Small or medium-scale focused research project (STREP)

Energy Demand-Aware Open Services for Smart Grid Intelligent Automation

SmartHG

EU FP7 Project #317761

Deliverable D4.2.1

Second Year Design of Grid Intelligent Automation Services

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Participant Organization Name	Participant Short Name	Country
Sapienza University of Rome	UNIROMA1	Italy
Aarhus University	AU	Denmark
IMDEA Energía	IMDEA	Spain
A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus	HMTI	Belarus
ATANVO GmbH	ATANVO	Germany
Panoramic Power	PANPOW	Israel
Solintel	SOLINTEL	Spain
SEAS – NVE	SEAS	Denmark
Kalundborg Municipality	KAL	Denmark
Minskenergo	MINSKENG	Belarus
Develco Products A/S	DEVELCO	Denmark

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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.

Project coordinator	Enrico Tronci
E-mail	`tronci@di.uniroma1.it`

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

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AD Activity Diagram

API Application Programming Interface

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&A Database and Analytics

DBService Database Service

DG Distributed Generation

DLC Direct Load Control

DRLC Demand Response and Load Control

DR Demand Response

DSO Distribution System Operator

DSSE Distribution System State Estimation

EBR Energy Bill Reduction

EDN Electric Distribution Network

ESS Energy Storage System

EUMF Energy Usage Modelling and Forecasting

EUMF-K Energy Usage Modelling and Forecasting for Control

EVT EDN Virtual Tomography

GIAS Grid Intelligent Automation Service

GOA Grid Operator Agent

HIAS Home Intelligent Automation Service

IAS Intelligent Automation Service

LV Low Voltage

MILP Mixed-Integer Linear Programming

MV Medium Voltage

PPSV Price Policy Safety Verification

SaaS Software as a Service

SCADA Supervisory Control And Data Acquisition

SD Sequence diagram

SE State Estimation

SMC SmartHG Market Controller

SOA Service-Oriented Architecture

TSO Transmission System Operator

UC Use Case

UML Unified Modeling Language

Executive Summary

Objectives The main objective of the SmartHG project is to develop effective Intelligent Automation Services (IASs) to minimise users energy bill for end residential users while optimising operation on the grid for Distribution System Operators (DSOs). This deliverable describes the second year SmartHG activities in WP4, that focuses on the Grid Intelligent Automation Services (GIASs) that are those services working on the DSO side. Since GIASs output must be directly available to DSOs, we also design direct communication between GIASs and DSOs.

Retrospect In the first year iteration, we built a prototype version of all the services working on the DSO side. Namely, the service dependencies, outputs, and functional specifications were clearly defined. The Database and Analytics (DB&A) service works as a communication channel between IAS and IAS and between home devices and IASs. The Demand Aware Price Policies (DAPP) service goal is to compute individualised power profiles for residential users, aiming at reducing energy bill for residential users and at the same time at saving on Electric Distribution Network (EDN) substations maintenance for the DSO. The Price Policy Safety Verification (PPSV) service is tailored to check that EDN substations safety is retained also if residential users may slightly deviate from their individualised price policies. The EDN Virtual Tomography (EVT) service aims at estimating the state of the EDN where sensors are not available. As for communication between DSO and IASs, a common database and an open protocol were designed.

Achievements During the SmartHG second year, the DAPP, the DB&A and the PPSV services underwent a complete re-design. Namely, the DAPP service has been split in two different services, DAPP-H and DAPP-K, to be used in two different scenarios: DAPP-H is used when peaks in the aggregated residential users demand have to be handled in a Demand Response (DR) approach, whilst DAPP-K is used when demand peaks have to be handled with an Energy Storage System (ESS) installed on an EDN substation. Moreover, the PPSV service now enables both a safety verification and an economic evaluation of the effect of DAPP-H individualised price policies. The EVT now includes a fully-functional State Estimation system that detects various types of bad data and replaces erroneous or missing inputs data with reliable estimates. Furthermore, we also describe the scenarios for direct communication between DSOs and IASs.

Limitations and Future Work In this year iteration, the DB&A authentication is still limited. We plan to add a multiple access level. EVT assumes that the distribution network is balanced in the three phases. Even this is a reasonable assumption, we plan to model the local electricity network, especially for the Minsk test-bed. DAPP service works on a simplified ESS model that we plan to refine in the third year.

Chapter 1

Retrospect

In this section we briefly recall the main achievements of the first year version of the SmartHG Grid Intelligent Automation Services (GIASs) design.

The activities in the project first year resulted in building a prototype version of all the GIASs, i.e., of the services working on the Distribution System Operator (DSO) side. Namely, the service dependencies, outputs, and functional specifications were clearly defined. In a nutshell, the following specifications were identified. The Database and Analytics (DB&A) service must work as a communication channel between Intelligent Automation Service (IAS) and IAS and between home devices and IASs. The Demand Aware Price Policies (DAPP) service goal is to compute individualised power profiles for residential users, so that both residential users and the DSO obtain an economic saving: the former by saving on the energy bill, the latter by saving on Electric Distribution Network (EDN) substations maintenance. The Price Policy Safety Verification (PPSV) service is tailored to check that EDN substations safety is retained also if residential users may either follow or not (on a probabilistic basis) the given individualised price policies. The EDN Virtual Tomography (EVT) service is tailored to estimate the state of the EDN and all the related physical quantities (e.g., voltage, current, power) at the relevant points of the EDN where sensors are not available. As for communication between DSO and IASs, a common database and an open protocol were designed. Finally, for each service mentioned above, a first version of algorithm meeting the corresponding specifications were designed.

The challenges identified for the second year were the following.

1. Second year design of DB&A (Task T4.1) must focus on adding a service capability and access permission concepts and improving the infrastructure management features.

2. Second year design of DAPP (Task T4.2) must focus on including user energy storage capacities, both on residential homes and on EDN substations.

3. Second year design of EVT (Task T4.3) must concentrate on introducing advanced services and state estimators to make use of historical data and provide more accurate state estimations and demand predictions and also to establish connection to the main database and integrate it with other SmartHG services.

4. Second year design of PPSV (Task T4.4) must work on integration with the EVT service. Moreover, it must allow for an economic validation of the whole DAPP–PPSV–EVT service chain.

5. Second year design of open protocol for DSO–IAS communication (Task T4.5) must work on improving security of the DSO configuration interface to ensure the proper handling of authentication.

Chapter 2

Introduction

Work Package 4 (WP4) is devoted to the design of the SmartHG Grid Intelligent Automation Services (GIASs). Such services are oriented to power network users, primarily Distribution System Operators (DSOs) and potentially energy retailers, and aim at improving the overall Electric Distribution Network (EDN) usage. From a functional point of view, GIAS control loops are the outer loops of the overall SmartHG functional schema, see highlighted part of Figure 2.1. From an architectural point of view, GIASs are those highlighted in the overall architectural schema of Figure 2.2. In the second year iteration of WP4, we re-designed the SmartHG GIASs. Such new design for SmartHG GIASs is described in this deliverable. The (Web-based) implementation of GIAS prototypes, based on the design described here, is described in Deliverable D4.2.2. Such prototypes are then used for the evaluation phase described in D5.2.1.

In this second year iteration, design of Demand Aware Price Policies (DAPP), EDN Virtual Tomography (EVT) and Price Policy Safety Verification (PPSV) has been modified so as to build a novel integrated methodology for EDN management. The proposed service architecture is shown in Figure 2.3. Database and Analytics (DB&A) now provides the other three GIASs with input coming directly (and in a real-time fashion) from the residential homes, which are the EDN endpoints. Evaluation of the second year versions of each GIAS is described (together with Home Intelligent Automation Services (HIASs)) in Deliverable D5.2.1.

This deliverable reports about the design progress for the services mentioned above, and performed in Tasks T4.1, T4.2, T4.3, T4.4 and T4.5 of WP4.

2.1 Motivation

The main motivations for developing our second year version of Grid Intelligent Automation Services (GIASs) are the following.

Security and Privace Issues Measurement data from residential homes main meters and sub-meters give great insight on the behavioural pattern of the humans living inside the residential premises, and the residents are getting increasingly aware of this. Thus, it is critical for the success of smart grids that these measurement data get treated with care through strict access and permission control. However, controlling data permission and access by itself does not provide the residential consumer with any functionality. In order to provide functionality by using the Intelligent Automation Services (IASs) in a cost-effective and robust way, the separation between them must be maintained.

