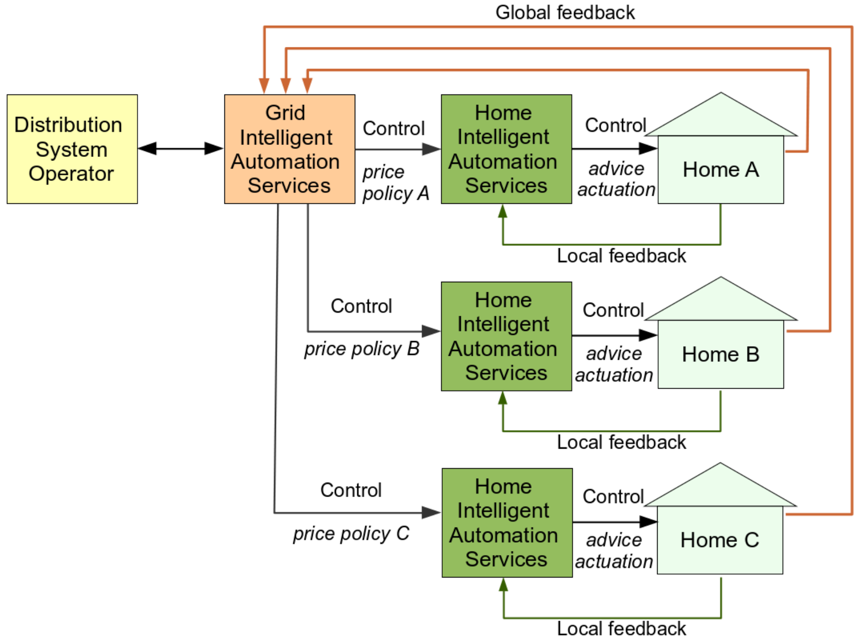

Figure 2.1: Functional schema of SmartHG IASs.

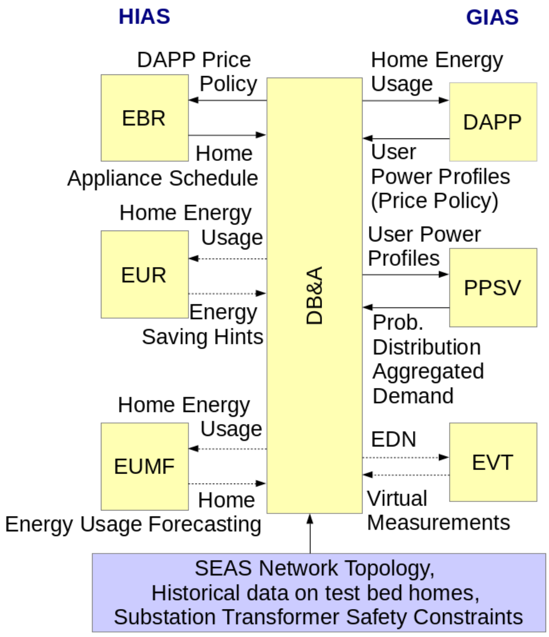

Figure 2.2: SmartHG IASs architecture.

just one service, namely EUR (respectively, EUMF). Second-year design and prototype implementation of HIASs can be found in, respectively, Deliverables D3.2.1 and D3.2.2.

GIASs comprise the following services: Demand Aware Price Policies for Homes (DAPP-H), Demand Aware Price Policies for Substation-Level Energy Storage Control (DAPP-K), Price Policy Safety Verification (PPSV), EDN Virtual Tomography (EVT), DB&A. Note that, both in the SmartHG proposal and in the first year deliverables, DAPP-H and DAPP-K were just one service, namely DAPP. Second-year design and prototype implementation of GIASs can be found in, respectively, Deliverables D4.2.1 and D4.2.2.

In this deliverable we evaluate SmartHG IASs from a technical (i.e., correctness w.r.t. design and computation time), economic (i.e., money saved) and environmental (i.e., reduction of CO_2 emissions) perspective. This allows us to evaluate to which extent IAS design meets the overall project goals.

To this aim, the second year iteration of the evaluation is organised as follows. First of all, we divide the IASs in the following categories (by suitably adapting the IAS categorisation made in the first year evaluation):

- five *monitoring services* which focus in monitoring usage of electrical energy in residential homes (EUR-H, EUMF-H, EUR-K, EUMF-K), or in the Electric Distribution Network (EDN) itself (EVT), as well as on providing auxiliary services to the control loop services;

- four *control loop services* which, on the basis of the information provided by the monitoring services, propose price policies to homes (DAPP-H), actions to residential home devices (EBR) or substation Energy Storage System (ESS) devices (DAPP-K), or evaluate the impact of price polices (PPSV);

- one *infrastructure service* (DB&A), which collects information (e.g., energy consumption data) from residential homes and provides it to the other services.

From the above we see that the monitoring and the infrastructure services only need to be evaluated from a technical point of view, in order to verify that they indeed behave as described in Deliverables D3.2.1 and D4.2.1. As a consequence, a technical evaluation is carried out on DB&A (Section 3.1), EVT, EUR-H, EUR-K, EUMF-H and EUMF-K (all in Section 3.3), showing that they fulfil their requirements. On the other hand, the control loop services need to be evaluated also from the an economic as well as from an environmental perspective in order to evaluate if SmartHG approach is indeed economically viable. To this aim, we proceed as follows.

1. We set up two *reference scenarios* (Section 3.2.1).

   The first one, containing only the total power demand from each residential home, is tailored to the evaluation of DAPP-H, DAPP-K and PPSV. Such a DSO-oriented scenario is based on data from the Kalundborg test-bed (provided by SEAS), and thus we will refer to it as *Kalundborg scenario*.

   The second scenario, containing detailed power demand for a number of appliances in a reference residential home, is tailored to the evaluation of EBR and is based on data from a home in the new Central District [?] test-bed in Israel (provided by PANPOW, see Deliverable D6.2.1). We call such a user-oriented scenario the *Central District scenario*.

   We run DAPP-H, DAPP-K and PPSV on the DSO-oriented scenario, and EBR on the Central District scenario. In order to close the service loop, we also run EBR on a selected home in the Kalundborg scenario, using the price policies output by DAPP-H. A summary of the main characteristics of both scenarios is presented in Table 3.1.

2. The results obtained from Step 1 are used to evaluate, from the *technical* perspective, the control loop services on the reference scenarios (Section 3.2). The goal of such a technical evaluation is to show that: i) the control loop services indeed behave as it is described in the design (Deliverables D3.2.1 and D4.2.1); and ii) their computational demand (in terms of RAM and CPU time) is indeed sustainable when such services are plugged into SmartHG control loop (see Figure 2.1), most notably, that the required computation time is less than the expected periodicity of each service. Sections 3.2.4 and 3.2.3 show that goals i) and ii) are indeed achieved.

3. The results obtained from Step 1 are used to evaluate the control loop services on the corresponding reference scenarios from an *economic* perspective (Section 4). Namely, we show that usage of the SmartHG control loop services on the reference scenarios reduce *both* the bill for residential users and the costs for DSOs (or retailers, when applicable). Reduction on residential users bill is shown by analysing the output of DAPP-H and EBR, whilst cost reduction for DSOs is shown by analysing the output of DAPP-H and DAPP-K (nominal case) and PPSV (off-nominal cases). A summary of our results is in Table 4.1 (analysing DAPP-H output), Table 4.2 (analysing PPSV output), Table 4.3 (analysing DAPP-K output), and Table 4.4 (analysing EBR output). Such results are summarised as follows: i) on average each *residential user* may save about 150.00 EUR per year (assuming a 10-year hardware amortisation plan); ii) on average, a *DSO* may save 0.6 EUR per year per residential user due to Transmission and Distribution (T&D) investment deferral; iii) notwithstanding the fact that peak shaving objectives can be at variance with

arbitrage, we show that, on average, a *energy supplier* may save 0.8 EUR per year per residential user due to arbitrage on the day-ahead energy market.

4. The results obtained from Step 1 are used to evaluate DAPP-H, DAPP-K and PPSV on the Kalundborg reference scenario from the *environmental* perspective (Section 5). Note that EBR is needed in order to allow residential users to follow DAPP-H price policies, thus it enables both the DAPP-H and the PPSV environmental evaluation.

   The environmental evaluation has the goal of checking that the demand shifting triggered by SmartHG services does not have a negative impact on CO_2 emissions due to electricity production when peak power plants are not needed. A summary of our results is in Table 5.1 (analysing DAPP-H output), Table 5.2 (analysing PPSV output) and Table 5.3 (analysing DAPP-K output). Such results show that when there is no need for peak power plants, reduction of CO_2 emissions does not follow from peak-shaving. Nevertheless, our environmental evaluation shows that, by shifting the user demand with SmartHG control loop services, on our reference scenario CO_2 emissions in Kalundborg are reduced by 5.05 Kg per year per residential user.

2.1 Outline

This deliverable is organised as follows. Sections 3, 4 and 5 describe, respectively, our technical, economic and environmental evaluations for SmartHG services. The overall results of this deliverable are summarised in Section 6. Furthermore, Section 6.1 describes in detail the advancements of this year evaluation w.r.t. the first year evaluation of the SmartHG IASs, discusses the current limitations and plans future work. Finally, Table 2.1 maps SmartHG WP5 tasks to sections of this deliverable.

Table 2.1: Mapping between SmartHG WP5 tasks and sections of this document

Task	**Task Name**	**Sections**
T5.1	Evaluation of EUMF service	Sections 3.3.2 and 3.3.4
T5.2	Evaluation of EBR service	Sections 3.2.2.3, 3.2.4.3 and 4.4
T5.3	Evaluation of EUR service	Sections 3.3.3 and 3.3.4
T5.4	Evaluation of DAPP service	Sections 3.2.2.1, 3.2.2.4, 3.2.4.1, 3.2.4.2, 4.1, 4.3, 5.1 and 5.3
T5.5	Evaluation of EVT service	Sections 3.2.4.5 and 3.3.1
T5.6	Evaluation of PPSV service	Sections 3.2.2.2, 3.2.4.4, 4.2 and 5.2
T5.7	Evaluation of DB&A service	Section 3.1

Chapter 3

Technical Evaluation of SmartHG Services

In this chapter we present the technical evaluation of all SmartHG Intelligent Automation Services (IASs). Namely, given the partition of SmartHG services outlined in Chapter 2, we show that the infrastructure (DB&A, Section 3.1) and the monitoring services (EUR-H, EUR-K, EUMF-H, EUMF-K and EVT, Section 3.3) indeed behave as designed in Deliverables D3.2.1 and D4.2.1. As for control loop services (DAPP-H, DAPP-K, PPSV and EBR, Section 3.2), since they have to compute actions (to be proposed either to residential homes or to EDN substations), we also show that the computational resources they need are acceptable.

For the sake of brevity, the results we report here are a selection of the experimental results we obtained in this second year. The complete report of the second year experimental results is available as a collection of Web pages in the Technical Section of the Project Web-site (see [?] and Deliverable D5.2.3).

3.1 Technical Evaluation of Infrastructure Services

The second year version of the Database and Analytics (DB&A) service provides a secure storage and (real-time) retrieval service for the data gathered from Home Energy Controlling Hubs (HECHs). Serving as the infrastructure service, the DB&A will allow other services (mainly Demand Aware Price Policies for Homes (DAPP-H) and Price Policy Safety Verification (PPSV)) to get the input they require by accessing a REpresentational State Transfer (RESTful) service. The technical evaluation of the DB&A service will thus consists on testing that the above described functionalities have been effectively implemented in the DB&A prototype described in Deliverables D4.2.1 and D4.2.2. We note that the second year version of all other IASs also rely on their own RESTful services, which are used to hold input and output of each service invocation. Since such RESTful services are built using DB&A as a template, this evaluation serves as an evaluation of the RESTful services for the above listed SmartHG services.

3.1.1 Test approach for DB&A

The technical evaluation of DB&A focuses on validating the Application Programming Interfaces (APIs) which populate and retrieve data from the DB&A underlying PostgreSQL

DataBase (DB), as well as on verifying if the APIs cover the services mentioned in the DB&A design (Deliverable D4.2.1).

For this purpose, tests are carried out for the following 3 main areas:

APIs As the DB&A Service is designed as a RESTful Web service, tests are planned for the following actions on data: retrieve (GET), insert (POST), update instances (PUT), update entries parameters (PATCH), delete (DELETE), list option parameters and limitations of an instance (OPTION), length overflow for a field, using wrong data format and using foreign-key without reference. The total number of tests is 51.

Functions Tests are planned to verify the functions extending the basic actions of a RESTful web service, namely filtering and bulk insertion.

APIs coverage Tests are planned to verify that all data objects (services) are covered by the APIs.

3.1.2 Test Results

Tests for the DB&A functions have been run as a batch job, which sent the HTTP requests to the DB&A RESTful service and then collect the responses. As a result, all 51 tests passed. This part of the DB&A testing is analogous to the first year version of the DB&A functions testing.

As for the APIs coverage, since the APIs have been deeply changed in implementing the second year version of DB&A, the second year version of the testing is much different from the first year one. Namely, the following APIs have been tested: dno_users (i.e., residential users), main_meters, operators (i.e., Distribution System Operators (DSOs)), meter_ports, measurements. The final result is that all of them are present, thus the test result is Pass.

Finally, the APIs coverage testing has been completed by checking APIs for authentication, which was missing in the first year version of DB&A. Also this test was successfully completed.

3.2 Technical Evaluation of Control Loop Services

In this section, we focus on computational effectiveness of the four SmartHG control loop services, namely Demand Aware Price Policies for Homes (DAPP-H), Demand Aware Price Policies for Substation-Level Energy Storage Control (DAPP-K), Price Policy Safety Verification (PPSV) and Energy Bill Reduction (EBR). First of all, we define (Section 3.2.1) two common *reference scenarios* for their evaluation. Within such scenarios, we will show that:

- DAPP-H is able to define customised price policies for all residential homes connected to the same substation (Section 3.2.4.1).
- DAPP-K is able to drive an Energy Storage System (ESS) installed on an Electric Distribution Network (EDN) substation so as to minimise total cost of electricity (Section 3.2.4.2).

- EBR is able to drive the energy storage appliances of a home so as to minimise the electrical energy bill (Section 3.2.4.3).
- PPSV is able to compute the probability distributions of the aggregated power demand at the substation level, when users may deviate from their price policies (Section 3.2.4.4).
- PPSV is also able to communicate with EDN Virtual Tomography (EVT), in order to estimate the impact of price policies output by DAPP-H on the entire EDN (Section 3.2.4.5).

Moreover, Section 3.2.3 shows that, in order to obtain such results, the control loop services require adequate computational resources (i.e., RAM and CPU).

Finally, the same reference scenarios used here for the technical evaluation will be used also for the economic (Section 4) and environmental (Section 5) evaluations.

3.2.1 Reference Scenarios

In this deliverable, we will focus on DSOs which are also retailers, as it happens in most cases. For a distinction between the two roles, see Deliverable D7.2.1.

In order to choose meaningful, challenging and real-world scenarios for the evaluation of control loop services, we set up the two *reference scenarios* described in Table 3.1. Such scenarios are based on the two test-beds currently available for the SmartHG project, i.e., the Kalundborg scenario (mainly used as DSO-oriented scenario) and the Central District scenario (mainly used as user-oriented scenario). Namely, all services working on the DSO side (i.e., DAPP-H, DAPP-K and PPSV) are evaluated in the Kalundborg scenario only, as the Central District scenario does not include information on EDN substations. Thus, the Central District scenario is used to strengthen the evaluation of EBR (and the auxiliary service Energy Usage Modelling and Forecasting for Control (EUMF-K)), which works on the residential users side. Finally, in Tables, 3.2, 3.3, 3.5, 3.7, 3.9 and 3.11 we also provide the parameters we will use in the economic and environmental evaluation of control loop services.

In the following, unless otherwise stated, electrical tariffs always give the final price to the residential user. Thus tariffs include energy as well as distribution costs (and taxes, where applicable).