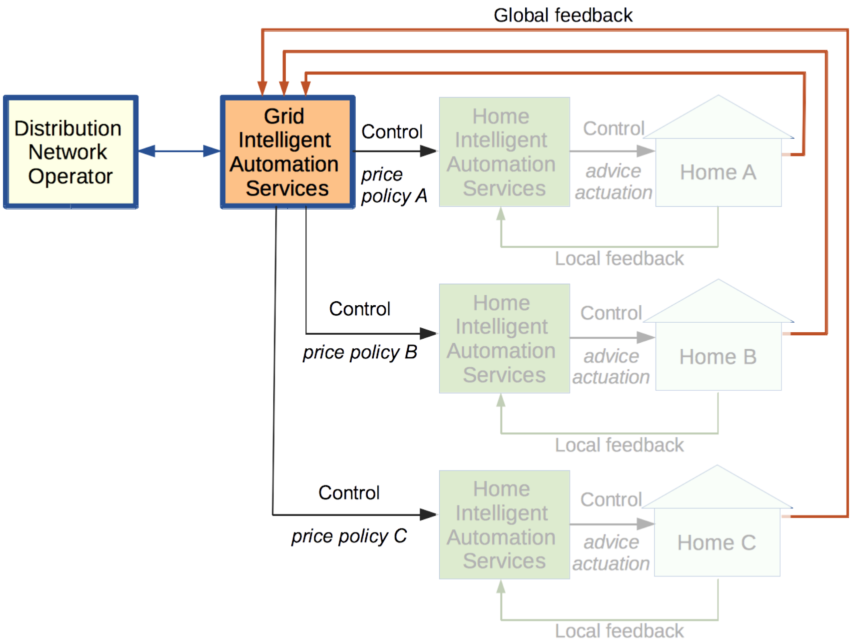

Figure 2.1: Functional schema of SmartHG GIASs.

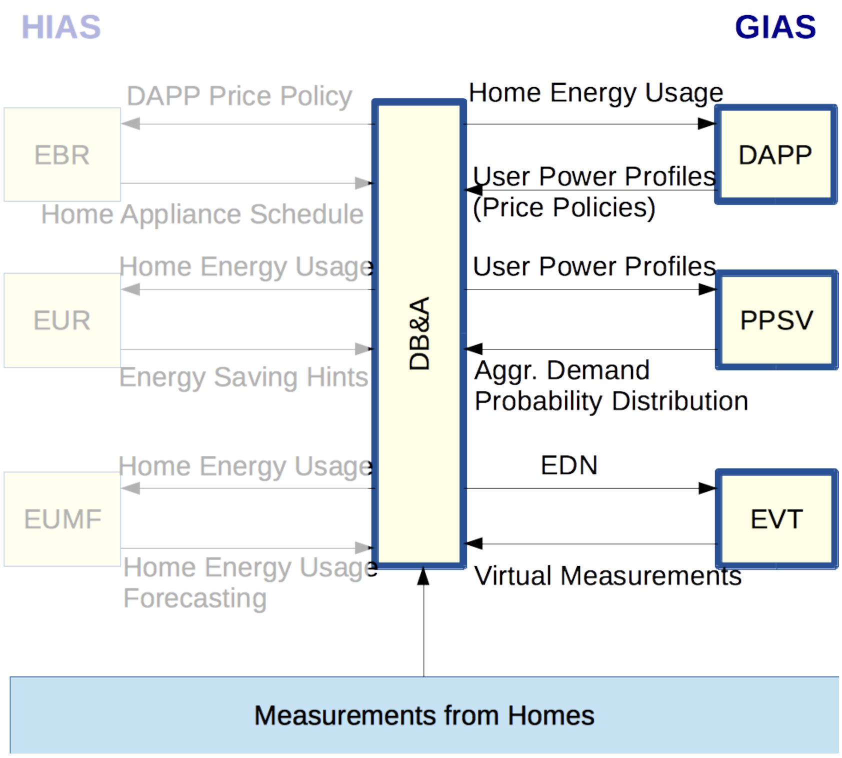

Figure 2.2: SmartHG GIASs architecture.

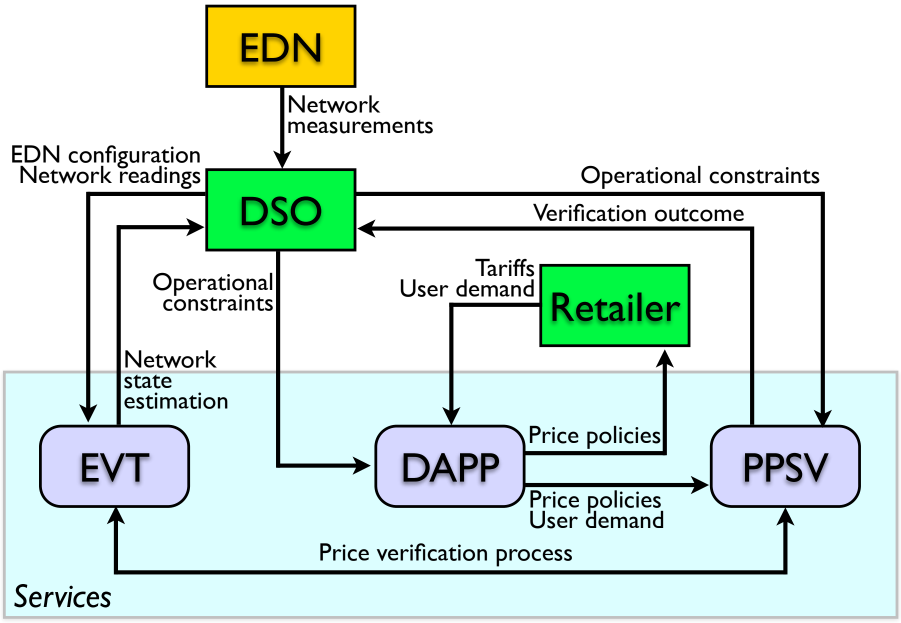

Figure 2.3: The proposed services architecture.

Residential Users Load Shifting In order to optimise EDN substations (feeders) usage, residential user power demand should be mostly flat throughout the day. On the contrary, typically residential user power demand is very low during night, morning and early afternoon, and has very high peaks during late afternoon and evening. To this aim, DSOs try to either force (Direct Load Control (DLC) methods) or motivate (Demand Response (DR) methods) users to shift their power demand. However, DLC methods are typically not accepted by users (as they require the DSO to see how they use their own home appliances), and DR methods are not enough to motivate users to shift their loads. Inclusion of Energy Storage Systems (ESSs) into the scheme is also essential as future trends indicate their usage will increase, both at residential homes level and at substation level.

Probabilistic Models for Residential Users Power Demand Residential users behaviour (i.e., aggregated power demand) is typically not exactly predictable, and only probabilistic models may be used. Basing on probabilistic models of residential users, DSOs need a service able to evaluate both safety of the EDN feeders (to check that very high peaks in user demand are unlikely) and variations in the economic gain.

EDN Monitoring Trends towards more actively-managed distribution systems are set to continue, and the integration of these technologies will lead to more frequent occurrences of problems in the distribution network, such as congestions and excessive voltage variations [1, 2]. This has led to interest in adapting network management techniques, previously only used at the transmission level, to distribution systems, such as state estimation and short-term operational planning [3, 4, 5, 6].

Communication Protocols for DR Methods A formal way to describe, model, and synthesize a DR communication protocol combined with user scenario and DR strategy is required as well as a simulation framework for the model verification. A holistic way to evaluate the performance of a DR communication protocol is needed.

2.2 Objectives

With respect to the motivations in Section 2.1, the main goals to be obtained by our second year version of GIAS are the following.