Table 3.1: Main characteristics of the reference scenarios used in the evaluation (see Table 1.1 for further information)

	Kalundborg scenario	**Central District scenario**
Composition	186 homes from Kalundborg test-bed, plus data on Plug-in Electric Vehicle (PEV) plug-in requests from the "Test-an-EV" project (see Deliverable D7.2.1). Each PEV has a 16.3 kWh battery with a 13 kW power rate	One home from Central District test-bed, plus data on PEV plug-in requests again from the "Test-an-EV" project. Each PEV has a 16.3 kWh battery and a 13 kW power rate
Reference period	From midnight of 1st September 2013 to midnight of 31th August 2014	From midnight of 5th June 2014 to midnight of 30th September 2014

Table 3.1: Main characteristics of the reference scenarios used in the evaluation (see Table 1.1 for further information)

	Kalundborg scenario	**Central District scenario**
Data available	Anonymised hourly data from each home about energy consumption/production	
Services involved	DAPP-H, DAPP-K, PPSV, EVT, Energy Usage Reduction for Control (EUR-K), EBR and EUMF-K	EBR and EUMF-K
Notes on substation	Aggregate power demand from residential homes must be kept below P_s =360 kW. Data provided by SEAS	Not applicable.
Overall EDN	200,000 residential users connected to 10,000 substations (conservative assumptions for general EDNs)	Not applicable
Cost of a substation	13,350 EUR (provided by SEAS)	Not applicable
Substation lifetime	Typical lifetime is 40 years, that becomes 60 years with an ideal loading (80% of nominal power). Data provided by SEAS	Not applicable

Table 3.2: Retail prices of energy for residential users used in the evaluation of DAPP-H and EBR

Type	**Value**	**Notes**
Flat	0.2 EUR/kWh	Residential users in the Kalundborg scenario use a flat tariff when neither DAPP-H nor EBR are used. The value we use for such a flat tariff is slightly smaller than the one used in Kalundborg, so as to take into account the average of flat tariffs used in Europe [?]. Finally, we use such flat tariff in both the Kalundborg and the Central District scenarios.
Inclining Block Rate (IBR) low tariff	0.1 EUR/kWh	The value for the IBR low tariff is also used for DAPP-H and EBR in the Kalundborg scenario. See below for how we selected such value.
IBR high tariff	0.3 EUR/kWh	The value for the IBR high tariff is also used for DAPP-H and EBR in the Kalundborg scenario. Values for high and low tariffs have been obtained by considering European as well as American studies on elasticity prices [?], which suggest that high tariffs are typically 200% of low tariffs.
Time of Usage (ToU)		The ToU tariff (used for EBR in the Central District scenario) is divided in three segments, the same ones as in the SEAS pilot study "Vind med nye elvaner" discussed in Deliverable D6.2.1 (Section 2.1.2).

Battery Type	**PCS + BOP (EUR/kW)**	**ESC IQR (EUR/kWh)**	**lifetime IQR (years)**	$\frac{\text{PCS+BOP}}{\text{AvgESC}}$ **(hour^{-1})**
Lead – Acid	172 + 70	102 - 171 - 314	5 - 8.5 - 15	1.42
Lithium – Ion	125 + 0	356 - 844 -2034	5 - 11.5 - 15	0.15
Sodium – Sulfur	171 + 53	178 - 256 - 400	5 - 8.5 - 15	0.88
Vanadium Redox Flow	271 + 63	110 - 398 - 809	5 - 9.5	0.84

Table 3.3: Battery costs per battery type from [?]. Meaning for acronyms are as follows. PCS: Power Conversion System; BOP: Balance of Plant; ESC: Energy Storage Capacity. For ESC and lifetime, the minimum, average and maximum values for the corresponding InterQuartile Range (IQR) are shown. In this evaluation, we neglect OM costs, and we consider the average IQR costs.

Table 3.2: Retail prices of energy for residential users used in the evaluation of DAPP-H and EBR

Type	**Value**	**Notes**
ToU night	0.05 EUR/kWh	Valid from 8PM to 6AM. In order to avoid giving energy for free as in the SEAS study mentioned above, we set the night tariff to the very low price 0.05 EUR/kWh.
ToU day	0.1 EUR/kWh	Valid from 6AM to 5PM.
ToU evening	0.91 EUR/kWh	Valid from 5PM to 8PM. in order to show the feasibility and the capabilities of EBR, we complete the ToU tariff by setting the peak tariff (from 5PM to 8PM) so that, without the EBR acting on ESS and PEV (i.e., using historical demand for the given home), it would be more convenient for the user to apply the flat tariff than the ToU tariff. This allows us to actually verify that the economic gains resulting from the evaluation are indeed due to EBR.

3.2.2 Running Control Loop Services on the Reference Scenario

Given the scenarios described above, the control loop services are run as follows.

3.2.2.1 Inputs for DAPP-H

Input and output of DAPP-H are described in Deliverable D4.2.1. Following such specifications, we run DAPP-H on the Kalundborg scenario, one execution for each day of the year in the reference period. Thus, we run DAPP-H 365 times, computing price policies for 186 homes with the goal of keeping aggregated power demand at the substation level below 80% of the substation nominal profile (i.e., 360 kWh). The complete list of input provided to DAPP-H is reported in Table 3.4. Moreover, Table 3.5 shows the main parameters which will be used for the economic and environmental evaluation of DAPP-H described in Sections 4.1 and 5.1. A selection of the most meaningful outputs is shown in Section 3.2.4.1.

Table 3.4: Inputs fed to DAPP-H for the second year evaluation (see Deliverable D4.2.1.)

Input	**Value**	**Notes**
Substation	Feeder 1 (substation 30378) of the Kalundborg scenario	See Table 3.1
Homes	The 186 homes in the Kalundborg scenario	See Table 3.1
Period	One day T (divided in hours) inside the reference period of the Kalundborg scenario	One run of DAPP-H is launched for each day in the reference period (i.e., DAPP-H is run 365 times in total), see Table 3.1
Substation power threshold	360 kW	80% of nominal power, see Table 3.1
Users contract	The energy contract C_u for each user u (this is part of the Kalundborg scenario)	Either 6 or 12 kW for energy consumption, either 0 or 6 kW for energy production
Output	A price policy, valid for day T, for each of the 186 homes	Also the DAPP-H collaborative profile for each of the 186 homes is returned (to be used by PPSV, see Table 3.6), together with the maximum energy in kWh each user needs to store/retrieve in order to follow the individualised price policy (users flexibility)

Table 3.5: Main parameters used for DAPP-H economic and environmental evaluation

Parameter	**Value**	**Notes**
Price policies for residential users	See Table 3.2	
Hour-by-hour electricity energy market prices for DSOs/retailers	ELSPOT DK2 prices from NordPoolSpot [?] (EUR/MWh)	
Current prices for ESSs	See Table 3.3	We focus on battery systems of four different types (namely Lead–acid, Lithium–ion, Sodium–sulfur and Vanadium Redox Flow). Prices in Table 3.3 are based on recent studies [?]
Hourly data about Denmark CO_2 emissions due to production of electrical energy	Provided by SEAS	

3.2.2.2 Inputs for PPSV

Input and output of PPSV are described in Deliverable D4.2.1. Following such specifications, we run two sets of experiments for PPSV, in both cases using input and output from DAPP-H: the first set of experiments refers to the *safety evaluation* in Deliverable D4.2.1, whilst the second refers to the *economic evaluation* in Deliverable D4.2.1.

The complete list of input provided to PPSV for both sets of experiments is reported in Table 3.6. Moreover, Table 3.7 shows the main parameters which will be used for the economic and environmental evaluation of PPSV described in Sections 4.2 and 5.2. A selection of the most meaningful outputs is shown in Section 3.2.4.4.

Table 3.6: Inputs fed to PPSV for the second year evaluation (see Deliverable D4.2.1)

Input	**Value**	**Notes**
Substation	Feeder 1 (substation 30378) of the Kalundborg scenario	Same as in DAPP-H, see Tables 3.4 and 3.1
Homes	The 186 homes in the Kalundborg scenario	Same as in DAPP-H, see Tables 3.4 and 3.1
Period (safety evaluation)	One day T (divided in hours) inside the reference period of the Kalundborg scenario	One run of PPSV is launched for each run of DAPP-H (i.e., PPSV is run 365 times in total), see Table 3.4
Period (economic evaluation)	One month $\tilde{T}$ (divided in hours) inside the reference period of the Kalundborg scenario	One run of PPSV is launched for each set of DAPP-H runs referring to the same month (i.e., PPSV is run 12 times in total), see Table 3.4
DAPP-H collaborative profiles	For each user u, the DAPP-H collaborative profile of u as computed by the corresponding DAPP-H execution	
Disturbance model	$\text{dist}(0) = 0.4, \text{dist}(\pm 0.2) = 0.2, \text{dist}(\pm 0.4) = 0.1$	Each user may either behave as the DAPP-H collaborative profile with a 40% probability, or deviate with a 60% probability. In this latter case, the difference of power w.r.t. the collaborative user may be either 20% less, 20% more (both with 20% probability), 40% less or 40% more (both with 10% probability). Note that such probability distribution is conservative w.r.t. the results of EBR, that is, PPSV allows users to deviate much more than EBR does (see Section 3.2.4.3). We will refer to the set of residential user profiles obtained by disturbing the DAPP-H collaborative profiles as described above as *PPSV profiles*
Output (safety evaluation)	A probability distribution on the aggregated power demand (quantised each 40 kW) of feeder 1 (substation 30378) in day T, if residential users follow the PPSV profiles	

Table 3.6: Inputs fed to PPSV for the second year evaluation (see Deliverable D4.2.1)

Input	**Value**	**Notes**
Output (economic evaluation)	24 probability distributions on the aggregated power demand (quantised each 40 kW) of feeder 1 (substation 30378) in month $\tilde{T}$, if users follow the PPSV profiles	Each probability distribution is referred to a possible hour of the day (from midnight to 1 AM, from 1 AM to 2 AM, ...)
Kalundborg EDN model	Modelling from IMDEA, see Section 3.3.1	This is needed in order to enable communication between PPSV and EVT. We consider the model in which the EDN is in a worst case scenario, i.e., in Winter.

Table 3.7: Main parameters used for PPSV economic and environmental evaluation

Parameter	**Value**	**Notes**
Hour-by-hour electricity energy market prices for DSOs/retailers	DK2 prices from NordPoolSpot [?] (EUR/MWh)	Same as in DAPP-H (see Table 3.5)
Hourly data about Denmark CO_2 emissions due to production of electrical energy	Provided by SEAS	Same as in DAPP-H (see Table 3.5)

3.2.2.3 Inputs for EBR

Input and output of EBR are described in Deliverable D3.2.1. Following such specifications, we use the EBR service to download the control software for driving a single home PEV and ESS. Unless otherwise stated, in the rest of this deliverable, by abusing terminology, we will call EBR such control software. Since currently there are no homes with PEV and ESS to be controlled in our test-beds, we run EBR in two configurations: connected to a simulator for test bed homes and connected to a IMDEA micro grid Smart Energy Integration Lab (SEIL) driven with the data gathered from our test beds. More in detail, we perform two kinds of experiments as described in the following.

Software based HECH simulation experiment The simulation is carried out by creating a simulation environment, to be run on the HECH (which is where the EBR service must be deployed). Such simulation environment has to reproduce the home demand, divided as follows: ESS, PEV, all other electrical energy consumption and all electrical energy production.

Micro grid based experiment This is performed at the IMDEA SEIL (see Deliverable D6.2.1). In this case, the EBR environment of the given home is directly provided by the microgrid facilities in operation at the SEIL, which are able to reproduce the behaviour of ESS, PEV, the energy production and the energy consumption by using electronic loads.

Such two types of experiments have different features. Namely, the micro grid based one allows us to test the effectiveness of the EBR output, by directly interfacing the EBR with actual power electronics devices that emulate the home ESS and PEV. However, when compared to the software simulation, the laboratory-based simulation has the following drawbacks:

- it is 25× slower;
- it is difficult to exactly reproduce the input home consumption and production, as they are emulated by power electronics devices.

As a consequence, the micro grid based experiment will only be run on selected EBR inputs, and the results will be used to double check the results from the software based simulation. The complete list of input provided to EBR is reported in Table 3.8. Moreover, Table 3.9 shows the main parameters which will be used for the economic evaluation of EBR described in Section 4.4. A selection of the most meaningful outputs is shown in Section 3.2.4.3.

Table 3.8: Inputs fed to EBR for the second year evaluation (see Deliverable D3.2.1)In the first column, "KAL" stands for the Kalundborg scenario, "CD" for the Central District scenario.

Scen.	**Input**	**Value**	**Notes**
KAL	Home	One of the 62 homes in the Kalundborg scenario, namely, the one having i) energy production from solar panels and ii) maximum energy consumption	
CD	Home	The home with the maximum energy consumption in the scenario	
KAL	Period (varies depending on the simulation type used)	The 1-year reference period (divided in hours) of the Kalundborg scenario when using the software based simulation, and the two months in the peak period (from mid December 2013 to all February 2014) when using the micro grid based experiment	This is indeed the input of the simulation environment, which feeds EBR inner cycle with hour-by-hour measurements (see text in Section 3.2.2.3)
CD	Period	The three months (divided in hours) of the reference period of the Central District scenario	All the inputs listed in the following apply to both the software and the micro grid based experiments.
KAL/ CD	Home consumption and production	From Kalundborg/Central District scenario	See point above

Table 3.8: Inputs fed to EBR for the second year evaluation (see Deliverable D3.2.1)In the first column, "KAL" stands for the Kalundborg scenario, "CD" for the Central District scenario.

	Input	Value	Notes
KAL/CD	PEV state of charge/expected charging hours	From Kalundborg/Central District scenario (when a plug-in starts) and simulation environment (expected charging hours)	See point above
KAL/CD	ESS state of charge	From simulation environment	See point above
KAL	Energy price policies for residential users	We use the DAPP-H output tariff with the IBR prices shown in Table 3.2	See comment to "Electrical energy price policies for residential users" in Table 3.5
CD	Energy price policies for residential users	We use the ToU tariff in Table 3.2	See Technical Annex for further details.

Table 3.9: Main parameters used for EBR economic evaluation

Parameter	Value	Notes
Energy price policies for residential users (Kalundborg)	Flat tariff from Table 3.2	We compare the cost of the energy bill obtained with the DAPP-H IBR tariff with the energy bill computed with the flat tariff
Energy price policies for residential users (Central District)	Flat tariff from Table 3.2	We compare the cost of the energy bill obtained with the ToU tariff with the energy bill computed with the flat tariff
Current prices for ESSs	See Table 3.3	As in Table 3.5, we focus on battery systems of four different types (namely Lead–acid, Lithium–ion, Sodium–sulfur and Vanadium Redox Flow). Prices in Table 3.3 are based on recent studies [?]

3.2.2.4 Inputs for DAPP-K

Input and output of DAPP-K are described in Deliverable D4.2.1. Following such specifications, we use the DAPP-K service to download the control software for driving a substation ESS. Unless otherwise stated, in the rest of this deliverable, by abusing terminology we will call DAPP-K such control software. Since currently there are no substations with an ESS to be controlled in our test-beds, execution of DAPP-K is *simulated*. Namely, we simulate execution of DAPP-K on feeder 1 (substation 30378) of the Kalundborg reference scenario. As we are interested in simulating DAPP-K on ESSs with high capacity (up to 1000 kWh), we cannot use the SEIL facilities, thus we will only use the program-based simulation (see Section 3.2.2.3). The complete list of input provided to DAPP-K is reported in Table 3.10. Moreover, Table 3.11 shows the main parameters which will be used for the economic and environmental evaluation of DAPP-K described in Sections 4.3 and 5.3. A selection of the most meaningful outputs is shown in Section 3.2.4.2.

Table 3.10: Inputs fed to DAPP-K for the second year evaluation (see Deliverable D4.2.1)

Input	Value	Notes
Substation	Feeder 1 (substation 30378) in the Kalundborg scenario	
Period	The 1-year reference period T (divided in hours) of the Kalundborg scenario	This is indeed the input of the simulation environment, which feeds DAPP-K inner cycle with hour-by-hour measurements (see text in Section 3.2.2)
Aggregated demand	From Kalundborg scenario	See point above
ESS state of charge	From simulation environment	
ESS characteristics	Capacities: varying from 0 to 100 kWh (with a 10 kWh step) and from 200 kWh to 1000 kWh (with 100 kWh step). Power rate: 2, 5 or 8 kW for capacities at most 100 kWh, 20, 50 or 80 otherwise	Thus, we perform 57 different experiments, varying capacity and power rate of the ESS installed on the substation
Substation power threshold	360 kW	80% of nominal power, see Table 3.1

Table 3.11: Main parameters used for DAPP-K economic and environmental evaluation

Parameter	Value	Notes
Hour-by-hour electricity energy market prices for DSOs/retailers	DK2 prices from NordPoolSpot [?] (EUR/MWh)	Same as in DAPP-H (see Table 3.5)
Hourly data about Denmark CO_2 emissions due to electricity production	Provided by SEAS	Same as in DAPP-H (see Table 3.5)
Current prices for ESSs	See Table 3.3	We focus on battery systems of four different types (namely Lead–acid, Lithium–ion, Sodium–sulfur and Vanadium Redox Flow). Prices in Table 3.3 are based on recent studies [?]

3.2.3 Computation Time for Control Loop Services

In this section we show the computational effectiveness of all SmartHG control loop services when run on the scenarios described in Section 3.2.1, in terms of CPU time. To this aim, we organise the results as in Table 3.12, where column meaning is as follows. For each service s in column **Service**, column **Periodicity** shows the time between two invocations of s (in the expected nominal usage of s once deployed). Columns **Min CPU**, **Avg CPU** and **Max CPU** show the minimum, the average and the maximum time of executions of s in the reference scenario described in Section 3.2.1. For all services, since

Service	Periodicity	CPU only			Total Time (CPU + I/O)		
		Min	Avg	Max	Min	Avg	Max
DAPP-H	1:0:0:0	0:0:0:32	0:0:2:27	0:0:3:54	0:0:32:50	0:0:35:1	0:0:36:41
DAPP-K (Web Service)	on demand	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:1
DAPP-K (control software)	0:1:0:0	0:0:0:0	0:0:0:0	0:0:0:3	0:0:0:0	0:0:0:0	0:0:0:3
PPSV (safety)	1:0:0:0	0:0:1:47	0:0:5:1	0:8:17:9	0:0:3:56	0:0:8:1	0:8:20:44
PPSV (economic, single)	30:0:0:0	0:0:52:12	0:3:0:17	0:10:31:53	0:0:56:49	0:3:6:34	0:10:54:30
PPSV (economic, overall)	365:0:0:0	1:12:7:36			1:13:22:58		
EBR (Web Service)	on demand	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:1
EBR (control software)	0:1:0:0	0:0:0:2	0:0:0:3	0:0:0:50	0:0:0:2	0:0:0:3	0:0:0:50
EUMF-K (Web Service)	on demand	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:1
EUMF-K (auxiliary software)	0:1:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0
EUR-K	on demand	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:1
EVT	on demand	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:0	0:0:0:1

Table 3.12: Execution times (in days:hours:minutes:seconds) for each of the SmartHG control loop services, compared with the corresponding periodicity used in the evaluation presented in this deliverable. We also report computation times for the monitoring services which directly interact with the control loop services. For PPSV when used for the economic evaluation, both statistics on the single monthly executions and the final computation time on the whole year are shown. RAM usage is negligible (order of MBs) for all services. Experiments have been performed as follows: directly on the HECH for EBR, and on a 3.0 GHz Intel Xeon Ubuntu machine with 8 GB of RAM for all other services.

column **Max CPU** is always several orders of magnitude lower than column **Periodicity**, we may conclude that control loop services are indeed sustainable. Finally, Table 3.12 also distinguish, for EBR and DAPP-K, between the Web Service invocation and the simulation of the control software output by the Web Service. To this aim, we note that the Web Service (which, being invoked on demand, has not a fixed periodicity) only takes a few seconds to let a user download the control software.

3.2.4 Output of Control Loop Services

In this section, in order to show SmartHG control loop services effectiveness, we show excerpts of their outputs, when run as described in Section 3.2.2. Such outputs are then used, in Sections 4 and 5, to perform the economic and environmental evaluations of the control loop services, respectively.

3.2.4.1 Outputs of DAPP-H

Given the input provided to DAPP-H described in Section 3.2.2.1 and summarised in Table 3.4, Figure 3.1 show the overall output of DAPP-H, obtained by concatenating all outputs of each single run of DAPP-H. Namely, Figure 3.1 aggregates, at the substation level, the DAPP-H collaborative profiles output by DAPP-H for each of the residential users connected to the input substation. For the sake of comparison, the historical data for aggregated demand at the substation level in the same period is also shown, together with the desired substation threshold (360 kW). As a result, we have that demand from residential users in the Kalundborg scenario is re-distributed in order to be always below the threshold, thus performing peak shaving.

In order to show that DAPP-H does not compress the residential users demand in the Kalundborg scenario, Figure 3.2 graphs the difference between the cumulative residential

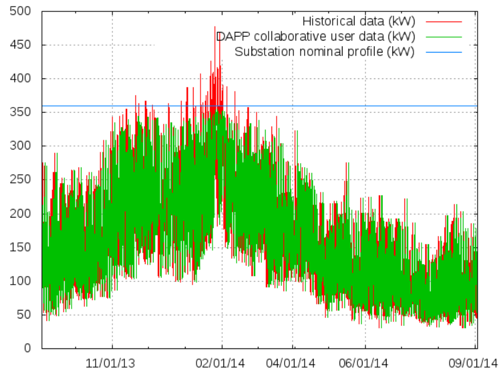

Figure 3.1: Output of DAPP-H from DSO perspective, combined on the whole evaluation period. See Section 3.2.4.1.

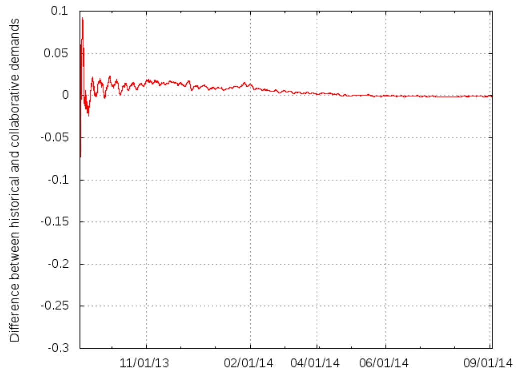

Figure 3.2: DAPP-H economic evaluation: difference between historical and DAPP-H collaborative energy demands, as a percentage of historical demand. See Section 1.6.

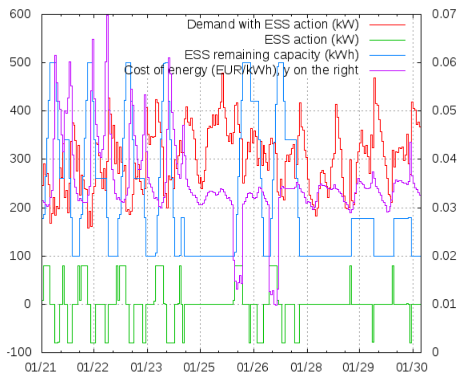

Figure 3.3: Output of DAPP-K on the last 10 days of January 2014 (this includes the peak period for aggregated demand), using an ESS with capacity 500 kWh and power rate 80 kW. See Section 3.2.4.2.

users aggregated demand with and without DAPP-H (i.e., DAPP-H collaborative demand vs. historical demand), as a percentage of the cumulative historical aggregated energy demand. That is, for each time-slot t we consider the result of summing the aggregated demand on all time-slots preceding t in the reference period. Figure 3.2 shows the values for such percentage in the whole reference period of one year. As a result, from Figure 3.2 we may note that the average of positive values for the difference between demand with and without DAPP-H (i.e., in which demand is compressed) is 1%, and never above 2% (excluding the first week of computation, where the difference may be 10%). Furthermore, at the end of the whole evaluation period, the difference is negative, thus the demand has been actually increased.

3.2.4.2 Outputs of DAPP-K

Given the input provided to DAPP-K (we recall that in the rest of this document, we call DAPP-K the control software downloaded from the DAPP-K Web Service) described in Section 3.2.2.4 and summarised in Table 3.10, Figure 3.3 shows the most meaningful output of DAPP-K. Namely, Figure 3.3 focuses on the experiment in which the maximum ESS capacity is 500 kWh and the power rate is 80 kW. From such experiment, Figure 3.3 shows ESS actions logged by the DAPP-K service running at the Kalundborg substation, in the most demanding week of the Kalundborg reference evaluation period, namely the last 10 days of January (see Section 3.2.4.1). Figure 3.3 also shows, for the same time period, the cost of energy (DK2 market price from Nordpoolspot [?]). We note that ESS is charged mainly energy is less expensive, in order to minimise the overall energy cost (*arbitrage*). Furthermore, Figure 3.3 shows, in the same time period, the resulting power demand at the substation level after ESS action. Finally, Figure 3.3 also shows the logged ESS capacity, which is always between the maximum capacity (500 kWh) and the 20% of the maximum capacity (100 kWh).

3.2.4.3 Outputs of EBR

Given the input provided to EBR (we recall that in the rest of this document, we call EBR the control software downloaded from the EBR Web Service) described in Section 3.2.2.3 and summarised in Table 3.8, Figures 3.4–3.5 show the most meaningful output of EBR. Namely, Figure 3.4 focuses on the actions computed by EBR in the most demanding periods of the Kalundborg reference scenario, whilst Figure 3.5 shows statistics on EBR output (on the Kalundborg scenario) which are useful for PPSV evaluation. In the following, we discuss each figure separately.

Figure 3.4: EBR output on the Kalundborg scenario Figure 3.4 shows ESS and PEV actions logged by the EBR service running on the HECH at the Kalundborg home. To this aim, we focus on the most demanding week of the reference evaluation period (see Section 3.2.4.1), and we show the two most demanding days for the given Kalundborg home, namely the 26th and the 27th of January. Moreover, we only show the logged actions from the experiment with the highest maximum ESS capacity, that is 9 kWh. Figure 3.4 also shows, for the same time period, either the IBR high tariff or the IBR low tariff applied, depending on the home demand resulting from ESS and PEV actions. Figure 3.4 shows such an alternation between the IBR high and low tariffs. As a result, we note that EBR succeeds in keeping most of the times the overall demand in the low tariff area, so that the IBR low tariff is applied most of the times, thus reducing the energy bill.

Figure 3.5: from EBR output to PPSV input The output of EBR on the Kalundborg home, which follows the DAPP-H tariff, is used to tune the PPSV input probabilistic disturbance model (see Table 3.6). Namely, the PPSV disturbance model has to account for both how much time a user may deviate from the Demand Aware Price Policies (DAPP) output price policy, and how much severe the deviation is. To this aim, Figure 3.5 presents the corresponding statistics of the EBR output on the Kalundborg home. Namely, Figure 3.5 shows both for how much time EBR is unable to keep the user demand inside the low tariff area ("Percentage outside low tariff area" curve) and the average deviation when the demand is outside the low tariff area ("Average demand outside low tariff area"). For the sake of completeness, also the remaining percentages on times (namely, for how much time the user demand is kept inside and for how much time the user is producing energy) are shown. As a result, we may state that, for the current user, i) EBR is forced to deviate from the low tariff area for less than the 20% of time; and

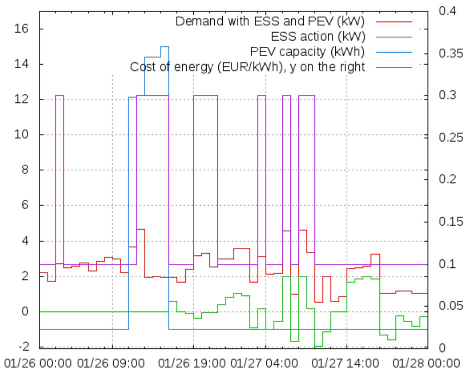

Figure 3.4: Output of EBR: actions for ESS and PEV on 26th and 27th January 2014 for the Kalundborg home (PEV capacity is -1 when PEV is not plugged). See Section 3.2.4.3.

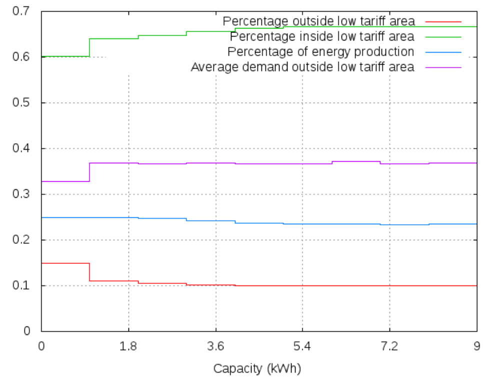

Figure 3.5: Output of EBR on DAPP-H tariff on Kalundborg home: useful statistics for PPSV. See Section 3.2.4.3.

ii) when a deviation occurs, it is at most 40% of the demand. If we assume that results are analogous for other users, this justifies the PPSV input disturbance model discussed in Section 3.2.1.

3.2.4.4 Outputs of PPSV

Given the input provided to PPSV described in Section 3.2.2.2 and summarised in Table 3.6, Figures 3.6 and 3.7 show the most meaningful output of PPSV. Namely, Figure 3.6 focus on the PPSV output when run on a day-by-day basis (safety evaluation), whilst Figure 3.7 focus on the PPSV output when run a monthly basis (economic evaluation). In the following, we discuss each figure separately.

Figure 3.6: PPSV for safety evaluation Figure 3.6 shows the PPSV output when used to check substation ideal loading (w.r.t. substation power threshold $P_s = 360$ kW) of DAPP-H output on the most demanding day in the reference period, namely the 27th January 2014. As a result, we have that DAPP-H collaborative demand is always below the 360 kW threshold, the PPSV demand may go beyond the substation threshold with a 8% probability, and, finally the historical demand may go beyond the substation threshold with a 17% probability. Note that the safety evaluation version of PPSV will also be used as part of the economic evaluation of DAPP-H when users may deviate from their price policies (namely for evaluating the saving stemming from Transmission and Distribution (T&D) investment deferral, see Section 4.2.1).

Figure 3.7: PPSV for economic evaluation Figure 3.7 shows the PPSV output when used to evaluate economic impact of DAPP-H output on the most demanding month in the reference period, namely January 2014. Since in this case PPSV outputs 24 probability distributions (one for each hour of the day), Figure 3.7 shows the output corresponding to the most demanding hour, that is from 6PM to 7PM. The output of the economic evaluation version of PPSV will be used to evaluate part of the economic saving for the DSO when DAPP-H is used and users may deviate from their price policies (namely for evaluating the saving stemming from arbitrage, see Section 4.2.2). Finally,

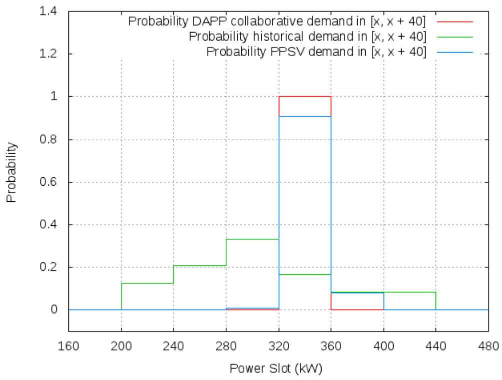

Figure 3.6: Output of PPSV when used to check DAPP-H execution of the 27th of January 2014. See Section 3.2.4.4.

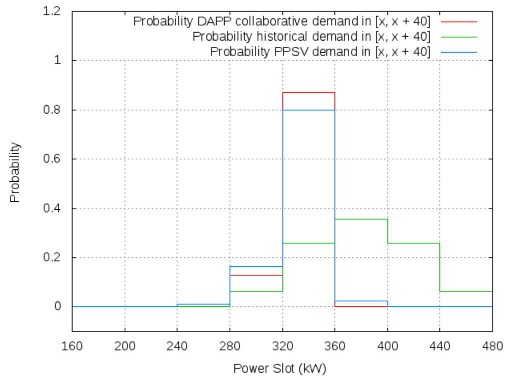

Figure 3.7: Output of PPSV on the timeslot from 6PM to 7PM, using all DAPP-H executions of January 2014. See Section 3.2.4.4.

the same result will be also used to evaluate the environmental saving when DAPP-H is used and users may deviate from their price policies (see Section 5.2).

3.2.4.5 Communication between PPSV and EVT

Given the input provided to PPSV described in Section 3.2.2.2 and summarised in Table 3.6, in this section we show that PPSV is able to communicate with EVT, in order to estimate the impact of price policies output by DAPP-H on the entire EDN. A graphical depiction of EVT output as an answer to the most meaningful PPSV requests is shown in Figures 3.8 and 3.9. Namely, in Figure 3.8, loading of the EDN substations exceeds ideal thresholds. On the contrary, in Figure 3.9 all EDN substations are under ideal loading. From PPSV output (Figure 3.6), we know that the probability of the scenario in Figure 3.8 is 8% if DAPP-H is applied but users may deviate from price policies. Such probability increases to 17% if DAPP-H is not applied (or users ignore price policies). On the other hand, the probability of the scenario in Figure 3.8 is 90% if DAPP-H is applied but users may deviate from price policies, which decreases to 16.6% if DAPP-H is not applied (or users ignore price policies). In the following, we discuss a comparison of the two figures.

Comparing Figures 3.8 and 3.9 Summing up, Figure 3.9 shows what hapndpens if all users follow the DAPP-H price policies (not only on the substation 30378, but also in all other Kalundborg EDN substations): very few alarm/recommendations. On the other hand, Figure 3.8 shows what happens either when users may probabilistically deviate from DAPP-H price policies, or when DAPP-H schema is not applied: there are important alarm/recommendations. By using PPSV, we have that the important alarm/recommendations probability is 8% with the DAPP-H schema (with user deviations) and 17% without the DAPP-H schema. Moreover, the very few alarm/recommendations probability is 91% with DAPP-H schema (and with users deviations), and 16.6% without DAPP-H schema. This demonstrates the feasibility of our approach in the Kalundborg scenario.

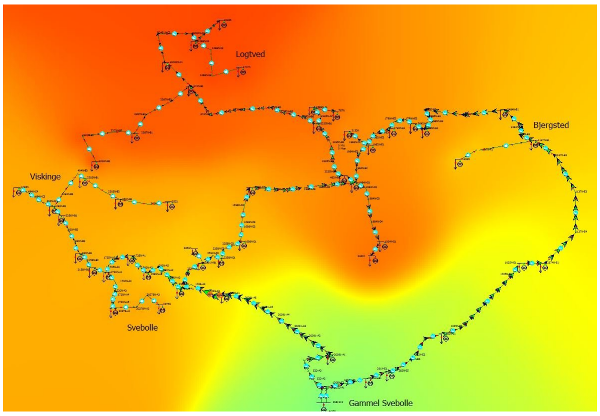

Figure 3.8: PPSV technical evaluation: communication with EVT. The figure shows the density of alarm/recommendations output by EVT when loading of the EDN substations exceeds ideal thresholds. See Section 3.2.4.5.