- To enhance the access control of the DB&A and narrow its capabilities towards its business goals. This way, the service facilitates the SmartHG ecosystem by providing a functionality that can serve other instances in the system. Such systems enable a reuse of services for other purposes and increase the robustness by not failing if a service breaks down.
- The DAPP service must be designed to facilitate both DR and DLC methods. Moreover, a support for ESSs at substation level is required. Finally, the DAPP output must be contractually clear for both users and DSOs.
- The PPSV service should be designed so as to be a support service for the proposed schema, consisting in proposing individualised profiles to residential users. To this aim, it must provide both a safety verification and an economic evaluation.
- The EVT service must be enhanced by including Distribution System State Estimation (DSSE), demand forecasting, and the generation of intelligent warnings, alarms and recommendations for the DSO. Moreover, integration of the EVT with the other GIAS services such as DAPP and PPSV must be performed.
- To propose a design methodology for evaluating the performance of DR protocols along with a DR strategy for the Smart Grid.

2.3 Achievements

The main achievements of the second year iteration are the following.

Re-design of DB&A DB&A has been re-designed to embrace two services, of which Database Service (DBService) primarily provides measurement data for third party service providers and SmartHG Market Controller (SMC) is responsible for the delegation of access. Furthermore, there has been a complete redesign of the DBService (formerly known as DB&A) and the SMC based on set of requirements and Use Cases (UCs). Thus, there is a link between a certain feature and user requirement, which ensures traceability when implementing the prototype. The new design is able to handle different types of users and store/provide measurement data more targeted towards services that analyse power and energy.

Re-design of DAPP Demand Aware Price Policies (DAPP) has been re-designed to include two different services, to be employed in two different scenarios for DSOs.

1. In the first scenario, the DSO (or the retailer, if it is directly providing a service to residential users) does not aim at changing the configuration of EDN substations, and instead aims at shifting user demand. In this scenario, the Demand Aware Price Policies for Homes (DAPP-H) service computes an individualised price policy for each residential home connected to a given substation. Such price policies are an indirect mechanism (as in DR) to steer each user demand as to follow a specific power

profile (individualised and convenient to each user). In order to avoid the problem of the limited responsiveness of residential users to price policies (see Deliverable D6.2.1 for a discussion on this point), such an indirect user demand steering mechanism is accompanied, at the level of the single household, by a Direct Load Control (DLC) strategy, implemented by the Energy Bill Reduction (EBR) HIAS, whose instances run at each home. Each EBR instance (see Deliverable D3.2.1) takes as input the price policy for the home it runs within, and automatically actuates home appliances in order both to meet user requirements and to stay within the low tariff area of the input price policy. This essentially allows us to use both a DLC-like strategy without harming or disappointing the user (no information about devices usage is sent to the DSO by the EBR), and a DR-like strategy without occurring in the users limited responsiveness problem. We note that, as in the first year version of DAPP, the fact that we have individualised price policies avoids the peak rebounds problem, as different users typically have different low tariff areas.

Finally, DAPP-H takes as input the users energy contract, and it computes the output so that the resulting individualised price policies are easily formalised as new energy contracts. To this aim, a measure of the residential user required *flexibility* (i.e., how much the user has to deviate from the habits in order to follow the price policy) is also computed.

2. In the second scenario, the DSO aims at fulfilling users demand as it is, by counteracting demand peaks with ESS installed at each EDN substation (or the more overloaded ones). In this scenario, we provide the DSO with the Demand Aware Price Policies for Substation-Level Energy Storage Control (DAPP-K) service which, once connected to the ESS, is able to drive its charge/discharge so that the overall cost is minimised (note that DAPP-K is the analogous of EBR for EDN substations).

Re-design of PPSV The PPSV service has been re-designed so as to enable both a safety verification (by performing a sort of robustness analysis) and an economic evaluation of effect of individualised price policies output by DAPP-H. To this aim, in order to model uncertainty of actual users power demand, PPSV takes as input a probabilistic model of how users may deviate from the power profiles expected for them, given their assigned price policies.

Improvement of EVT The EVT now includes a fully-functional State Estimation (SE) system developed basing on detailed recordings from the Kalundborg test site EDN. This SE system has the capability to detect various types of bad data which can occur due to metering or communication errors, and to replace erroneous or missing input data with reliable estimates. Demand forecasting techniques have been developed in order to forecast electricity demand profiles at the distribution substation level. Such demand forecasts are important as an input to the SE, and also for the EVT to provide early warning of potential network issues, and generate recommendations and advices for the DSO.

GIASs Integrated Methodology EVT, DAPP and PPSV offer now an integrated approach for improving EDN usage, by exploiting the EDN hierarchy induced by EDN substations interconnection (see Figure 2.3). Such an approach works as follows:

Table 2.1: Mapping between SmartHG tasks inside WP4 to chapters of this deliverable

Task	Task Name	Chapters
T4.1	Design and Development of DB&A	Chapter 3
T4.2	Design and Development of energy DAPP service	Chapter 5
T4.3	Design and Development of the EVT service	Chapter 4
T4.4	Design and Development of the PPSV service	Chapter 6
T4.5	Design and Development of Open Standard Internet based communication between DSO and IASs	Chapter 7

1. EVT is used to help DSO to define desired power profiles on each EDN substation;
2. for each EDN substation s, DAPP computes individualised price policies for residential users connected to s, in order to motivate them to follow specific power profile which, although being convenient, sum up to the desired aggregated power profile on s;
3. for each EDN substation s, PPSV evaluates both safety of s under the assumption that users connected to s are allowed to probabilistically deviate from the power profiles they are expected to follow given their price policies;
4. results of PPSV are collected and their effect on the entire EDN are evaluated by using again EVT.

Other Achievements Furthermore, a design methodology for IASs has been developed to model, simulate, and evaluate DR communication protocols together with DR strategies for smart grids applications.

Finally, user-friendly Web interfaces, as well as RESTful Application Programming Interfaces (APIs) which may be automatically called by other services, have been developed for DAPP, PPSV and EVT (see Deliverable D4.2.2).

2.4 Outline

This deliverable is organised as follows. Chapters 3, 5, 4 and 6 describe the advances in the design of DB&A, DAPP, EVT and PPSV, respectively. Furthermore, Chapter 7 describes the communication protocols between DSOs and SmartHG GIASs. The overall results of this deliverable are summarised in Chapter 8. Furthermore, Section 8 describes in detail the advancements of this year GIASs design w.r.t. the first year design of the same services, discusses the current limitations and plans future work. Finally, Table 2.1 shows the correspondence between SmartHG tasks inside WP4 and sections of this deliverable.

Chapter 3

DB&A Service Design Description

In the process of creating an independent and self-sufficient service for the smart grid, a restructuring of entities from the first year System Architecture has been done. The measurement data from residential homes are essential for other services in the SmartHG ecosystem to operate, thus it supports the communication among residential consumers, other services and the Distribution System Operator (DSO). Without such a service, both data acquisition and data dissemination would be impossible in the SmartHG ecosystem. Consequently, to adapt the Database and Analytics (DB&A) being both an infrastructure service and a software service, the SmartHG project defines the DB&A to contain both functionalities. To clarify the separation, each entity is therefore assigned responsibilities and user requirements. Based on the user requirements, a number of use cases are listed together with their identified stakeholders.

3.1 DB&A Service Overview

The purpose of Service-Oriented Architecture (SOA) services is to provide application functionality autonomously and to be reusable in different contexts. Furthermore, a service can be comprised of a group of services as long as they provide a functionality for other services or stakeholders.

In this iteration, the DB&A service has been redefined to grasp the functionality of storing measurement data and consumer specific data, but also ensure binding between services such that services can subscribe to each other based on their capabilities. This means that the concept of DB&A service covers both the SmartHG Market Controller (SMC), Database Service (DBService) and the Grid Operator Agent (GOA). This point is illustrated in Figure 3.1.

The purpose of this restructuring is to let DB&A entity embrace the functionality of collecting useful measurements for other services in the SmartHG ecosystem but also to incorporate a flexible data access policy to increase the privacy. By having an independent SMC service inside the DB&A service, the SMC could in principle be operated by a vendor different than the vendor of the DBService. This does not only increase the separation of concerns principle but also the sustainability of the SmartHG project, since there can exist multiple "DBService" developers. The delegation of responsibility in the DB&A service are summarized in Table 3.1.

In this iteration, the focus has mainly been on the DBService and the SMC. Since the GOA will support the demand response operations of the DSO, these features can be attached later in the process.

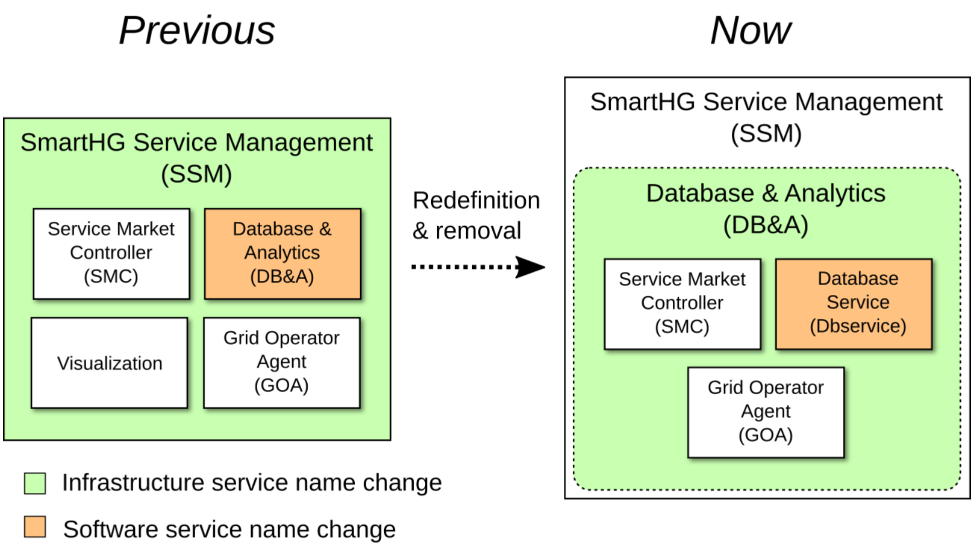

Figure 3.1: Redefinition of the infrastructure service and software service.

Entity / Service	Scope of responsibility
Service Market Controller	The main responsibility of this controller is to authenticate and authorize services to other services for getting data access in the SmartHG ecosystem. Furthermore, all services root API are registrated in the controller to provide a flexible service infrastructure.
Database Service	It is responsible for storing measurement data from the residential consumers and other relevant measurements, such as CO2 forecasts and weather data which can be useful for other services[1]. Furthermore, the DBService is responsible of tracking ownership of data within the service itself, and only allow data access to authenticated and authorized stakeholders. Last, it must be able to represent measurement data in common formats, e.g. temporal filtered, condensed, and aggregated.
Grid Operator Agent	An agent working on behalf of the DSO and negotiates with the home agent about the data granularity and time requirements of the measurement data from residential houses.

Table 3.1: Delegation of responsibility in the DB&A service.

[1] In principle the CO2 forecast services and weather services are self-contained services, but for the sake of having a RESTful SmartHG ecosystem, this is built into the DB service.

Chapter 4

EVT Service Design Description

The supervision and control of distribution networks becomes increasingly important with the integration of Distributed Energy Resources (DER). High penetrations of DER results in an increase in the variability of EDN power flows and, as a direct consequence, more detailed knowledge on the network state is required in order to manage the EDN. However, in most EDNs only few measurements are taken due to technical or economic issues. The use of a detailed simulation model of an EDN allows a wide range of physical values to be computed and the state of the network to be estimated. The results of the state estimation can then be used to automatically generate warnings and alarms if a value approaches or exceeds its limits. The EVT service described below is comprised of two modules, or functions: (A) the estimation of the EDN state; and (B) the generation of warnings, alarms and advices for the Distribution System Operator (DSO).

4.1 State Estimation

The EVT module to estimate the state of the grid is given in Fig. 4.1. The inputs are the static network parameters (bus and branch information), along with measurement data (e.g. real-time recordings of voltages, power angles, active/reactive power injections, active/reactive power flows). These data are fed to the state estimator described in [6], which identifies bad data, such as erroneous or missing values in the input measurements. Power flow analysis is then carried out in order to calculate the grid state, expressed as a set of estimates of the voltages, power injections, and power flows throughout the EDN.

The Distribution System State Estimation (DSSE) uses a combination of different types of input data, comprising both real-time measurements from the distribution network Supervisory Control And Data Acquisition (SCADA) system, and load pseudo-measurements, based on historical smart meter recordings. Each of these input data types potentially contains significant noise and gross errors. It was found that a least-squares estimator based on robust statistics [7] was required to produce acceptable performance in this application. Estimators based on robust statistics are particularly suited to dealing with gross errors and outlier values which can cause computational problems for conventional State Estimation (SE) solvers.

The development of the DSSE service for EDN Virtual Tomography (EVT) was carried out using data from the Kalundborg test site Medium Voltage (MV) network, where it was that the level of imbalance across the three phases is not critical. The robust DSSE solution outlined here would need to be modified to include phase imbalances, in order

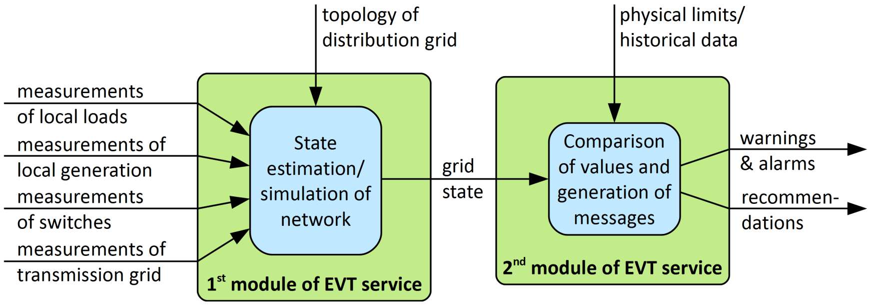

Figure 4.1: Inputs and outputs of the two modules of EVT.

to apply it to Low Voltage (LV) networks, or to MV networks with single and two-phase laterals.

4.2 Design of Demand Profile Forecasting Service

The forecasting of demand at the substation level allows the EVT service to predict the future states of the network, and provide early warning to the DSO of potential network congestions and voltage excursions. This service requires high-quality estimates of demands and Distributed Generation (DG) output profiles at each distribution network substation. In addition to this, the demand profile forecasts are required as an input to the DSSE described in previous sections.

Several of the most common approaches for short-term load forecasting were tested in the design of the demand forecasting service, using recorded demands from the Kalundborg test network. The intention was to investigate some of the most commonly-used methods for load estimation, in order to find a suitable approach for forecasting MV substation demand profiles.

Most previous work in the area in load estimation applies to the estimation of much larger, more aggregated loads, e.g. prediction of regional or national demands [8, 9]. However, novel techniques for load estimation at a much more localised level are required for the accurate assessment and management of voltages and flows in the distribution networks, where the focus is on local-level load estimation (e.g. for few tens to hundreds or customers at the secondary distribution network substation).

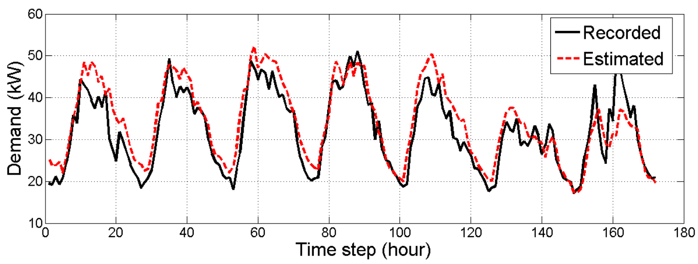

Figure 4.2: Sample of day-ahead estimates of residential MV substation demand.

4.3 Short-term Operational Planning for Distribution System

A short-term planning approach, similar to the standard procedures used by a Transmission System Operator (TSO) for hours/days-ahead operational planning was proposed for the EVT. The input data to the EVT should include the expected network configuration changes due to e.g. scheduled maintenance on distribution system components, or other expected changes to substation running arrangements etc.).

These are applied, along with the forecasted demand profiles in order to carry out a network analysis for the relevant time-frame (e.g. peak hour day-ahead). The expected distribution network power flows are calculated, and contingency/fault analysis can also be carried out as required. This allows the user to estimate if any of the network technical constraints will be violated in the considered time-frame. If so, appropriate warnings and alarms are issued by the EVT, providing early warning of potential issues to the DSO.

The overall status of the system is described according to the "operating state" categories outlined below, where the overall network state is described in one of three categories, which are used to direct DSO decisions around corrective actions.