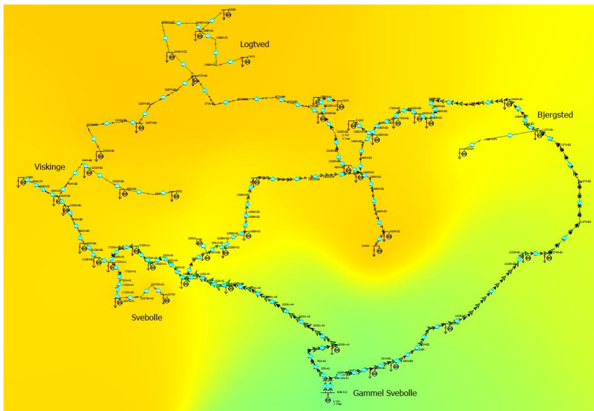

Figure 3.9: PPSV technical evaluation: communication with EVT. The figure shows the density of alarm/recommendations output by EVT when the EDN substation are under ideal loading (i.e., users always follow the DAPP-H price policies). See Section 3.2.4.5

3.3 Technical Evaluation of Monitoring Services

In this section, we focus on the technical evaluation of the monitoring services, namely the EVT (Section 3.3.1), EUMF-K (Section 3.3.2), EUR-K (Section 3.3.3), Energy Usage Modelling and Forecasting for Homes (EUMF-H) and Energy Usage Reduction for Homes (EUR-H) (discussed together in Section 3.3.4) services.

3.3.1 Technical Evaluation of the EVT Service

In order to demonstrate the key functions of the EVT service, we show how it may be used on the Kalundborg test network (which includes the Kalundborg scenario used for control loop services). Namely, we model a scenario demonstrating a low voltage issue at the most electrically distant part of the Kalundborg network (Logtved). According to the EU standards for public distribution systems (EN50160 and EN61000), voltage magnitude limits throughout all points in the Low Voltage (LV) and Medium Voltage (MV) networks should remain within $+/-10\%$ of nominal (taken as 10 min average of the Root Mean Square (RMS) voltage). There are also other specific limits around temporary under- and over-voltages that are not considered here.

Due to the fact that there may be considerable voltage drop along LV feeders, particularly on long lines in rural areas, the DSO may wish to tighten the limits at the feeder head, or secondary (10:0.4kV) substation to e.g. $+/-3\%$, since voltage is generally worse at the feeder extremities. In general, the DSO will set nominal voltages higher than $1.0p.u.$ particularly at full-load, in order to provide more headroom for voltage drop and to reduce network RI^2 losses. In this example, primary substation voltage set-point is $V = 1.02p.u.$ and tap ratio is 1.0125 (+2 taps).

Figure 3.10 shows the PowerWorld Simulator output for the above described scenario,

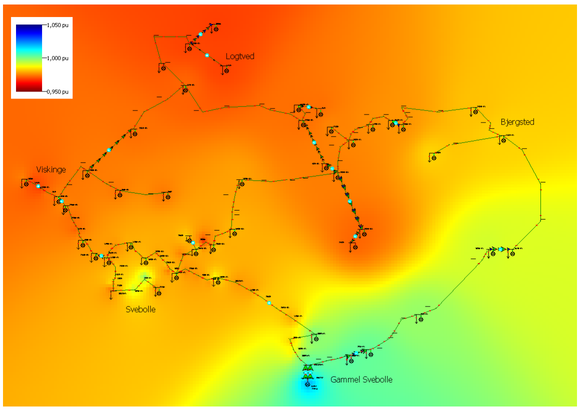

Figure 3.10: EVT technical evaluation: before corrective actions on Kalundborg scenario. See Section 3.3.1.

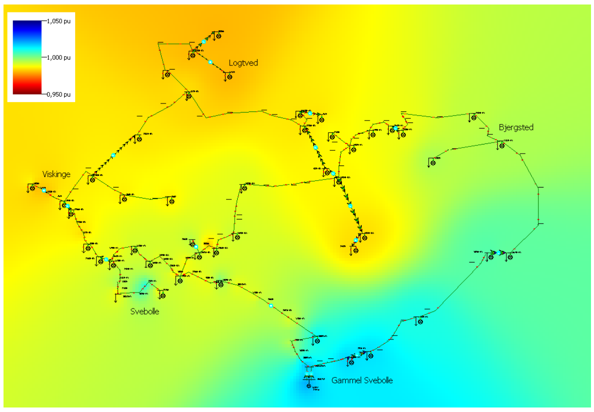

Figure 3.11: EVT technical evaluation: after corrective actions on Kalundborg scenario. See Section 3.3.1.

where low voltages occur in parts of the network which are further from the primary substation. The warnings/alarms and corrective actions generated by the EVT are given below:

- **Warning/alarm**: Voltage below $0.97 p.u.$ at Bus 46, Bus 47 and Bus 48.
- **Recommendation**: Adjust transformer taps at primary transformer (50:10kV) by +2 ($2 * 0.00625$) to increase voltage throughout the network.

Figure 3.11 shows the PowerWorld Simulator output for the above described scenario, after the corrective action recommended by EVT has been taken, where the voltage has reached a normal level throughout the system.

3.3.2 Technical Evaluation of EUMF-K

In this section, we discuss the technical evaluation of the EUMF-K service. To this aim, we use the EUMF-K service to download the software to compute demand forecast (given demand history). As this take a few seconds, as we have done for EBR and DAPP-K we focus the EUMF-K evaluation on the downloaded software, which by abusing terminology we call EUMF-K. The technical evaluation of EUMF-K is then carried out in two different ways, one direct and one indirect. The direct way, described in Section 3.3.2.1, consists in comparing the known historical power demand with the power demand forecasted by EUMF-K, in both the Kalundborg and the Central District scenarios (see Table 3.1). The indirect way, described in Section 3.3.2.2, focuses on two IASs relying on EUMF-K (namely, EBR and DAPP-K), and compares the economic saving which such services obtain, in both the Kalundborg and the Central District scenarios, when EUMF-K is used and when the exact historical demand is used (i.e., when EUMF-K is a kind of "oracle" forecasting exact power demand). Finally, we note that computation times for EUMF-K are negligible (see Table 3.12).

3.3.2.1 Direct Comparison: Historical vs. Forecasted Demand

In order to directly compare the demand forecasted by EUMF-K with the actual historical demand, we proceed as follows. We run EUMF-K in the same way it is called inside

EBR for the evaluation of EBR (see Table 3.8 and Section 3.2.2.3). Namely, we run EUMF-K on both the Kalundborg and the Central District home, for each hour h in the corresponding reference periods (i.e., one year for the Kalundborg home and 3 months for the Central District home), each time using as input a 10-days-long sliding window of historical demand for the given home (i.e., the 240 hours preceding h). Then, we compare the forecasted demands with the known historical demands.

The results are shown in Figures 3.12 (for Kalundborg home) and 3.13 (for Central District home). Figures 3.12 and 3.13 show the frequency distribution of the relative forecast error in the Kalundborg and Central District scenarios, respectively. Namely, for each time-slot (of one hour) in the EUMF-K technical evaluation, we compute the relative forecast error as $\frac{|\text{forecasted\_demand} - \text{historical\_demand}|}{\text{historical\_demand}}$. Then, Figures 3.12 and 3.13 show on the x axis the possible values for the relative forecast error, and on the y axis the frequency of such error, i.e., which is the percentage of hours with that error w.r.t. the total number of hours.

As a result, from Figures 3.12 and 3.13 we may see that the error is 130% on average (mainly due to the very low values for the historical demand) for the Kalundborg home, and 47% for the Central District home. Note however that the maximum relative forecast error for the Kalundborg home (not shown in Figure 3.12) is 320%, which is attained in just one hour out of 365*24 hours (i.e., with frequency 2×10^{-4}). Frequency of errors higher than 100% is only 17%, and most of the times (above 60%) errors are below 50%. These results allow EBR to obtain the results presented in Section 4.4.

3.3.2.2 Indirect Comparison: EUMF-K vs. Oracular EUMF-K for DAPP-K and EBR

In this section, we focus on two IASs relying on the EUMF-K service, namely DAPP-K (which operates on the DSO side) and EBR (which operates on the residential user side). Our goal is to show that, even if EUMF-K is replaced with an "oracle" able to *exactly* forecast the future power demand, the saving which are obtained by using such services does not change too much. To this aim, for each *causal* experiment run with DAPP-K (see Table 3.10 and Section 3.2.2.4) and EBR (see Table 3.8 and Section 3.2.2.3) we run a twin *non-causal* experiment with the same parameters, but where EUMF-K is replaced by the "oracle" described above.

Comparison of causal and non-causal experiments Since each non-causal experiment is by construction more precise than the corresponding causal experiment, it is sufficient to compare the final economic saving after one year obtained by the two experiments to show EUMF-K forecasting reliability. In other words, we compare the saving obtained with the DAPP-K and the EBR services with the saving the DAPP-K and the EBR service would obtain if it "oracularly" knew the correct future demand. Note that the saving stemming from causal experiments is presented in Section 4.3 for DAPP-K (namely, we will use the values in Figure 4.9, all in the Kalundborg scenario), and in Section 4.4 for EBR.

To this aim, for each value of the ESS capacity Q and power rate R, we compute the percentage of the difference of the corresponding savings w.r.t. the non-causal saving (i.e., we consider $\frac{\text{saving}(Q,R) - \text{saving\_non\_causal}(Q,R)}{\text{saving\_non\_causal}(Q,R)}$). Then, in Table 3.13, we show the minimum, average and maximum values of such percentage of difference. Namely, the first row in Table 3.13 shows the results for DAPP-K on the Kalundborg scenario (with

Service	Notes	Min	Avg	Max
DAPP-K	Kalundborg scenario, ELSPOT prices	0.56	0.6	0.65
EBR	Central District scenario, ToU tariff	0.17	0.19	0.22
EBR	Kalundborg scenario, DAPP-H IBR tariff	0.14	0.42	0.49

Table 3.13: EUMF-K technical evaluation: how services relying on EUMF-K and involving a controller (i.e., DAPP-K and EBR) may improve if the exact forecast were known. See Section 3.3.2.2.

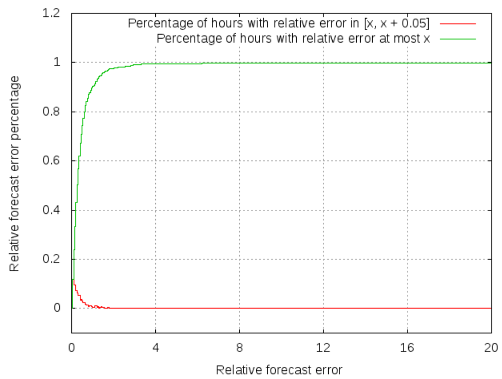

Figure 3.12: EUMF-K technical evaluation: relative forecast error frequency distribution for Kalundborg scenario. See Section 3.3.2.

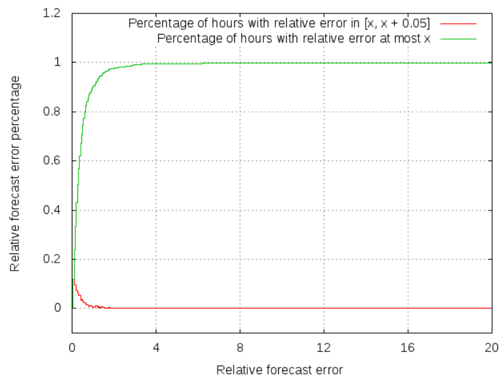

Figure 3.13: EUMF-K technical evaluation: relative forecast error frequency distribution for Central District scenario. See Section 3.3.2.

Q and R varying as in Table 3.10), the second row shows the results for EBR on the Kalundborg scenario (with Q varying as in Table 3.8, and $R = 2$kW), and the third shows the results for EBR on the Central District scenario (with Q varying as in Table 3.10, and $R = 2$kW).

Results from Table 3.13 As a result, we may see that the saving obtained by using DAPP-K for one year is at most 65% (and 60% on average) smaller than the saving obtained with the "oracular" DAPP-K (i.e., if DAPP-K may exactly forecast the future aggregated demand of Kalundborg users, it would obtain a saving which is 60% better, on average). Analogously, the saving obtained by using EBR for one year in the Kalundborg scenario is at most 49% (and 42% on average) smaller than the saving obtained with the "oracular" EBR (i.e., if EBR may exactly forecast the future demand of the Kalundborg user, it would obtain a saving which is 42% better, on average). Finally, the saving obtained by using EBR for one year in the Central District scenario is at most 22% (and 19% on average) smaller than the saving obtained with the "oracular" EBR (i.e., if EBR may exactly forecast the future demand of the Central District user, it would obtain a saving which is 19% better, on average).

3.3.3 Technical Evaluation of EUR-K

In this section, we discuss the technical evaluation of the EUR-K service. First of all, we note that, for all other IASs evaluation, we use *historical* data, which were available to SEAS for the Kalundborg scenario and to PANPOW for the Central District scenario (see

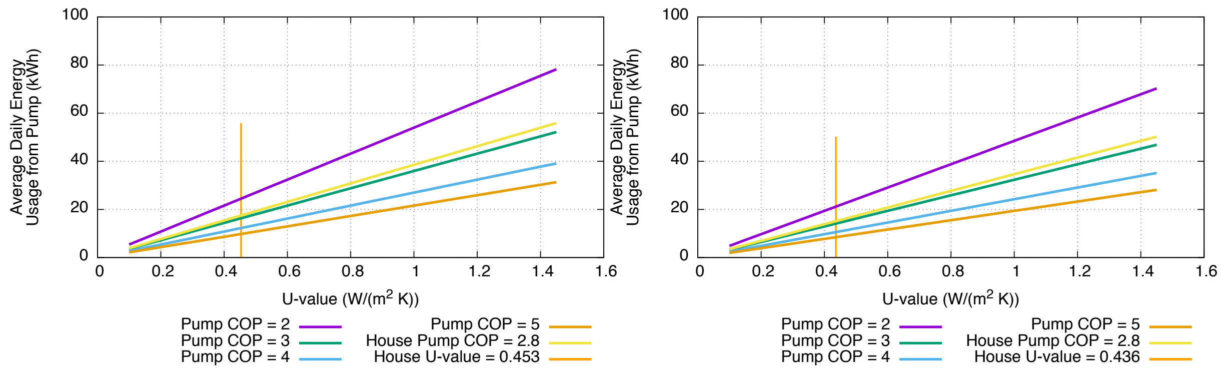

Figure 3.14: EUR-K technical evaluation: output on two selected homes in the Kalundborg scenario. See Section 3.3.3.

Table 3.1). However, EUR-K requires in input (for the given home) the consumption for the heat pump only, as well as the outside and the inside temperature every few minutes (see Deliverable D3.2.1). Such information was not available neither to SEAS nor to PANPOW. Thus, for the evaluation of EUR-K, we use the data collected directly from the field, in the Kalundborg test-bed, thus exploiting the new smart meters installed in this second year as part of the demonstration activities WP6 (see Deliverable D6.2.1).

EUR-K Evaluation Scenario The evaluation scenario for EUR-K is taken from the Kalundborg scenario, by selecting 7 homes for which, thanks to the new smart meters installed as part of the demonstration activities in WP6, we have all the inputs required by EUR-K, namely the temperature inside and outside the home (taken every 10 seconds) and the consumption profile of a heat pump installed in the home. Such data have been completed by the Coefficient of Performance (COP) of the heat pumps and the area of the homes external walls. The computation times required by EUR-K are shown in Table 3.12.

Outputs of EUR-K Figure 3.14 shows the output of EUR-K on two selected homes, out of the 7 used for the evaluation. From such an output, the user may understand if it is more convenient to reduce the U-value of the home (e.g., by thermal insulation, or by improving thermal habits of the people living in the home), or to buy a heat pump with an higher COP. As an example, for the house in the left part of Figures 3.14, the current daily consumption due to the heat pump is about 17 kWh. In order to reduce it to 10 kWh, which would result in a 1.4 EUR/day saving with the 0.2 EUR/kWh flat tariff in Table 3.2, the user may either upgrade to a heat pump with COP 5, or reduce the U-value to 2 W/m^{2}K. Of course, the cost of both such solutions must be considered and amortised in order to obtain an actual saving.

3.3.4 Technical Evaluation of EUMF-H and EUR-H

We conclude the technical evaluation of monitoring services by evaluating the EUMF-H and EUR-H services. Note that, in this evaluation, EUR-H and EUMF-H are considered as one integrated service. To this aim, we use the EUMF-H and EUR-H services to compute demand forecast of a given residential home in Minsk. Namely, we use the Web interface of EUMF-H and EUR-H services to compute the energy consumption forecast on the 7th December 2014, for the home in Minsk at Belskogo n.9a–16. In order to obtain such a forecast, the historical data for energy consumption on the same home from 28th of November to 4th of December 2014 are used.

To this aim, Figures 3.15 and 3.16 shows statistics of the forecast error of EUR-H and EUMF-H services, for the selected Minsk home and one-day period. Namely, Figure 3.15 shows the co-variance between the forecasted values and the correct values (i.e., how much the two values change together). On the other hand, Figure 3.16 shows the sum, the mean and the standard deviation (dispersion) of the correct and forecasted values.

As a result, from Figures 3.15 and 3.16 we may see that the covariance is at most 0.6%, and that the dispersion is always below 0.2 kW. This allows us to conclude that the forecast output by EUMF-H and EUR-H in the proposed evaluation scenario is good.