- **Normal**: Normal network operation, no action required.
- **Warning**: Network operating close to allowed limits, potential for violation of system constraints. In this case, a warning is issued by the EVT, and recommendations are provided to the DSO, for instance, adapting network production/consumption to the network situation.
- **Alarm**: Network constraints are violated, generating alarms from the EVT. Such situations will require a re-configuration of the network, or if this still cannot resolve the violation(s), direct load management or DG curtailment is required to return network to a secure operating state.

Chapter 5

DAPP Service Design Description

To meet objectives listed in Section 2.2, the second year version of Demand Aware Price Policies (DAPP) is now synergic with the Energy Bill Reduction (EBR) Home Intelligent Automation Service (HIAS) (described in Deliverable D3.2.1). DAPP now includes two different services: Demand Aware Price Policies for Homes (DAPP-H) and Demand Aware Price Policies for Substation-Level Energy Storage Control (DAPP-K).

5.1 DAPP Overview

The first service is called DAPP-H and (as it was the case for the first year version of DAPP) computes an individualised price policy for each residential home connected to a given substation.

Each price policy is defined by giving power usage lower ($P^{-}(t)$) and upper ($P^{+}(t) > P^{-}(t)$) bounds for each time-slot t (typically lasting one hour) of a set of future contiguous time-slots. If a user, in a time slot t, will use an average power within the interval $[P^{-}(t), P^{+}(t)]$, a low tariff will be applied for the power absorbed from the grid and a high tariff is applied for the (locally generated) power sold to the grid. We call *low tariff area* the set of intervals $[P^{-}(t), P^{+}(t)]$ for each t.

Price policies are used by the Distribution System Operator (DSO) as an indirect mechanism (as in Demand Response (DR)) to steer each user demand as to follow a specific (individualised) power profile. Such individualised power profiles are convenient to each user, exploit a limited flexibility in user demand (modelled as an Energy Storage System (ESS)), and sum up to an aggregated power demand which is always within the given desired substation power profile.

This indirect (DR-like) approach to steer demand at the substation-level is accompanied by a direct mechanism (Direct Load Control (DLC)-like) at the level of the single household, where a locally installed instance of the EBR HIAS (see Deliverable D3.2.1) automatically actuates (some of the) home appliances in order both to meet user requirements and to stay within the low tariff area of the price policy assigned to that user.

The second service is called DAPP-K and works on a different scenario. Instead of proposing price policies to residential users, such service works on the assumption that an ESS is installed at the Electric Distribution Network (EDN) substation. More in detail, DAPP-K controls such an ESS (by sending charge/discharge commands) so that the overall electricity cost is minimised.

Nominal usage for DAPP-H and DAPP-K is as follows:

- DAPP-H should be called once a day (or every few days). The computed individualised price policies will be applied the next day (resp. the next few days). Households power usage predictions for the next day (resp. next few days) are provided either by the Energy Usage Modelling and Forecasting (EUMF) HIAS (see Deliverable D3.2.1) or by looking at the power demand of the last two weeks;

- DAPP-K should be launched once and for all, and runs forever in order to control the ESS installed at the substation. Note that, differently from all other Grid Intelligent Automation Services (GIASs), DAPP-K (like the HIAS EBR) is a real-time service, thus it cannot by provided as a Software as a Service (SaaS) like the other Intelligent Automation Services (IASs). On the contrary, it must be installed and executed by the final user, i.e., the DSO owning the substation (see Deliverable D4.2.2). In this respect, it is analogous to the HIAS EBR, which is executed by a residential user.

5.2 DAPP Specification

In this section we describe the input-output behaviour of DAPP-H and DAPP-K.

We first define the notation we use (which is in common with PPSV). T is a finite set of contiguous time-slots, all having the same duration. A *power profile* is a function $P : T \to \mathbb{R}$ (being $\mathbb{R}$ the set of real numbers). A *power profile tube* (or *region*) is a pair of power profiles (P_l, P_h) defined over the same set of time-slots T, such that $P_l(t) \leq P_h(t)$ for all $t \in T$. A power profile P *follows* a power profile tube (P_l, P_h) if and only if $P_l(t) \leq P(t) \leq P_h(t)$ for all $t \in T$.

5.2.1 DAPP-H: Input and Output

Here we describe in detail input and output for DAPP-H (for a high-level view, see Figure 5.1). DAPP-H requires the following input:

- a set of homes U connected to a substation s;
- a set of contiguous time-slots T (with a time span one day in the future);
- the desired power profile P_s on T for the substation s, as decided by the DSO on the basis of EDN Virtual Tomography (EVT) output;
- for each user $u \in U$, a power profile d_u on the (say, $k > 0$) days preceding T, representing the power demand (i.e., consumption minus production) in the given period;
- for each user $u \in U$, the contract C_u for electricity consumption and production (e.g., 3 or 6 kW);
- a parameter α which defines the minimum energy αC_u kWh that each user u is guaranteed to be able to user each day.

The main output of DAPP-H is a set of *individualised price policies*, defined on the basis of individualised power profile regions $(P_{u,l}, P_{u,h})$ on T, which we also refer to as *low tariff areas*, for each residential user $u \in U$. Namely, if user energy consumption (resp., production) is inside the low tariff area, a low (high) tariff is applied, otherwise a high (low) tariff is applied.

5.2.2 DAPP-H: Algorithm

The main idea underlying DAPP-H algorithm is to model users load shifting as a virtual (and ideal) ESS. Thus, users are able to shift loads only by accumulating energy during off-peak periods and using accumulated energy in on-peak periods. Hence, DAPP-H also outputs the maximum energy which users need to accumulate to stay inside their low tariff area and satisfy their demand, as well as an actual plan for accumulating energy/using stored energy (*DAPP-H collaborative profile*).

More in detail, the input-output behaviour described in Section 5.2.1 is achieved by setting up a Mixed-Integer Linear Programming (MILP) problem. Such MILP problem is based on a forecast of the demand of each residential user for the future time-slots in T. Such forecast is computed using the Energy Usage Modelling and Forecasting for Control (EUMF-K) service, basing on the most recent demand data available for each residential user (typically, we whole day preceding DAPP-H execution). Thus, the MILP problem is defined so as to minimise the residential users required flexibility (i.e., the maximum capacity for the ESS) under the following constraints, for each of the future time-slots in T:

- for each residential user u, the energy, which may be used in the output low tariff area for the whole future time-slots T, must include at least α times the home contract C_u (in kWh). As an example, if the contract is 12 kW and $\alpha = 3$, then the user must be allowed to use at least 36 kWh (in the whole day) at a low price;
- for each residential user u, the DAPP-H collaborative profile, resulting from applying to the forecast of the demand the plan for the charge/discharge actions of the ESS, must always be inside the low tariff area;
- at any time-slot, the energy stored in the ESS must not be used to send energy to the substation (that is, the ESS may be discharged only if there is a positive demand which is greater than the discharge);
- for each user, the resulting maximum capacity for the ESS is proportional to the average daily demand;
- for each user, the starting and the ending capacity of the battery must be the same;
- if all users synchronise and use the maximum energy allowed in the low tariff areas, the resulting aggregated demand must be below the substation desired threshold.

Once the MILP problem has been created, it is solved by means of a MILP solver (either CPLEX of GLPK). Finally, since the required charge/discharge action at time t for the ESS is a decision variable in the MILP problem, the value for such action is extracted from the solution of the MILP problem returned by the MILP solver.

5.2.3 DAPP-K: Input and Output

Here we describe in detail input and output for DAPP-K (for a high-level view, see Figure 5.2). DAPP-K is an executable program, running on some device or computer connected to an EDN substation s on which an ESS is installed. DAPP-K consists in an infinite loop which, every T seconds (one hour in the DAPP-K evaluation in Deliverable D5.2.1), reads data and reacts with commands. Namely, in each iteration of such a loop, occurring at time t, the following measurements are read:

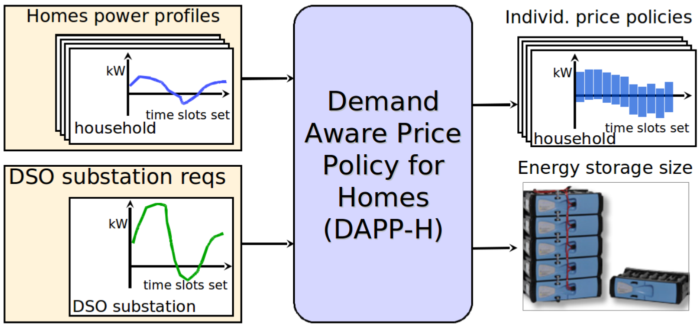

Figure 5.1: DAPP-H input and output.