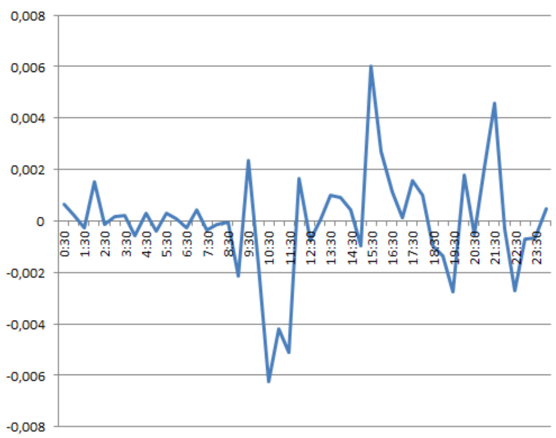

Figure 3.15: EUMF-H and EUR-H technical evaluation: co-variance of forecasted demand and historical correct demand. See Section 3.3.4.

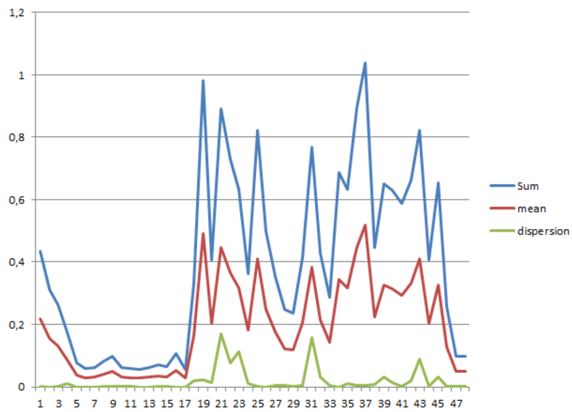

Figure 3.16: EUMF-H and EUR-H technical evaluation: statistics of forecasted demand w.r.t. historical correct demand. See Section 3.3.4.

Chapter 4

Economic Evaluation of Control Loop Services

In this chapter we present the economic evaluation of the SmartHG control loop services, namely Demand Aware Price Policies for Homes (DAPP-H) (Section 4.1), Price Policy Safety Verification (PPSV) (Section 4.2), Demand Aware Price Policies for Substation-Level Energy Storage Control (DAPP-K) (Section 4.3) and Energy Bill Reduction (EBR) (Section 4.4).

Note that the economic evaluation is carried out *from the users perspective* for EBR (which enables use of DAPP-H output on a residential home), *from the Distribution System Operator (DSO) perspective* for PPSV (which analyses the effect of DAPP-H output on the given set of residential homes) and DAPP-K (which operate on an Energy Storage System (ESS) installed on an Electric Distribution Network (EDN) substation), and finally *from both users and DSO perspective* for DAPP-H (which targets both residential homes and the substation they are connected to).

4.1 Economic Evaluation of the DAPP-H Service

This section is divided in two parts: in the first one (Section 4.1.1) we evaluate the DAPP-H service from users economic perspective, in the second one (Section 4.1.2) we evaluate the DAPP-H service from DSO economic perspective. In both cases, we will use the outputs of DAPP-H when run as described in Table 3.4 and in Section 3.2.2.1.

4.1.1 DAPP-H Economic Evaluation from Users Perspective

In order to evaluate the DAPP-H service (when run as described in Table 3.4 and in Section 3.2.2.1) from users economic perspective in the Kalundborg scenario (see Table 3.1), we proceed as follows. Our goal is to show that, by following the price policy output by DAPP-H in the Kalundborg reference scenario, users are able to save money, without having to cut their power demand. Please note that energy tariffs used for this evaluation also account for energy distribution and taxes (see Table 3.2). To this aim, we organise part of the outputs of DAPP-H (with the inputs described in Table 3.4) in Figures 4.1–4.4, which we discuss in the following Sections 4.1.1.1–4.1.1.3 (one section per each figure). Moreover, a summary of the main results for DAPP-H economic evaluation is presented in Table 4.1.

Table 4.1: Main results for DAPP-H economic evaluation in the Kalundborg reference scenario (see Table 3.4 for DAPP-H inputs).

Figure	**Result**
Figure 4.1	For all residential users, the saving is at least 200 EUR, and for 85% of residential users is at least 470 EUR
Figure 4.2	When equipping the home to follow DAPP-H price policies, the ESS required capacity is less than 12 kWh for nearly 80% of residential users, and less than 30 kWh for all residential users.
Figure 4.4	More than 90% of residential users save more than 1,500 EUR on 10 years, and the most part of residential users save more than 2,000 EUR in the same period.
Figure 4.5	The saving for the DSO stemming from arbitrage is 160 EUR/year for each substation and 0.8 EUR per year per user.
Figure 4.6	As an example, if we conservatively assume that there are 200,000 residential users in the EDN, we have that the economic saving for the DSO on the whole EDN stemming from arbitrage is about 160,000 EUR/year.
	The saving for the DSO stemming from Transmission and Distribution (T&D) investment deferral is about 0.6 EUR per year per user (e.g., if 200,000 users adopt DAPP-H we have, on average, a saving of 120,000 EUR per year).
	The saving for the DSO stemming from arbitrage *and* T&D investment deferral is 1.4 EUR/year per residential user (e.g., if 200,000 users adopt DAPP-H we have, on average, a saving of 280,000 EUR per year).

4.1.1.1 Saving for Residential Users Disregarding Equipment Cost

In this section we evaluate the saving for residential users stemming from application of DAPP-H price policies in the Kalundborg scenario, ignoring the fact that users will need additional equipment to follow the price policies. In the following Sections 4.1.1.2 and 4.1.1.3 this assumption will be removed.

To this aim, we compare the residential user energy bills *before* (i.e., without) and *after* (i.e., with) the application of DAPP-H price policies. Such comparison is shown in the two curves of Figure 4.1: the first one shows the percentage of users for which the saving is in the corresponding 100 EUR interval on the x axis, whilst the second one shows the percentage of users for which the saving is *at least* the corresponding on the x axis.

Results from Figure 4.1 As a result, Figure 4.1 shows that all residential users save money by using DAPP-H for one year in the Kalundborg scenario. More in detail, for all users, the saving obtained by adhering to DAPP-H schema is at least 200 EUR, and for 85% of users is at least 470 EUR.

4.1.1.2 Equipment Required for Residential Users Flexibility

In the following, we assume that users will equip their home with an ESS (driven by EBR) in order to follow the price policies (i.e., we model users flexibility with an ESS). In order to include the ESS cost amortisation inside the evaluation of saving for residential users, we need to know the main characteristics of the ESS needed by each user, i.e., the maximum capacity and the maximum power rate. To this aim, we recall that the maximum power rate is fixed to 2 kW (for all users) in our evaluation, whilst the maximum capacity is an output of DAPP-H (see Table 3.4). Given this, Figure 4.2 shows the frequency distribution of the ESS capacities as output by DAPP-H. Namely, Figure 4.2 shows, on the x axis, the maximum ESS capacity (in kWh), and on the y axis the percentage of residential users. In such coordinates, two curves are shown: the first one shows the percentage of users for which the required maximum ESS capacity is in the corresponding 1 kWh interval on the x axis, whilst the second one shows the percentage of users for which the maximum capacity is at most the corresponding on the x axis (i.e., the second curve is the integral of the first curve).

Results from Figure 4.2 As a result, Figure 4.2 shows that the ESS needed capacity is less than 12 kWh for nearly 80% of users, and less than 30 kWh for all users.

4.1.1.3 Saving for Residential Users Considering Equipment Cost

In this section, we complete the evaluation of the saving for residential users by also considering the ESS cost amortisation. To this aim, we assume that all users equip their home with a Lead-Acid battery, with power rate 2kW (see Table 3.4) and capacity as output by DAPP-H (see Figure 4.2). By using the minimum cost for such a battery shown in Table 3.3, and assuming that users power demand and yearly saving do not vary too much for 10 years, we obtain the saving frequency distribution, after 10 years of ESS and DAPP-H usage, shown in Figure 4.4. Namely, Figure 4.4 shows, on the x axis, the saving (in EUR) for the residential users after 10 years (also considering ESS cost amortisation), and on the y axis the percentage of residential users. In such coordinates, two curves are shown: the first one shows the percentage of users for which the saving is in the corresponding 100 EUR interval on the x axis, whilst the second one shows the percentage of users for which the saving is at least the corresponding on the x axis (i.e., the second curve is the complement of the integral of the first curve).

Results from Figure 4.4 As a result, from Figure 4.4 we may see that more than 90% of end users in the Kalundborg reference scenario save more than 1,500 EUR on 10 years, and the most part of end users save more than 2,000 EUR in the same period.

4.1.2 DAPP-H Economic Evaluation from DSO Perspective

In order to evaluate the DAPP-H service (when run as described in Table 3.4 and in Section 3.2.2.1) from DSO economic perspective in the Kalundborg scenario (see Table 3.1), we proceed as follows. Our goal is to show that, if all residential users follow their individualised price policy (i.e., if they follow the DAPP-H collaborative profile computed by DAPP-H, see Table 3.4), then the DSO pays less for energy (arbitrage) and saves money for substation maintenance (T&D investment deferral), thus obtaining a saving by using DAPP-H.

To this aim, we organise part of the outputs of DAPP-H (with the inputs described in Table 3.4) in Figures 4.5–4.6, which we discuss in the following Sections 4.1.2.1–4.1.2.3. Moreover, a summary of the main results for DAPP-H is presented in Table 4.1.

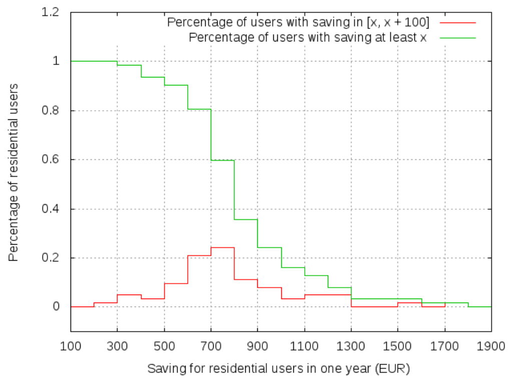

Figure 4.1: DAPP-H economic evaluation: frequency distribution of the saving for residential users (in EUR) disregarding equipment cost. See Section 4.1.1.1.

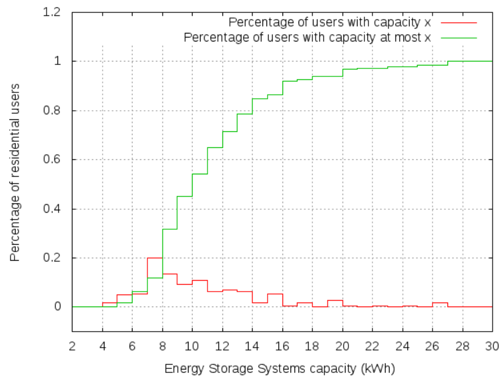

Figure 4.2: DAPP-H economic evaluation: frequency distribution of resulting equipment characteristics (as ESS capacities, in kWh). See Section 4.1.1.2.

4.1.2.1 Saving for DSO Stemming from T&D Investment Deferral

In this section we focus on evaluating the saving stemming from T&D investment deferral.

The main interest in peak shaving, from a DSO perspective, is to delay T&D investments. We note that indeed, for most DSOs, severe peaks of aggregated demand is not a problem now. However, this is expected to become a problem in the near future when more and more people will have heat pumps and possibly Plug-in Electric Vehicles (PEVs). So, T&D saving refers indeed to a future scenario where demand peaks will challenge the EDN.

Of course, it is not our goal to develop a precise model relating demand peaks to EDN equipment wearing. An underestimation of such costs will do in our setting, since such costs will be considered in our evaluation as saving for the DSO stemming from the usage of SmartHG Intelligent Automation Service (IAS).

We underestimate T&D costs due to demand peaks by only considering average costs arising from the need to replace a substation transformer, before its nominal lifetime, due to overloading stemming from demand peaks. Let p be the probability of such an event. Then the expected DSO saving (per transformer per year) stemming from a successful peak shaving technology will be pK, where K is the average cost of a transformer. Furthermore, the expected saving on the whole network of n transformers will be pKn EUR per year. Finally, if the network has on average q users per transformer the expected saving per year per user will be $\frac{pK}{q}$.

Conservatively (since they yield small savings to the DSO) we consider scenarios with small values of p (that is, demand peaks have, on average, a small effect on a transformer lifetime).

In our Kalundborg scenario (see Table 3.1) we can take $K = 13000$ EUR, q about 200 (regarding them as average values for our network). If p is in the order of 0.01 in our reference scenario above we get an average saving of about 130 EUR per year per transformer and of about 0.6 EUR per year per user.

4.1.2.2 Saving for DSO Stemming from Arbitrage on One Substation

The (DSO) goal of peak shaving and that (of the energy supplier) of buying electrical energy when it is less expensive (*arbitrage*) may be conflicting. For example, from Figure

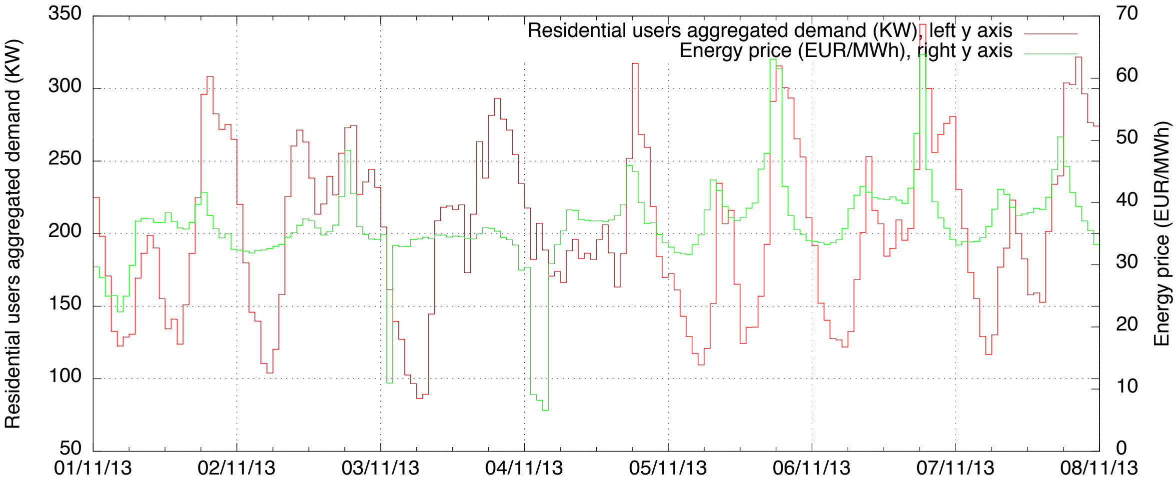

Figure 4.3: ELSPOT Energy prices day-ahead market vs. aggregated demand

4.3 we see that there are times when aggregated demand peaks are also cost peaks but there are also cases in which the latter peaks correspond to minimum in the cost function. Accordingly it is important to verify that the DAPP-H does not have a detrimental effect on energy cost. This is the goal of this section.

In this section, as well as in the following Sections 4.1.2.1–4.1.2.2, we evaluate the saving for the DSO in the Kalundborg scenario, when all residential users strictly follow their individualised price policy (for the case in which deviations from price policies are allowed, see Section 4.2). More in detail, in this section we focus on the saving stemming from arbitrage, i.e., buying energy when it costs less. To evaluate the economic saving stemming from arbitrage, we proceed as follows. We compare the energy cost (in EUR, using data from the day-ahead market ELSPOT [?]) for the DSO when:

1. the demand is obtained by aggregating (hour by hour) all historical demands of each residential user;
2. the demand is obtained by aggregating (hour by hour) all DAPP-H collaborative profiles.

The difference between the two values above is the economic saving stemming from arbitrage obtained by the DSO when using DAPP-H in the Kalundborg scenario. Figure 4.5 shows the values for such difference in the whole period of one year of the Kalundborg scenario. Namely, Figure 4.5 shows, on the x axis, the time-slots in the reference period for the Kalundborg scenario, and on the y axis the following two curves: i) the corresponding value for the difference defined above in the current time-slot ("current saving" curve); and ii) the corresponding value for the difference defined above, accumulated in all time-slots preceding the current one ("cumulative saving" curve).

Results from Figure 4.5 As a result, from Figure 4.5 we may note that the saving increases in most demanding periods (e.g., January) and decreases in less demanding periods (e.g., July). At the end of the reference period, we have that, in the Kalundborg scenario, the economic saving for DSO stemming from arbitrage is 160 EUR/year.

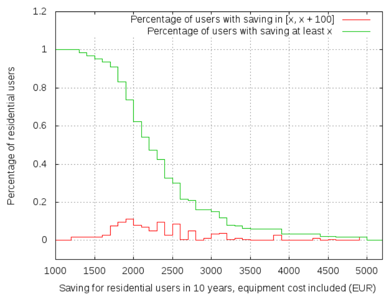

Figure 4.4: DAPP-H economic evaluation: frequency distribution of the saving for residential users (in EUR), including equipment cost amortisation. See Section 4.1.1.3.