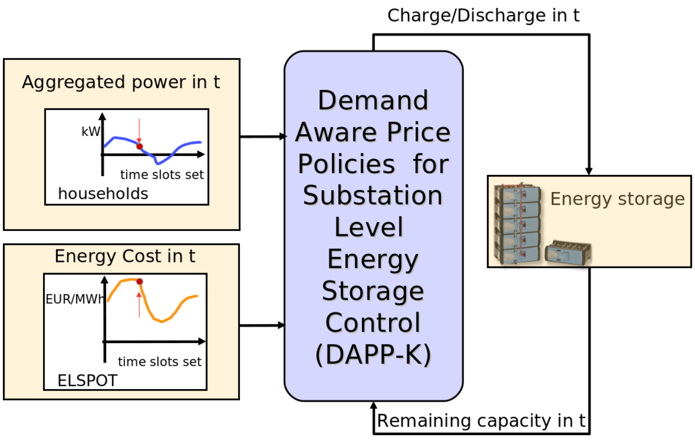

Figure 5.2: DAPP-K input and output.

- the remaining capacity of the ESS (in kWh) at time t. This information is directly available from the ESS sensors;
- the power demand at the substation level at time t, obtained by aggregating the power demand at time t of all homes connected to the substation. This information is available from the substation sensors;
- the cost of energy at time t (energy market price, in EUR/MWh). This information may be obtained from the one-day ahead market. To this aim, an auxiliary process, running in parallel with the actual controller, downloads (once a day) from the Internet the new prices when they are ready, and feeds them to DAPP-K.

Moreover, DAPP-K may be customised with the following parameters:

- the maximum power rate (in kW) for the ESS;
- the round-trip efficiency of the ESS;
- the maximum capacity (in kWh) for the ESS;
- the desired power threshold for the substation;

- the number of days on which to average (up to the current time t) the aggregated power demand, before comparing with the desired power threshold. Namely, DAPP-K will allow the aggregated demand to sometimes exceed the substation desired power threshold, provided that the average of the aggregated demand on the last days is always below the threshold.

Finally, DAPP-K outputs the charge/discharge action at time t for the ESS on s.

5.2.4 DAPP-K: Algorithm

The input-output behaviour described in Section 5.2.3 is achieved by setting up, for each time t, a MILP problem. Such MILP problem is based on a forecast of the aggregated demand in the a number N of future time-slots after t. Such forecast is computed using the EUMF-K service, basing on the aggregated demand recorded in the last M time-slots. Thus, the MILP problem is defined so as to minimise the cost of energy for the DSO under the following constraints, for each of the N future time-slots (including t):

- it is possible to either charge or discharge the ESS, and not both;
- the ESS capacity at the next time-slot is obtained by applying a charge/discharge action in the current time-slot to the ESS capacity, by also considering the round-trip efficiency (the starting ESS capacity at time-slot t is the one read from ESS sensors);
- the resulting ESS capacity must always be within 0 and the maximum ESS capacity;
- the power actually required to the substation from residential users results from the aggregated demand plus the charge/discharge action for the ESS;
- the power computed in the previous point, when averaged on the last given number of days, must be below the given desired threshold for the substation.

Once the MILP problem has been created, it is solved by means of a MILP solver (either CPLEX of GLPK). Finally, since the required charge/discharge action at time t for the ESS is a decision variable in the MILP problem, the value for such action is extracted from the solution of the MILP problem returned by the MILP solver.

Chapter 6

PPSV Service Design Description

The purpose of this chapter is to report about second year activities carried out in Task T4.4 of the SmartHG project.

To meet the objectives listed in Section 2.2, the second year version of Price Policy Safety Verification (PPSV) service computes as a result both an economic and a safety evaluation of the price policies computed by the DAPP service.

6.1 PPSV Overview

PPSV service aims at verifying if price policies computed by the DAPP service lead to savings for the DSO, while making the probability of safety violations low. Moreover, PPSV has to take into account that residential users may deviate from price policies computed by DAPP.

More in detail, the main goal of PPSV is to verify safety of a given substation s, when to each residential user connected to s is applied the corresponding individualised price policy computed by the Demand Aware Price Policies for Homes (DAPP-H) service.

PPSV service consider *DAPP collaborative* and *DAPP non-collaborative* users. DAPP collaborative users are those users whose consumption power profile is always inside the low tariff area. They can reach this result by properly storing energy/using stored energy, and shifting the foreseen demand power.

In order to model DAPP non-collaborative users, we consider a *probabilistic disturbance model* for deviations from the ideal energy consumption profile defined by the low tariff area in their individualised price policy. Starting from historical data, this probabilistic model provides a distribution of how many residential users will deviate, and how much they deviate.

To evaluate the probability of safety violations, PPSV provides as output a probability distributions on the aggregated power demand. Such a probability distribution is approximated, but the algorithm underlying PPSV ensures that, with high statistical confidence, errors are guaranteed to be less than a given thresholds. In other words, PPSV returns the probability that the aggregated power demand is in a given interval (for interested readers, details will be given in Section 6.2.2).

Finally, the PPSV output can be used for economical evaluation. By considering a probability distribution for the aggregated power demand at each hour in a day, the Distribution System Operator (DSO) can estimate the electricity cost affected by user deviations.

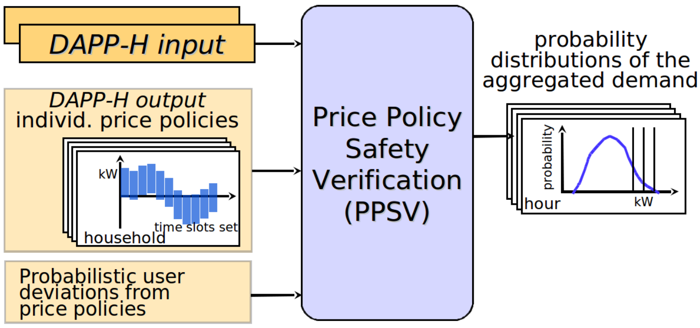

Figure 6.1: PPSV input and output.

6.2 PPSV Specification

In this section, we give a detailed and formal descritption of the PPSV input-output behaviour (see Figure 6.1).

6.2.1 PPSV Input

PPSV takes as input the following data:

- All inputs required by DAPP-H (see Section 5.2).
- A quantisation step $\gamma \in \mathbb{R}$.
- Confidence and tolerance on the overall PPSV output $\delta, \varepsilon \in [0, 1]$;
- the DAPP-H output $\{(P_{u,l}, P_{u,h}) \mid u \in U\}$ (where U is the set of all users connected to substation s).
  - From the low tariff area $(P_{u,l}, P_{u,h})$ of each user u, it is possible to compute the *DAPP collaborative user*, that is a power profile $\tilde{P}_u$ for u which, by properly storing energy/using stored energy, shifts the (foreseen) demand power profile d_u to be always inside the low tariff area.
- A probabilistic disturbance model describing how users may deviate from the power profile tube assigned to them by DAPP-H (i.e., the low tariff areas entailed by the price policies).
  - The disturbance model is defined by means of a function $\text{dist} : A \to [0, 1]$, being A a finite subset of $[-1, 1]$, with $\sum_{d \in A} \text{dist}(d) = 1$. Namely, $\text{dist}(d) = p$ iff, for each user u, p is the probability that, in a random time-slot t, the actual power used by u in t is $P_u^{(d)}(t) = \tilde{P}_u(t)(1 + d)$.

6.2.2 PPSV Output

As for the output, PPSV aims at providing probability distributions on the aggregated power demand of s induced by the probabilistic disturbance model, in order to analyse the *robustness* of DAPP-H output price policies. Namely, PPSV output is organised so as to provide two different types of evaluation of the DAPP-H output:

- *Economic evaluation.* In this case, 24 probability distributions for the aggregated power demand are returned, one for each hour of the day. By knowing how the electricity price varies on such hours, it is possible to have an estimate of how overall electricity cost is affected by user deviations.
- *Safety Evaluation.* In this case, one probability distribution for the aggregated power demand is returned for each different value v of the desired substation power profile (i.e., for each v in the image of P_s). This allows DSOs to check that the probability that the aggregated power demand is greater than v (i.e., the probability of safety violation) is low.

In both cases, PPSV computes a set of probability distributions of the aggregate power demand, one for each hour of the day in the first case, and one for each value of the substation desired power profile in the second case. Each of such computed probability distributions are formally certified to be (ε, δ)-approximations (for any input values of ε and δ) of the *true* distributions. This means that the maximum relative error in the computation of each aggr_v is guaranteed to be bounded by ε with statistical confidence $1 - \delta$.

More formally: let $P_{max} = \max_{d \in A, t \in T} \sum_{u \in U} P_u^{(d)}(t)$ be the maximum value that the aggregated demand can take under the probabilistic user deviation model, and let $R = \{r \mid 0 \leq r < P_{max}, r = k\gamma, k \in \mathbb{N}\}$ be the finite set of all possible γ-quantised values within P_{max}.

In case PPSV is used for the economic evaluation, the output is a set of functions $\{\text{aggr}_v : R \to [0, 1]\}$ for the aggregated disturbed Demand Aware Price Policies (DAPP) collaborative profiles, one for each hour v of the day (i.e, $v \in [0, 23]$). For any $r \in R$, $\text{aggr}_v(r) = p$ if and only if, taken a random time-slot t within hour v, the probability that the aggregated power demand (under probabilistic user deviations) in t belongs to interval $[r, r + \gamma)$ is in $[p(1 - \varepsilon), p(1 + \varepsilon)]$. The result is formally certified to be correct with statistical confidence $1 - \delta$.

In case PPSV is used for the safety evaluation, the output is a set of functions $\{\text{aggr}_v : R \to [0, 1]\}$ for the aggregated power demand (under probabilistic user deviations), one for each value v of the desired substation power profile (i.e., for each v in the image of P_s). For any $r \in R$, $\text{aggr}_v(r) = p$ if and only if, taken a random time-slot t among the time-slots for which $P_s(t) = v$, the probability that the aggregated power demand (under probabilistic user deviations) in t belongs to interval $[r, r + \gamma)$ is in $[p(1 - \varepsilon), p(1 + \varepsilon)]$. Again, the result is formally certified to be correct with statistical confidence $1 - \delta$.

The output of PPSV, in particular pairs $(r, \text{aggr}_v(r))$ for which $\text{aggr}_v(r) > 0$, are sent back to EDN Virtual Tomography (EVT), in order to set meaningful and challenging scenarios for Electric Distribution Network (EDN) safety verification (see Figure 2.3). The final verification outcome computed by EVT is then sent back to the DSO.

Chapter 7

Open Standard Internet-Based Communication Between Distribution System Operator (DSO) and Intelligent Automation Services (IASs)

The viability of a Demand Response (DR) protocol in a real world setup depends on multiple factors, each having an impact on the performance of a protocol. For instance, a given user behaviour will have an impact on the control. Likewise, a change of DR strategy will influence how the user is requested to change behaviour. Therefore, we apply an approach that allows engineers to model the user behaviour while also having a DR scheduling algorithm.

In order to assess if a given DR protocol is suitable for a smart grid environment, we take into account the evaluation parameters associated to the DR protocol and the resulting consumption pattern of all households. The evaluation parameters for the protocol include transmission overhead and time responsiveness between the device client and the DR server. These metrics allow DR protocol developers to benchmark the protocols for judging them against real-time requirements, but also for making comparisons between them. Furthermore, the specification of DR protocols often gives the possibility of adjusting parameters of the protocol e.g., the request frequency. Tuning these parameters may have an impact on the protocol evaluation, but also on how successful the DR strategy is in shifting the electricity consumption of the household.

In Figure 7.1 a scenario description is shown (A) as well as the modelling strategy (B). Also, the green block labelled as C refers to the evaluation of the protocol.

7.1 Describing Household Scenarios, Demand Response Strategy, and Protocol

The description of household scenarios accounts for the majority of the dynamic behaviour in the system, thus their compositions are essential for the evaluation but also the alignment with the real world. They should be written in plain language with minimal technical details such that a non-technical person can understand and create them. The household scenarios should only include information relevant for the scope of the simulation, however the order of execution is obligatory for the formal transformation.

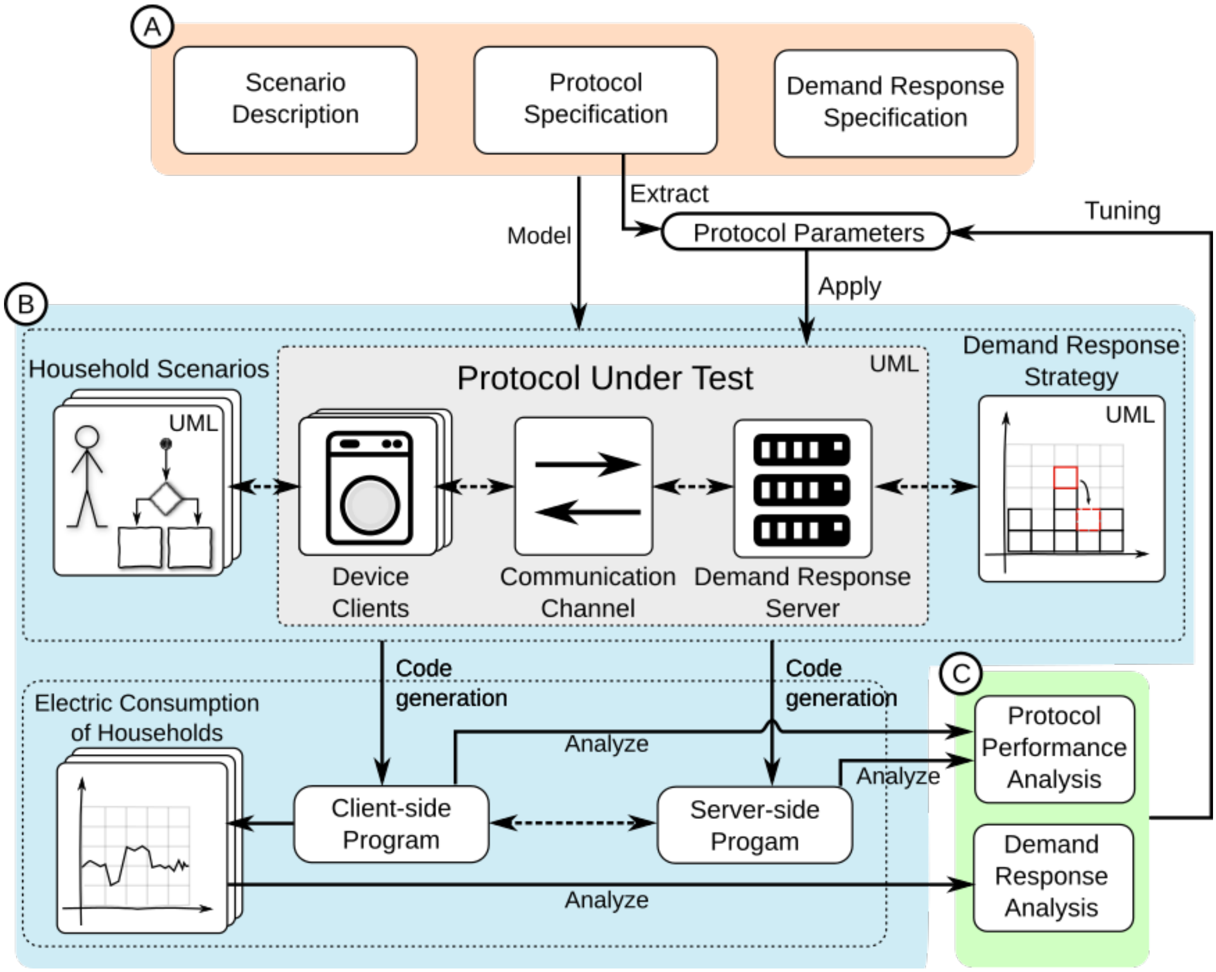

Figure 7.1: Detailed overview of the proposed methodology for evaluating and tuning demand response protocols.

To gain greater insight into the temporal progress, details about the execution time can be included.