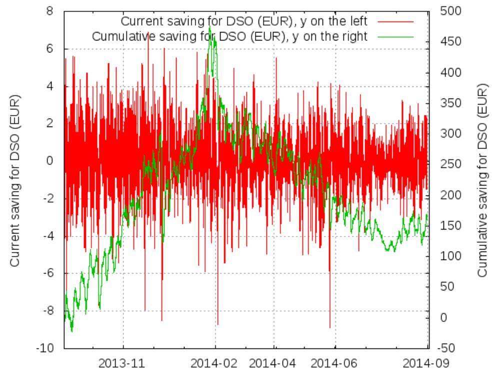

Figure 4.5: DAPP-H economic evaluation: saving for DSO stemming from arbitrage on a single substation. See Section 4.1.2.2.

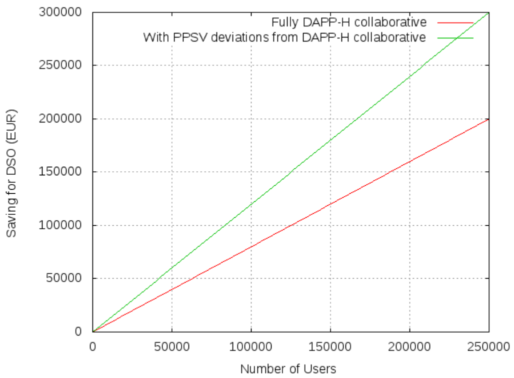

Figure 4.6: DAPP-H economic evaluation: saving for DSO stemming from arbitrage on the entire EDN. See Section 4.1.2.3.

4.1.2.3 Saving for DSO Stemming from Arbitrage on a Whole EDN

The evaluation shown in Section 4.1.2.2 applies to the only one substation in the Kalundborg scenario. In order to estimate the saving for the DSO stemming from arbitrage on an entire EDN, when residential users always follow the DAPP-H price policies, we proceed as follows. Since there are 186 residential users connected to the substation in the Kalundborg reference scenario (see Table 3.1), and since the saving for DSO stemming from arbitrage is 160 EUR/year (see Section 4.1.2.2), we have that the such saving is $\frac{160}{186} \approx 0.8$ EUR/year per residential user. This allows us to graph, in Figure 4.6 (namely in curve "Fully DAPP-H Collaborative"), the saving for the DSO stemming from arbitrage, estimated on the whole EDN, in the Kalundborg scenario, as a function of the number of users in the EDN itself.

Results from Figure 4.6 As a result, if we conservatively assume that there are 200000 residential users in the EDN, we have that the economic saving on the whole EDN stemming from arbitrage is about 160000 EUR/year.

4.2 Economic Evaluation of the PPSV Service

In this section we show how results from PPSV service, when run as described in Table 3.6 and in Section 3.2.2.2, may be used to evaluate the DAPP-H service from the DSO economic perspective in the Kalundborg reference scenario. Namely, differently from Section 4.1, where residential users are assumed to exactly follow their individualised price policies, in this section we consider probabilistic deviations from such policies. We recall that we refer to DAPP-H collaborative profiles disturbed by the PPSV disturbance model as *PPSV profile* (see Table 3.6). The evaluation is split in two cases:

- we evaluate the saving stemming from T&D investment deferral (Section 4.2.1), by using the safety evaluation version of PPSV;
- we evaluate the saving stemming from arbitrage (Section 4.2.2), by using the economic evaluation version of PPSV.

We organise part of the outputs of PPSV (with the inputs described in Table 3.6) in Figures 4.7 and 4.8, which we discuss in the following Sections 4.2.1 and 4.2.3 (one section for each figure). Moreover, a summary of the main results for PPSV economic evaluation is presented in Table 4.2.

Table 4.2: Main results for PPSV economic evaluation in the Kalundborg reference scenario (see Table 3.6 for PPSV inputs). The economic saving reported here refer to the scenario in which DAPP-H schema is used, but users may deviate from their individualised price policies.

Figure	**Result**
Figure 4.7	The saving for the DSO stemming from T&D investment deferral is about 0.6 EUR per year per user (e.g., if 200,000 users adopt DAPP-H but may deviate from individualised price policies, we have, on average, a saving of 120,000 EUR per year).
Figure 4.8	The saving for the DSO stemming from arbitrage is about 1.2 EUR/year per residential user .
Figure 4.6	As an example, the saving for the DSO stemming from arbitrage, estimated on the whole EDN, is about 240,000 EUR/year, if we assume that 200,000 residential users in the EDN adopt DAPP-H but may deviate from individualised price policies.

4.2.1 Saving Stemming from T&D Investment Deferral

In this section we focus on the saving for the DSO, when residential users follow the PPSV profiles (see Table 3.6), stemming from T&D investment deferral, i.e., improve lifetime of EDN substations, thus saving money for maintenance and replacement. To evaluate such saving, analogously to Section 4.1.2.1, we proceed as follows. First of all, we show that DAPP-H allows DSOs to keep the EDN substations under ideal loading with a high probability, if residential users follow the PPSV profiles. To this aim, Figure 4.7 shows, by concatenating the outputs of PPSV when used to directly check DAPP-H on a day-by-day basis (safety evaluation version of PPSV), the probability that the aggregated demand at the substation level exceeds the given threshold for ideal substation loading (360 kW,

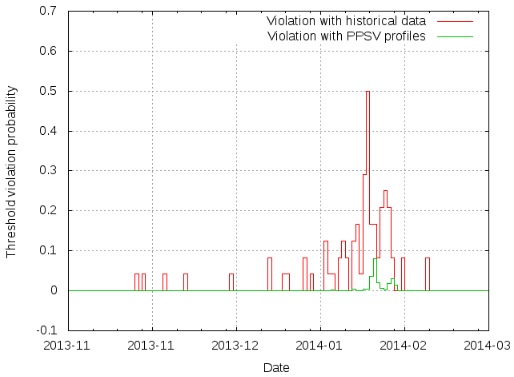

Figure 4.7: PPSV economic evaluation: substation ideal loading threshold violation probability when residential users follow the PPSV profiles (from safety evaluation version of PPSV). See Section 4.2.1.

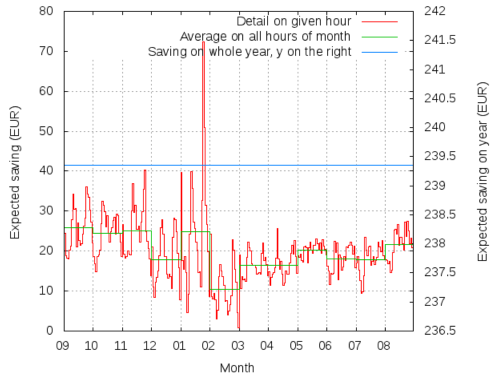

Figure 4.8: PPSV economic evaluation: expected saving for the DSO stemming from arbitrage when residential users follow the PPSV profiles (from economic evaluation version of PPSV). See Section 4.2.2.

i.e., 80% of substation nominal power), when users follow the PPSV profiles. For the sake of comparison, Figure 4.7 also shows ("historical data" curve) the fraction of the day in which the aggregated demand from input data is exceeding the same threshold. For both curves, Figure 4.7 restricts the x axis to the cold months only (from November to March), since the probability of exceeding the threshold is 0 in the other periods of the year. As a result, the frequency of threshold violation w.r.t. the cold months in historical data is 2.3%. PPSV output shows that the probability of threshold violation with DAPP-H price policies is 0.15%, more than 15 times smaller. This allows us to state that DAPP-H allows the DSO to use the substation feeder in the Kalundborg reference scenario under ideal conditions, also in case of residential users deviations from their price policies.

Results from Figure 4.7 As a result, the economic saving for the DSO is is about 0.6 EUR per year per residential user as in Section 4.1.2.

4.2.2 Saving Stemming from Arbitrage in One Substation

In this section we focus on the saving for the DSO, when residential users follow the PPSV profiles (see Table 3.6), stemming from arbitrage, i.e., to buy energy when it costs less. To this aim, Figure 4.8 shows the final expected saving on the whole one year period ("Expected saving on whole year" constant curve), together with the expected saving averaged on each month separately ("Average on all hours of month" curve) and on each hour of each month separately ("Detail on given hour" curve). In order to build Figure 4.8, we exploit the fact that the economic evaluation version of PPSV is able to output a probability distribution for the aggregated demand for each hour of the day (i.e., 24 probability distributions, see Table 3.6). This allows us to use the hourly-based ELSPOT energy market prices for energy (see again Table 3.7).

Results from Figure 4.8 As a result, the expected saving stemming from arbitrage in the whole reference year is about 240 EUR/year.

4.2.3 Saving Stemming from Arbitrage on a Whole EDN

The evaluation shown in Section 4.2.2 applies to the substation in the Kalundborg scenario. In order to estimate the saving for the DSO stemming from arbitrage on an entire EDN, when residential users follow the PPSV profiles, we proceed as follows. Since there are 186 residential users connected to the substation in the Kalundborg reference scenario (see Table 3.1), and since the saving for DSO stemming from arbitrage is 240 EUR/year (see Section 4.1.2.2), we have that such saving is approximately $\frac{240}{186} \approx 1.2$ EUR/year per residential user. This allows us to graph, in Figure 4.6 (namely in curve "With PPSV deviations from DAPP-H collaborative") the saving stemming from arbitrage, estimated on the whole EDN, for the DSO in the Kalundborg scenario (when residential users follow the PPSV profiles), as a function of the number of users in the EDN.

Results from Figure 4.6 As a result, if we conservatively assume that there are 200,000 residential users in the EDN, we have that the economic saving stemming from arbitrage is about 240,000 EUR/year.

4.3 Economic Evaluation of the DAPP-K Service

In this section we evaluate the DAPP-K service from the economic perspective, on the Kalundborg reference scenario. To this aim, we will use the outputs of DAPP-K when run as described in Table 3.10 and in Section 3.2.2.4. Since DAPP-K is a service for DSOs, and since it aims at satisfying residential users demand as it is (by suitably controlling an ESS installed on a given EDN substation), the economic evaluation of DAPP-K will be carried out by estimating the saving for the DSO in the Kalundborg scenario (see Table 3.1). In fact, differently from DAPP-H, residential users are not aware of DAPP-K (as they do not have to follow individualised price policies), thus an economic evaluation from residential users perspective is not needed. Moreover, w.r.t. the economic evaluation of the DAPP-H service from DSO perspective in Section 4.1.2: i) we do not need to show that residential users demand is not compressed (since the residential users demand is satisfied as it is) and ii) there is no saving for T&D investment deferral, as the substation is not kept under ideal loading.

Thus, to evaluate the DAPP-K service from the DSO economic perspective we compute the economic saving stemming from arbitrage (i.e., to buy energy when it costs less), which is the main goal of DAPP-K. To this aim, we organise part of the outputs of DAPP-K (with the inputs described in Table 3.10) in Figures 4.9–4.12, which we discuss in the following Sections 4.3.1–4.3.4. Moreover, a summary of the main results for DAPP-K economic evaluation is presented in Table 4.3. Finally, we recall that the optimality of the actions decided by DAPP-K (i.e., how much DAPP-K depends on a "good" forecast of aggregated power demand from Energy Usage Modelling and Forecasting for Control (EUMF-K)) is discussed in Section 3.3.2.2.

Table 4.3: Main results for DAPP-K economic evaluation in the Kalundborg reference scenario (see Table 3.10 for DAPP-K inputs).

Figure	**Result**
Figure 4.9	The saving after one year for the DSO is between 370 and 1510 EUR/year if an ESS with capacity between 200 and 1000 kWh is used. Such saving are currently not enough to cover ESS costs after 5 years (half of ESS lifetime) of DAPP-K user.
Figure 4.10	If we focus on an ESS with capacity 500 kWh and 80 kW, the average (i.e., obtained using average InterQuartile Range (IQR) costs for the ESS, see Table 3.3) trend factor at 5 years is $k = 15.3$. That is, the ratio between the battery cost and the saving should decrease by 15.3 times in order to have a break even point at 5 years. Such value for k is obtained with a Lead–Acid battery. As an example of a trend scenario in which $k = 15.3$, the energy costs gap may increase by 250% and battery costs may decrease of 340%.
Figure 4.11	With a Lead–Acid battery of capacity 500 kWh and power rate 80 kW, and assuming a trend factor $k = 15.3$, the saving for the DSO after 10 years, including battery cost amortisation, is 62,000 EUR.
Figure 4.12	If we conservatively assume that the DSO installs a 500 kWh-80kW Lead–Acid battery and DAPP-K on 100 substations with 100 residential users each, then the overall saving (assuming a trend factor $k = 15.3$) for the DSO in the Kalundborg reference scenario is 3,300,000 EUR after 10 years.

4.3.1 Saving Disregarding Equipment Cost

In this section we evaluate the saving for the DSO stemming from arbitrage when using DAPP-K in the Kalundborg scenario, ignoring the fact that DSO will need to buy and install an ESS on the substation. In the following Sections 4.3.2–4.3.4 this assumption will be removed.

In order to compute the saving defined above, we suitably adapt the evaluation of the saving stemming for the DSO stemming from arbitrage when using DAPP-H (see Sections 4.1.2.2 and 4.1.2.3). That is, we compute the saving by comparing the cost of energy for the DSO when DAPP-K is used and when DAPP-K is not used. Such saving is shown, for capacities from 200 to 1000 kWh, in Figure 4.9. As a result, Figures 4.9 shows that the saving is between 370 and 1510 EUR/year.

4.3.2 Equipment Cost Estimation

Differently from the DSO economic evaluation of DAPP-H in Section 4.1.2, and analogously to the residential users economic evaluation of DAPP-H in Section 4.1.1, part of the final saving shown in Figure 4.9 must be used to cover the cost of the ESS equipment for the substation. As a result, given the current prices for the batteries we consider in this evaluation (see Table 3.3), it is not currently convenient for DSOs to use DAPP-K. However, since future trends suggest that ESSs cost will decrease [?, ?, ?], whilst difference between peak and non-peak cost of energy will increase [?, ?, ?], we may perform the following evaluation. Let saving(Q, R) be the saving for the DSO (as shown in Figure 4.9) and battery_cost(Q, R) be the cost for the ESS (computed using data from Table 3.3) when the ESS capacity is Q kWh and the ESS power rate is R kW. If we assume that the saving in different years does not significantly vary, then we have that, in order to cover the ESS cost in years years, the following must hold:

$$k * \mathit{years} * \text{saving}(Q, R) = \text{battery\_cost}(Q, R) \tag{4.1}$$

Here, the parameter k is the "trend factor", telling us how much the ratio between the battery cost and the saving for the DSO should decrease in order to have a break even point in *years* years (i.e., to cover the cost of the ESS in years years). In other words, for any pair $k_e, k_b > 1$ s.t. $k_e k_b = k$, we have that k_e may be interpreted as how much the saving for the DSO should increase (e.g., because the gap between low energy costs at non-peak hour and high energy costs at peak hours increases) in order to have a break even point at y years, whilst k_b may be interpreted as how much the battery cost should decrease for the same goal.

Figure 4.10 shows the values of the trend factor k computed as above, for $Q \geq 200$ kWh and $R = 80$ kW, by using the minimum IQR costs in Table 3.3 and assuming to recover the ESS cost in 5 years (i.e., approximately half of the average ESS lifetime from Table 3.3). Namely, Figure 4.10 shows, on the x axis, the capacities from 200 kWh to 1000 kWh, and on the y axis the values for the trend factor k when the power rate is 80 kW. Note that five curves are shown, one for each battery type (which corresponds to different battery costs) in Table 3.3.

Results from Figure 4.10 As a result, from Figure 4.10 we may see that the least values for the trend factor k are obtained with a Lead–Acid battery. For $Q = 500$ kWh, we have that $k = 15.3$ with a Lead–Acid battery. As an example of a trend scenario in which $k = 15.3$, we may say that, if energy costs gap increases by 250% (i.e., $k_e = 3.5$) and battery costs decrease of 340% (i.e., $k_b = 4.4$), then the 500 kWh – 80 kW Lead–Acid average battery cost (i.e., approximately 22,000 EUR) is covered in 5 years.

4.3.3 Saving Considering Equipment Cost on One Substation

Once the trend factor k defined in Section 4.3.2 is known for 5 years (see Section 4.3.2), the saving for the DSO, when using DAPP-K for 10 years (i.e., approximately the average ESS lifetime from Table 3.3), is easily computed as $k * (10 - 5) * \text{saving}(Q, R)$, for any value of the ESS capacity Q and power rate R (see Equation (4.1). Figure 4.11 shows such saving, with the same assumptions of Figure 4.10.

Results from Figure 4.11 As a result, from Figure 4.11 we may see that, for $Q = 500$ kWh and with a Lead–Acid battery, and assuming a trend factor of 15.3 (see Section 4.3.2), the saving for the DSO after 10 years on the Kalundborg reference scenario, including battery cost amortisation, is 62,000 EUR.

4.3.4 Saving for DSO on a Whole EDN

The evaluation shown in Section 4.3.3 applies to the only one substation in the Kalundborg scenario. In order to estimate the saving for the DSO stemming from using DAPP-K on the entire Kalundborg EDN (i.e., installing an ESS on each EDN substation and using DAPP-K to control it), we proceed as follows. We assume that the saving computed above

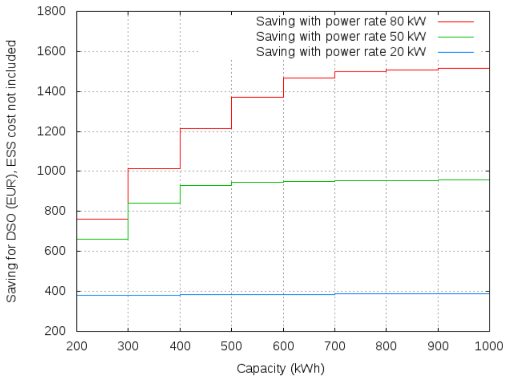

Figure 4.9: DAPP-K economic evaluation: saving for DSO, with ESSs with capacity at least 200 kWh. See Section 4.3.1.

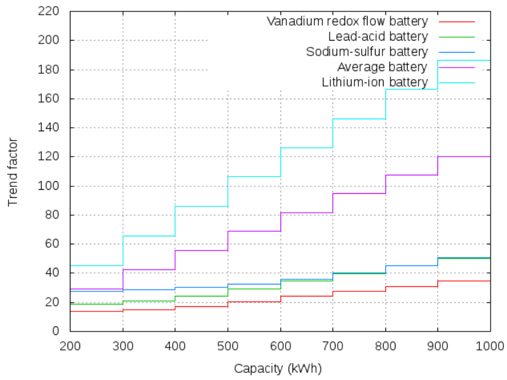

Figure 4.10: DAPP-K economic evaluation: trend factor k on 5 years for ESSs with capacity at least 200 kWh and power rate 80 kW, using the average IQR costs in Table 3.3. See Section 4.3.2.

on the Kalundborg scenario is proportional to the number of users connected to each EDN substation (substation_density in the following), and we recall that the substation in the Kalundborg scenario has density 186. Then, we may estimate the saving for the DSO on the whole EDN as $62000\frac{N * \text{substation\_density}}{186}$, being N the number of substations in the EDN on which the ESS and DAPP-K are installed. This allows us to graph in Figure 4.12 the overall saving (i.e., estimated on the whole EDN) for the DSO in the Kalundborg scenario, as a function of the number of residential users connected to the N substations on which DAPP-K is used.

Results from Figure 4.12 As a result, if we conservatively assume that the DSO installs a 500 kWh–80 kW Lead–Acid battery and DAPP-K on 100 substations with 100 residential users each, and assuming a trend factor of 15.3 (see Section 4.3.2), then the overall saving for the DSO in the Kalundborg reference scenario is 3,300,000 EUR after 10 years.

4.4 Economic Evaluation of the EBR Service

In this section we evaluate the EBR service from the economic perspective, on both the Kalundborg and the Central District reference scenarios. To this aim, we will use the outputs of EBR when run on the Home Energy Controlling Hub (HECH) of two users (one in the Kalundborg and one in the Central District scenarios) as described in Table 3.8 and in Section 3.2.2.3. Please note that energy tariffs used for this evaluation also accounts for energy distribution and taxes (see Table 3.2). Finally, we will compare results of EBR when run on the HECH and on the IMDEA Smart Energy Integration Lab (SEIL), in order to show feasibility of EBR when interacting with real power electronics.

In order to evaluate the EBR service from the residential users economic perspective, we proceed analogously to the economic evaluation of DAPP-K (see Section 4.3). That is, we compute the economic saving stemming from arbitrage (i.e., to buy energy when it costs less), in the following steps:

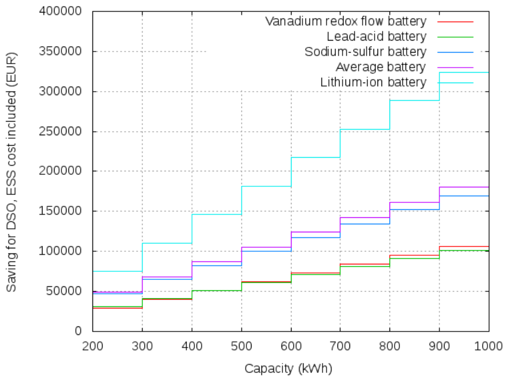

Figure 4.11: DAPP-K economic evaluation: saving for the DSO (also considering ESSs cost) on 10 years for ESSs with capacity at least 200 kWh and power rate 80 kW, using trend factor from Figure 4.10 and the minimum IQR costs in Table 3.3. See Section 4.3.3.

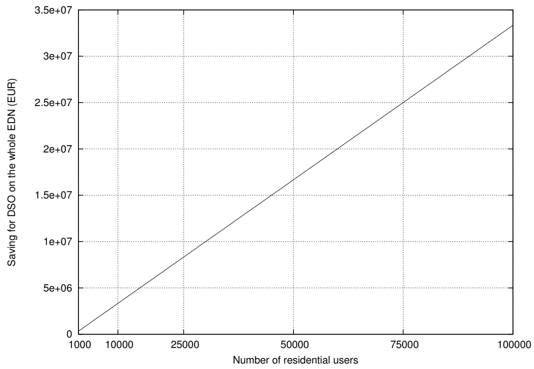

Figure 4.12: DAPP-K evaluation: saving for DSO on the entire EDN as a function of number of residential users per substation, if a 500 kWh ESS is installed on each substation. See Section 4.12.

1. Compute the saving disregarding equipment (i.e., ESS and power electronics) cost, by comparing user energy bills with and without usage of EBR. Results for Kalundborg user are shown in Figure 4.13.

2. Compute the trend factor needed to amortise the equipment cost within half of ESS lifetime (5 years). Results for Kalundborg users are in Figure 4.14.

3. Using the trend factor computed above, compute the saving after the whole ESS lifetime (10 years). Results for Kalundborg users are in Figure 4.15.

All main results, for both Kalundborg and Centrl District users, are summarised in Table 4.4.

Table 4.4: Main results for EBR economic evaluation in the Kalundborg and in the Central District reference scenarios (see Table 3.8 for EBR inputs). In the first column, "KAL" stands for the Kalundborg scenario, "CD" for the Central District scenario.

	Figure	**Result**
KAL		Differences in final saving, as computed from experiments on the HECH (software based simulation) and on the SEIL (micro grid based experiment), are at most 1.7%. This shows feasibility of EBR when interacting with real power electronics.
KAL	Figure 4.13	The Kalundborg user saves, after using EBR for one year and without considering the ESS cost, between 120 EUR (when EBR controls the 16-kWh PEV only) and 280 EUR (when EBR controls both a 9-kWh ESS and the 16-kWh PEV).
KAL	Figure 4.14	After 5 years (half of ESS lifetime) of EBR usage, the Kalundborg user may cover the cost of an ESS up to 3kWh, if such ESS is a Lead – Acid battery.

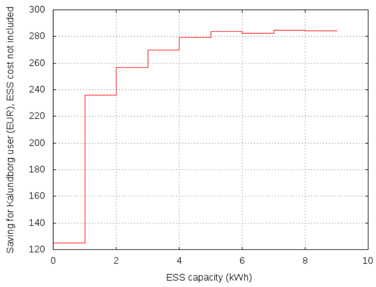

Figure 4.13: EBR economic evaluation: saving for the user in the Kalundborg scenario (DAPP-H tariff), by varying the ESS capacity (PEV capacity, as well as ESS and PEV power rates, is fixed). See Section 4.4.

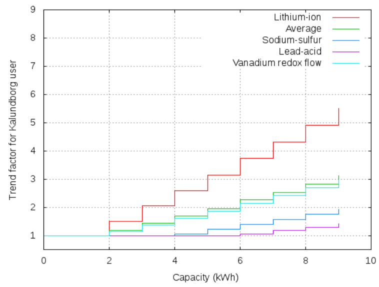

Figure 4.14: EBR economic evaluation: trend factor k on 5 years for the user in the Kalundborg scenario (DAPP-H tariff), by varying the ESS capacity (PEV capacity, as well as ESS and PEV power rates, is fixed) and using the average IQR costs in Table 3.3. See Section 4.4.

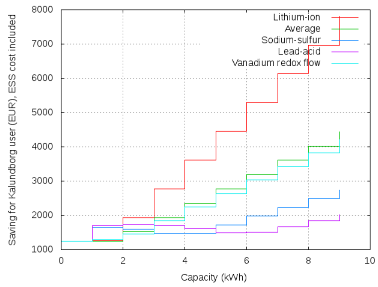

Figure 4.15: EBR economic evaluation: saving on 10 years (also considering ESSs cost) for the user in the Kalundborg scenario (DAPP-H tariff), by varying the ESS capacity (PEV capacity, as well as ESS and PEV power rates, is fixed), and using trend factor from Figure 4.14 and average IQR costs in Table 3.3. See Section 4.4.

Table 4.4: Main results for EBR economic evaluation in the Kalundborg and in the Central District reference scenarios (see Table 3.8 for EBR inputs). In the first column, "KAL" stands for the Kalundborg scenario, "CD" for the Central District scenario.

	Figure	**Result**
KAL	Figure 4.15	Using a Lead – Acid battery with 3 kWh of capacity and 2 kW of power rate (we recall that the PEV has a 16 kWh capacity and 13 kW power rate), the final saving for the Kalundborg user after 10 years of EBR usage, also considering the ESS cost, is 1,470 EUR.
CD		Differences in final saving, as computed from experiments on the HECH (program based-simulation) and on the SEIL (laboratory-based simulation), are at most 0.3%. This shows feasibility of EBR when interacting with real power electronics.
CD		The Central District user saves, after using EBR for one year and without considering the ESS cost, between 580 EUR (when EBR controls the 16-kWh PEV only) and 1,290 EUR (when EBR controls both a 4-kWh ESS and the 16-kWh PEV).
CD		After 5 years (half of ESS lifetime) of EBR usage, the Central District user may cover the cost of any battery up to 4kWh.
CD		Using a Lead – Acid battery with 4 kWh of capacity and 2 kW of power rate (we recall that the PEV has a 16 kWh capacity and 13 kW power rate), the final saving for the Central District user after 10 years of EBR usage, also considering the ESS cost, is 11,500 EUR.

Chapter 5

Environmental Evaluation of Control Loop Services

In this chapter we present the environmental evaluation of the SmartHG control loop services. Our evaluation will target CO_2 emissions from Electric Distribution Network (EDN) substations, thus we will only consider the control loop Grid Intelligent Automation Services (GIASs), namely Demand Aware Price Policies for Homes (DAPP-H) (Section 5.1), Price Policy Safety Verification (PPSV) (Section 5.2), and Demand Aware Price Policies for Substation-Level Energy Storage Control (DAPP-K) (Section 5.3), all in the Distribution System Operator (DSO)-oriented reference scenario. Moreover, the evaluation will only consider the DSO perspective. We however note that the Home Intelligent Automation Service (HIAS) control loop service Energy Bill Reduction (EBR), though not mentioned in this section, is needed for enforcing ideal loading on substations when using DAPP-H, and thus in obtaining the environmental results presented for DAPP-H.

5.1 Environmental Evaluation of the DAPP-H Service

The goal of peak shaving and that of reducing CO_2 emissions may be conflicting. For example, from Figure 5.1 we see that there are times when aggregated demand peaks are also CO_2 emission peaks, but there are also cases in which the latter peaks correspond to minimum in the cost function. Accordingly it is important to verify that the DAPP-H does not have a detrimental effect on CO_2 emissions. Analysing the environmental effect of peak shaving due to DAPP-H is the goal of this section.

In order to evaluate the DAPP-H service from the environmental perspective, when run in the Kalundborg scenario as described in Table 3.4 and in Section 3.2.2.1, we proceed as follows. Our goal is to show that, if all residential users follow their individualised price policy (i.e., if they follow the DAPP-H collaborative profile computed by DAPP-H, see Table 3.4), then there is a reduction in CO_2 emissions, thus obtaining an environmental gain by using DAPP-H.

To this aim, we organise part of the outputs of DAPP-H (with the inputs described in Table 3.4) in Figure 5.2, which we discuss in the following. A summary of the main results for DAPP-H environmental evaluation is presented in Table 5.1.

CO_2 Emissions Reduction on One Substation First of all, we evaluate the CO_2 reduction in the Kalundborg scenario, when all residential users strictly follow their individualised price policy (for the case in which deviations from price policies are allowed, see

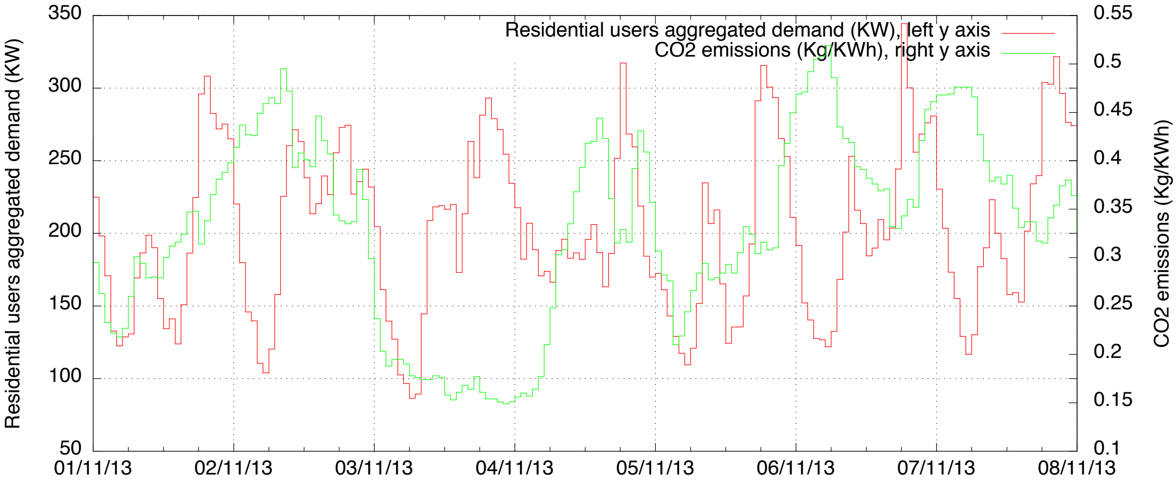

Figure 5.1: CO_2 emissions vs. aggregated demand.

Table 5.1: Main results for DAPP-H environmental evaluation in the Kalundborg reference scenario (see Table 3.4 for DAPP-H inputs).

Result
At the end of the reference period in the Kalundborg scenario, we have that the CO_2 emissions reduction is 940 kg/year, i.e., 5.05 kg/year per residential user.
If we conservatively assume that there are 200,000 residential users in the EDN, we have that the overall CO_2 emissions reduction on the whole EDN is about 1,000,000 kg/year (see Figure 5.2).

Section 5.2). To this aim, we exploit the fact that SEAS provided the SmartHG consortium with hour-by-hour data for CO_2 emissions per energy demand (in kg/kWh) on the whole reference period. Thus, analogously to the arbitrage economic gain computation for DAPP-H shown in Section 4.1.2.2, we compute the environmental gain by comparing the CO_2 emissions when DAPP-H is used and when DAPP-H is not used. As a result, at the end of the reference period in the Kalundborg scenario, we have that the CO_2 emissions reduction is 940 kg/year.

Figure 5.2: CO_2 Emissions Reduction on a Whole EDN The evaluation shown above applies to the only one substation in the Kalundborg scenario. In order to estimate the CO_2 emission reduction for the DSO on an entire EDN, we proceed as follows. Since there are 186 residential users connected to the substation in the Kalundborg reference scenario, we have that the CO_2 emissions reduction is $\frac{940}{186} \approx 5.05$ kg/year per residential user. This allows us to graph, in Figure 4.6 (namely in curve "Fully DAPP-H Collaborative") the CO_2 emissions reduction, estimated on the whole EDN, in the Kalundborg scenario, as a function of the number of users in the EDN itself.

Results from Figure 5.2 As a result, if we conservatively assume that there are 200,000 residential users in the EDN, we have that the overall CO_2 emissions reduction on the whole EDN is about 1,000,000 kg/year.

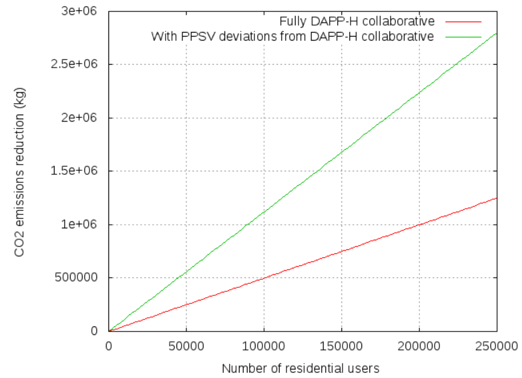

Figure 5.2: DAPP-H and PPSV environmental evaluation: CO_2 emissions reduction on a whole EDN as a function of the number of residential users. See Sections 5.3 and 5.2.