7.2 Platform-Independent and Executable Descriptions

Unified Modeling Language (UML) and Profiles are the core of the proposed methodology (Figure 7.2) as a standard and interoperable representation of the scenario, DR strategy, and protocol descriptions. In this work, three types of UML diagrams have been used to model such descriptions.

Class diagram, a static structure diagram, is used to capture the structure of the system. Sequence diagram (SD), an interaction diagram, that shows the sequence of messages exchanged between system objects that need to carry out the functionality of the communication scenario. SD is used to depict the interactions between the customer and his/her appliances and also for modelling the DR protocols. Activity Diagram (AD), a behaviour diagram, that shows workflows of stepwise activities and actions. AD is used to capture the behavioural part of system components.

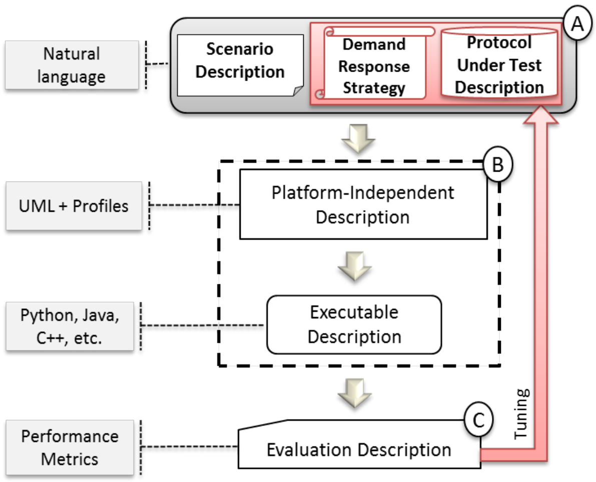

Figure 7.2: Methodology of design flow.

Chapter 8

Conclusions

In this deliverable we described the second year version of the design of all SmartHG Grid Intelligent Automation Services (GIASs), i.e., of the SmartHG services which work on the Distribution System Operator (DSO) side. Prototypes of such services are described in Deliverable D4.2.2. In the following, we present advancements with respect the first year iterations, main limitation and we will draw some directions for future work.

8.1 Advancements

In this section, we discuss the main advancements we obtained with this year SmartHG GIASs design w.r.t. the first year version of the GIASs design. To this aim, we discuss the enhancements for each GIAS.

DB&A: The most important enhancement w.r.t. the first year version are the following: i) complete re-design and implementation of the structure of the Database and Analytics (DB&A) service, where data related to consumption, production and topology are stored in separate a Web service called Database Service (DBService), and where authentication related functionality is designed into the SmartHG Market Controller (SMC); ii) design improvements that create a distinction between main meters and submeters; iii) design improvements that create independence between appliances and submeters in the data layer, such that meters that is malfunctioning or are moved to other locations do not conflict with existing measurements; iv) Limited OAuth2 support that can be extended with an external authentication service. v) Limited support for collecting aligned measurements from multiple meter ports within a time period, so that virtualization of data can be based on multiple sources. vi) Get aggregated consumption or production on residential house level.

DAPP-H: This year design of Demand Aware Price Policies for Homes (DAPP-H) went through a complete restyling w.r.t. the first year version of its ancestor Demand Aware Price Policies (DAPP). First of all, DAPP-H is more clear than DAPP as for the residential user energy contract, as it requires as input the current contractual limit for both energy production and consumption (which was not considered in the first year version of DAPP). Second, in the current year version of DAPP-H we model users flexibility (i.e., how much users has to modify their habits to stay inside low tariff areas) as Energy Storage System (ESS), with capacity proportional to each residential user average demand. On the other hand, the previous year of DAPP tried to generate low tariff areas as close as possible to the residential users power demand. Last, the interoperability of DAPP-H and Energy Bill Reduction (EBR) is strengthened, as both are based on the assumption that an ESS is used in each residential home.

PPSV: There are two main differences with the first year version of Price Policy Safety Verification (PPSV): i) this year version of PPSV relies on a parallel algorithm, i.e., it may run on a cluster of workstations in order to lower down the computation time; ii) PPSV may be run in two different ways, with two different expected outputs. Namely, the *safety evaluation* version of PPSV essentially resembles the first year version of PPSV (apart from the fact that it is now parallel). On the other hand, the *economic evaluation* version of PPSV is new, and outputs 24 probability distributions for the aggregated residential users power demand (one for each hour of the day) instead of just 1 probability distribution (as in the safety evaluation version and in the first year version of PPSV). The economic evaluation version of PPSV allows to assess the economic viability of the whole DAPP-H-EBR schema.

DAPP-K: The Demand Aware Price Policies for Substation-Level Energy Storage Control (DAPP-K) service has been developed this year, thus it cannot be compared with any first year version. However, DAPP-K covers a lack of the first year DAPP service, in order to support ESS usage at the substation level. This allows the DSO to satisfy residential user power demand as it is, i.e., without trying to change residential users habits.

EVT: The main differences w.r.t. the first year version of EDN Virtual Tomography (EVT) includes the implementation and testing of a suitable Distribution System State Estimation (DSSE), a substation demand forecasting service, and improvements in the generation of intelligent warnings, alarms and recommendations for the DSO.

DSO–IAS communication: The first year design was limited to handling the normal Demand Response and Load Control (DRLC) user scenarios and has been made more robust with respect to foreseen end-user behavior such as a sudden cancellation of a DRLC program.

8.2 Limitations and Future Work

Limitations of the second year evaluation, together with the planned actions to overcome them, are discussed in Table 8.1.

Table 8.1: Limitations for the second year design of GIASs & how we plan to overcome such limitations in the third year GIASs design.

Topic/GIAS	**Limitations of second year**	**Future work for third year**
DB&A	This iteration of the design for the DB&A service does not include the design of SMC and Grid Operator Agent (GOA)	The design of the SMC and of the GOA is currently under development, and will be completed within the third year.
		Continued on next page

Table 8.1 – continued from previous page

Topic/GIAS	Limitations of second year	Future work for third year
DB&A	This iteration of the design for the DB&A service does not include a uniform way of exposing the DB&A capabilities	The DB&A capabilities presentation will be made uniform
DB&A	The authentication part is currently limited to the superuser account (i.e., once logged in, anyone may see and modify all data)	The authentication part will be completed by implementing multiple access levels (i.e., each user will see only the data for which it has been authorised)
EVT	One limitation of the work on DSSE is that the techniques developed have assumed that the distribution network in question is balanced in the three phases. This is a reasonable assumption in the case of the Kalundborg test site Medium Voltage (MV) distribution network, since the level of imbalance between the phase in this type of network configuration is not critical. However, in order to implement the State Estimation (SE) in the Low Voltage (LV) parts of the network, or in certain types of MV network configurations which are inherently unbalanced, modelling of the networks in three phases would be required, adding to the complexity of the DSSE	Future work will include the modelling of the local electricity distribution network for Minsk test site, and simulation through the EVT service using data from this site. It will also further develop the state estimation and load forecasting services in order to improve their performance and ease-of-use and integration with the other services.
DAPP	Both DAPP-K and DAPP-H are currently based on a simplified model of ESSs	In order to improve results with currently available technology, we plan to develop more precise ESS models.
DAPP-H	Communication with DB&A has been designed but still not tested.	Communication with DB&A will be completed in the third year.
DAPP-K	It is difficult to estimate if it is indeed convenient to buy an ESS (with given characteristics), install it on a given substation and let DAPP-K drive it, before buying the ESS itself.	A Web-based service able to perform such an estimation, using the Software as a Service (SaaS) paradigm, is currently being tested. It will be released in the third year.

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Table 8.1 – continued from previous page

Topic/GIAS	**Limitations of second year**	**Future work for third year**
PPSV	A way of automatically analysing the EVT answer to PPSV requests is missing.	In the third year we will investigate how such an automatic analysis may be carried out.
DSO–IAS communication	The mapping of the platform-independent description of the consumer scenario, demand response strategy, and the protocol under test into executable description has been done manually. The methodology does not address stochastic behaviour of the user's scenario.	As for the design methodology for Intelligent Automation Service (IAS), future work will focus on designing a tool to convert Unified Modeling Language (UML) models into an executable code, as well as in investigating modelling of stochastic scenarios.
DSO–IAS communication	There is no dynamic method for distributing certificates in the SmartHG architecture.	A dynamic method for distributing certificates in the SmartHG architecture will be studied.

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