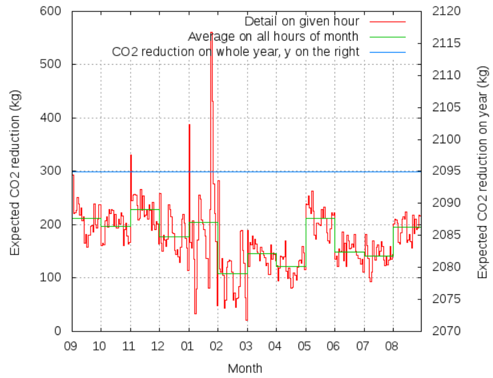

Figure 5.3: PPSV environmental evaluation: expected CO_2 emissions reduction, when residential users follow the PPSV profiles (from economic evaluation version of PPSV). See Section 5.2.

Table 5.2: Main results for PPSV environmental evaluation in the Kalundborg reference scenario (see Table 3.6 for PPSV inputs). The environmental CO_2 reductions reported here refer to the scenario in which DAPP-H schema is used, but users may deviate from their individualised price policies.

Figure	**Result**
Figure 5.3	The expected CO_2 emissions reduction in the whole reference year is about 2,090 kg/year, i.e., 11.2 kg/year per residential user.
Figure 5.2	If we conservatively assume that there are 200,000 residential users in the EDN, we have that the CO_2 emissions reduction is about 2,240,000 kg/year.

5.2 Environmental Evaluation of the PPSV Service

In this section we show how results from PPSV service, when run as described in Table 3.6 and in Section 3.2.2.2, may be used to evaluate the DAPP-H service from the environmental perspective in the Kalundborg reference scenario. Namely, differently from Section 5.1, where residential users are assumed to exactly follow their individualised price policies, in this section we consider probabilistic deviations from such policies (analogously to the economic evaluation presented in Section 4.2). We recall that we refer to DAPP-H collaborative profiles disturbed by the PPSV disturbance model as *PPSV profile* (see Table 3.6).

In order to evaluate the PPSV service from the environmental perspective, We organise part of the outputs of PPSV (with the inputs described in Table 3.6) in Figures 5.3 and 5.2, which we discuss in the following. Finally, a summary of the main results for PPSV economic evaluation is presented in Table 5.2.

Figure 5.3: CO_2 Emissions Reduction on One Substation In this section we show how results from PPSV service may be used to evaluate the environmental gain of DAPP-H from the DSO perspective on the DSO-oriented reference scenario. Namely, differently from Section 5.1, where residential users are assumed to exactly follow their individualised price policies, in this section we consider probabilistic deviations from such policies. Namely, our goal is to show that, even if residential users are allowed to deviate

from their individualised price policy then there is a reduction in CO_2 emissions, thus obtaining an environmental gain by using DAPP-H on the DSO-oriented scenario. To this aim, Figure 5.3 shows the final expected CO_2 emissions reduction on the whole one year period. Note that this is the analogous of Figure 4.8 in Section 4.2, but using the CO_2 emissions per consumed energy (in EUR/kg) instead of the ELSPOT energy cost (in EUR/kWh).

Results from Figure 5.3 As a result, the expected CO_2 emissions reduction in the whole reference year is about 2,090 kg/year.

Figure 5.2: CO_2 Emissions Reduction on a Whole EDN The evaluation shown above applies to the only one substation in the Kalundborg scenario. In order to estimate the CO_2 emissions reduction for the DSO on an entire EDN, when residential users follow the PPSV profiles, we proceed as follows. Since there are 186 residential users connected to the substation in the Kalundborg reference scenario (see Table 3.1), and since the CO_2 emissions reduction is 2,090 kg/year (see Figure 5.3), we have that such reduction is approximately $\frac{2090}{186} \approx 11.2$ kg/year per residential user. This allows us to graph, in Figure 5.2 (namely in curve "With PPSV deviations from DAPP-H collaborative") the CO_2 emissions reduction, estimated on the whole EDN, in the Kalundborg scenario (when residential users follow the PPSV profiles), as a function of the number of users in the EDN.

Results from Figure 5.2 As a result, if we conservatively assume that there are 200,000 residential users in the EDN, we have that the CO_2 emissions reduction is about 2,240,000 kg/year.

5.3 Environmental Evaluation of the DAPP-K Service

In this section we evaluate the DAPP-K service from the environmental perspective, on the Kalundborg reference scenario. To this aim, we will use the outputs of DAPP-K when run as described in Table 3.10 and in Section 3.2.2.4. To this aim, our goal is to show that, if an Energy Storage System (ESS) controlled by DAPP-K is installed on the substation in the Kalundborg scenario (see Table 3.1), then there is a reduction in CO_2 emissions, thus obtaining an environmental gain by using DAPP-K.

To this aim, we organise part of the outputs of DAPP-K (with the inputs described in Table 3.10) in Figure 5.4, which we discuss in the following. A summary of the main results for DAPP-K environmental evaluation is presented in Table 5.3.

CO_2 Emissions Reduction on One Substation First of all, we evaluate the CO_2 emissions reduction when using DAPP-K in the Kalundborg scenario. To this aim, as we have done in Section 5.1 for the environmental evaluation of DAPP-H, we exploit the fact that SEAS provided the SmartHG consortium with hour-by-hour data for CO_2 emissions per energy demand (in kg/kWh) on the whole reference period. Thus, analogously to the economic evaluation of DAPP-K described in Section 4.3.1, we compute the environmental gain by comparing the CO_2 emissions when DAPP-K is used and when DAPP-K is not used. As a result, if we focus on the same Lead–Acid battery with capacity 500kWh and

Table 5.3: Main results for DAPP-K environmental evaluation in the Kalundborg reference scenario (see Table 3.10 for DAPP-K inputs).

Result
If we focus on the same Lead–Acid battery with capacity 500kWh and power rate 80 kW used in Section 4.3, the DSO may obtain a CO_2 emissions reduction of 1,360 kg/year when using DAPP-K in the Kalundborg reference scenario.
If we conservatively assume that the DSO installs a 500 kWh–80 kW Lead–Acid battery and DAPP-K on 100 substations with 100 residential users each as in Section 4.3, then the overall CO_2 emissions reduction in the Kalundborg reference scenario is 73,000 kg/year (see Figure 5.4).

power rate 80 kW used in Section 4.3, the DSO may obtain a CO_2 emissions reduction of 1,360 kg/year when using DAPP-K in the Kalundborg reference scenario.

Figure 5.4: CO_2 Emissions Reduction on a Whole EDN The evaluation shown above applies to the only one substation in the Kalundborg scenario. In order to estimate the CO_2 reduction when using DAPP-K on the entire Kalundborg EDN (i.e., installing an ESS on each EDN substation and using DAPP-K to control it), we proceed analogously to Section 4.3. Namely, we assume that the CO_2 emissions reduction computed above on the Kalundborg scenario is proportional to the number of residential users connected to each EDN substation (substation_density). Given this, we estimate the CO_2 emissions reduction on the whole Kalundborg EDN as $1360\frac{N*\text{substation\_density}}{186}$, being N the number of substations in the EDN on which the ESS and DAPP-K are installed. This allows us to graph, in Figure 5.4, the CO_2 emissions reduction estimated on the whole EDN in the Kalundborg scenario, as a function of the number of residential users connected to the N substations on which DAPP-K is used.

Results from Figure 5.4 As a result, if we conservatively assume that the DSO installs a 500 kWh–80 kW Lead–Acid battery and DAPP-K on 100 substations with 100 residential users each as in Section 4.3, then the overall CO_2 emissions reduction in the Kalundborg reference scenario is 73,000 kg/year.

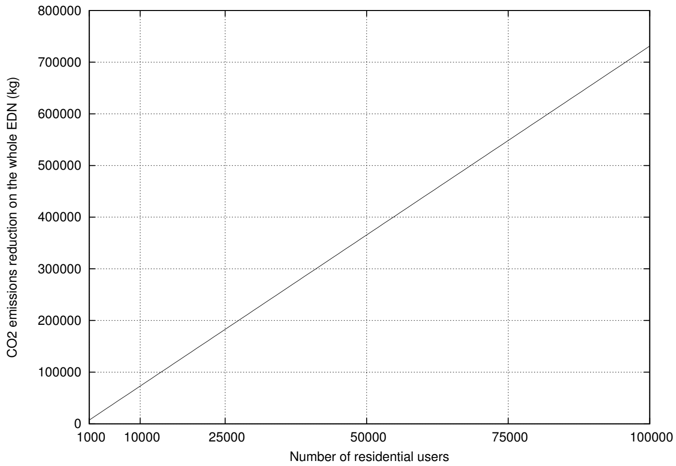

Figure 5.4: DAPP-K environmental evaluation: CO_2 emissions reduction on the whole EDN as a function of number of residential users per substation, assuming that all substations are equipped with a Lead–Acid battery having capacity 500 kWh and power rate 80 kW. See Section 5.3.

Chapter 6

Conclusions

In this deliverable we have evaluated the second year version of all SmartHG Intelligent Automation Services (IASs). As a first step, all services have been evaluated from a technical point of view. This resulted in concluding that they have been correctly designed and implemented (the description of such phases is in D3.2.1, D3.2.2, D4.2.1 and D4.2.2). Then, for the control loop services, which are devoted to collect information from other SmartHG services and propose actions to residential homes and/or the grid itself (namely Demand Aware Price Policies for Homes (DAPP-H), Price Policy Safety Verification (PPSV), Demand Aware Price Policies for Substation-Level Energy Storage Control (DAPP-K) and Energy Bill Reduction (EBR)), we presented an economic and an environmental evaluation. This allowed us to show that such SmartHG services are indeed *economically viable*, which is one of the main goals of the SmartHG project. We point out that, since all other SmartHG services (namely, Energy Usage Reduction for Homes (EUR-H), Energy Usage Modelling and Forecasting for Homes (EUMF-H), Energy Usage Reduction for Control (EUR-K), Energy Usage Modelling and Forecasting for Control (EUMF-K), EDN Virtual Tomography (EVT) and Database and Analytics (DB&A)) are needed by the control loop services in order to provide the economic and environmental results described in this document, this entails that all SmartHG IASs are economically viable.

This section is divided in two parts. First of all, in Section 6.1 we compare this year iteration of the SmartHG services evaluation with the first year iteration. Then, in Section 6.2 we discuss the limitations of this year iteration of the SmartHG services evaluation and, for each of such limitations, we outline the foreseen work to be done in the third year evaluation.

6.1 Advancements

In this section we outline the main advancements of our second year evaluation of SmartHG services w.r.t. our first year iteration.

Reference scenarios: First, we considered homes from *Central District (Israel)* test-bed. Second, we considered *all* homes connected to our Kalundborg substation feeder. Third, by adding to the above data those about Plug-in Electric Vehicle (PEV) usage from Danish project "Test-An-EV", we *virtually* equipped all homes in our the test-beds with a PEV.

DB&A: We tested the new authentication features of DB&A as well as all of its new Application Programming Interfaces (APIs).

DAPP-H: In the second year we model *user flexibility* as energy storage capability. Accordingly, we also considered Energy Storage System (ESS) cost when computing money saving for residential users. Furthermore, as for Kalundborg test-bed on the energy supply side, we also evaluated the impact of DAPP-H on *arbitrage* (using day-ahead market ELSPOT [?] data) and Danish CO_2 emissions due to electricity production (using data from SEAS-NVE).

PPSV: This year PPSV has been extended in order to support a one hour time resolution. Such an extension enabled our second year detailed robustness analysis of SmartHG control loop services from the safety, economic and environmental point of views. Finally, we evaluated effectiveness of communication between PPSV and EVT.

DAPP-K: Since the DAPP-K service has been developed this year, its evaluation is only present this year.

EBR: Second year EBR is a controller (running on the Home Energy Controlling Hub (HECH)) managing home ESS and PEV recharging (first year EBR was just a planner for home appliances). We evaluated our second year EBR at IMDEA Smart Energy Integration Lab (SEIL) using test-bed sensor data to drive SEIL electronics load and generators and PEV data to drive SEIL batteries.

EVT: This is the first evaluation of the EVT by using the real network data. The service successfully produced warnings, alarms and recommendations as defined in the original specifications and according to different test scenarios used. In order to test some warning and alarm signals (not triggered during the network normal operation) heavy loading at certain network points was applied.

EUR-H, EUMF-H: This year version of these two services present a unified interface, whilst it consisted in two separate interfaces in the first year. This year evaluation has been changed accordingly and carried out using historical data from Minsk test bed.

EUR-K: Since the EUR-K service has been developed this year, the evaluation of EUR-K is only present in this year evaluation.

EUMF-K: Since the EUMF-K service has been developed this year, the evaluation of EUMF-K is only present in this year evaluation.

6.2 Limitations and Future Work

Table 6.1 outlines the main limitations of SmartHG second year evaluation and identify future works to overcome them.

Table 6.1: Limitations for the second year evaluation & how we plan to overcome such limitations in the third year evaluation.

Topic/IAS	**Limitations of second year**	**Future work for third year**
Minsk test-bed	Because of the shipping problems we had with Belarus customs, this year only historical data from Minsk test-bed have been used (in EUR-H and EUMF-H evaluation).	We have already solved this problem by deploying a new test-bed in Central District (Israel). If data from Minsk will be available by the summer 2015 we will use them in our third year evaluation, otherwise only historical data will be used from Minsk test-bed.
Central District test-bed	Our present evaluation only uses one of the homes in Central District test-bed.	Third year evaluation will use data from all homes in Central District test-bed.
Kalundborg test-bed	Our present evaluation only focuses on one of the feeders of Kalundborg substation.	Data from another feeder of Kalundborg substation has already been collected. We will use such data in the third year evaluation of the control loop services.
IMDEA micro-grid	Because of the limited capacity of the ESS available at IMDEA SEIL micro grid we could not evaluate DAPP-K there.	In the third year we will investigate methods to automatically downscale batteries usage, so that we may evaluate DAPP-K at SEIL.
DAPP-H	This year evaluation of DAPP-H has been focused only on one substation in the Kalundborg test-bed.	We plan to evaluate the third year version of DAPP-H also on Feeder 3 of substation 30378 in Kalundborg.
DAPP-H	While second year *flexibility* provides a quantitative measure for users to evaluate the *contract* they are making when accepting the DAPP-H service, we note that it is still a notion not easy to grasp for most users.	Accordingly, a version of DAPP-H enabling the Distribution System Operator (DSO) to offer a clear, easily verifiable contract about energy prices to the residential user would be an important step towards bringing DAPP-H to the market.
PPSV	We evaluate economic gain by running PPSV to estimate the probability distribution of the aggregated demand at each hour of the day, averaging on one month. As a consequence, the output of PPSV has a non-negligible variance.	In the third year we will investigate methods to decrease such a variance, for example by running PPSV once a day (and solving the computational problems that this would entail).
DAPP-K	The evaluation of DAPP-K is not performed on the SEIL micro grid. This is due to the limited capacities of the ESS available in SEIL.	We plan to investigate methods to automatically downscale batteries usage, so that we may evaluate DAPP-K using SEIL.

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Table 6.1 – continued from previous page

Topic/IAS	Limitations of second year	Future work for third year
DAPP-K	The evaluation of DAPP-K has been performed on one substation only.	We plan to evaluate the third year version of DAPP-K also on the feeder 3 of substation 30378 in Kalundborg, as well as on a substation in Minsk.
EBR	It was not possible to evaluate EBR directly on the HECH of an actual home, as there are currently no homes with either PEV or battery.	It is not in the project plans to provide an home with a PEV and/or a battery. However, it is foreseen that the third year version of EBR will address thermal energy storage, by exploiting results from EUR-K. Accordingly, we plan to evaluate the third year version of EBR using with Develco actuators for heat pumps.
EBR	We evaluated EBR running on a Raspberry Pi (HECH hardware platform) connected to a home simulator and by running EBR on the computers controlling IMDEA SEIL electronics loads and batteries. This allows us to evaluate EBR effectiveness as home electrical energy manager, however does not allow us to test communication between home devices (i.e., IMDEA SEIL electronics loads and batteries) and EBR.	In the third year we plan to install a HECH at the IMDEA SEIL and actuate SEIL loads, generators and batteries through the HECH. This will allow us to evaluate also the communication aspects between HECH and home devices.
EUR-K	The evaluation of EUR-K has been performed on 7 homes from the Kalundborg test-bed.	We plan to evaluate the third year version of EUR-K also on Central District homes, possibly considering the *cooling* operation mode.
EUR-K	The evaluation of EUR-K does not address the issue of exploiting home thermal capacity for energy storage and does not quantify the trade-offs between the available user options: do nothing (since energy savings do not pay for home retrofitting), buy a heat pump with better Coefficient of Performance (COP), retrofit by improving home thermal insulation.	We plan to perform such an economic evaluation in the third year.

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Table 6.1 – continued from previous page

Topic/IAS	Limitations of second year	Future work for third year
EUMF-K	The evaluation of EUMF-K has been performed on two homes, one from the Kalundborg test-bed and one from the Central District test-bed.	We plan to evaluate the third year version of EUMF-K more homes from Kalundborg and Central District test beds.
EUR-H and EUMF-H	The evaluation of EUR-H and EUMF-H is currently limited only to historical data from Minsk test-bed.	We plan to evaluate EUR-H and EUMF-H on Kalundborg and the Central District scenarios too.