Smart TSO-DSO interaction schemes, market architectures and ICT Solutions for the integration of ancillary services from demand side management and distributed generation

Results of Pilot B (Denmark)

D5.2

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About SmartNet

The project SmartNet (http://smartnet-project.eu) aims at providing architectures for optimized interaction between TSOs and DSOs in managing the exchange of information for monitoring, acquiring and operating ancillary services (frequency control, frequency restoration, congestion management and voltage regulation) both at local and national level, taking the European context into account. Local requirements for ancillary services in distribution systems should be able to co-exist with system requirements for balancing and congestion management. Resources found in distribution systems, like demand side management and distributed generation, are supposed to take part in the provision of ancillary services both locally and for the entire power system in the context of competitive ancillary services markets.

Within SmartNet, answers are looked for to the following questions:

- Which ancillary services could be provided from distribution grid level to the whole power system?
- How should the coordination between TSOs and DSOs be organized to optimize the processes of procurement and activation of flexibility by system operators?
- How should the architectures of the real time markets (the markets for frequency restoration and congestion management) be consequently revised?
- What information must be exchanged between system operators and how should the communication (ICT) be organized to guarantee observability and control of distributed generation, flexible demand, and storage systems?

The objective is to develop an ad hoc simulation platform capable of modeling physical network, market, and ICT to analyze three national cases (Italy, Denmark, Spain). Different TSO-DSO coordination schemes are compared with reference to three selected national cases (Italian, Danish, Spanish).

The simulation platform is then scaled up to a full replica lab, where the performance of real controller devices is tested.

In addition, three physical Pilots are developed for the same national cases testing specific technological solutions regarding:

- monitoring of generators in distribution networks while enabling them to participate in frequency and voltage regulation,
- capability of flexible demand to provide ancillary services for the system (thermal inertia of indoor swimming pools, distributed storage of base stations for telecommunication).

Partners

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List of Abbreviations and Acronyms

Acronym	Meaning
API	Application Programming Interface
AWS	Amazon Web Services
BRP	Balance Responsible Party
CHP	Combined Heat and Power
CMP	Commercial Market Player
DER	Distributed Energy Resource
DH	District Heating
DMS	Data Management System
DR	Demand Response
DSO	Distribution System Operator
E-MPC	Economic MPC
ETP	Energy Technology Perspectives
EV	Electric Vehicle
HIL	Hardware-In-the-Loop
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ICT	Information and Communication Technology
IoT	Internet of Things
IT	Information Technology
JSON	JavaScript Object Notation
mFRR	manual Frequency Restoration Reserve
MO	Market Operator
MPC	Model Predictive Control
PV	Photovoltaic
RES	Renewable Energy Source
REST	REpresentational State Transfer
RPM	Regulating Power Market
SE-OS	Smart-Energy Operating System
T-D	Transmission and Distribution
TSO	Transmission System Operator
WebGUI	Web Graphical User Interface
WP	Work Package
XML	eXtensible Markup Language

Executive Summary

This deliverable describes the realization of the Danish Pilot under the Horizon2020 SmartNet project. The primary purpose of Danish Pilot is to implement and evaluate the concept of model-based control principles for activation of flexibility from swimming pools to provide system balancing and grid congestion services at Transmission System Operator (TSO) and Distribution System Operator (DSO) levels. In 2018 in Denmark, it was seen that almost 43.5% of the electricity load was covered by the fluctuating and partly unpredictable wind power generation. This substantial penetration of the stochastic wind power often leads to balancing problems. The Pilot aims at assessing the potential of the provision of ancillary services from an aggregation of Danish summer houses with swimming pools. Summer houses with swimming pools consume substantial amounts of electricity for water heating and humidity control. The electricity demand from summer houses is particularly flexible. For example, swimming pools have a large thermal capacity, thus, the load to heat pool water can be disconnected or shifted with little consequences on the occupants' comfort within given intervals, which in turn depends on the thermal capacity, i.e. on the volume of the heated environments. This makes them particularly well-suited to the provision of ancillary services. As a result, the Danish Pilot intends to assess and demonstrate, to which extent, the flexibility of summer houses can be exploited to provide both Transmission and Distribution (T-D) grid levels with ancillary services.

The Danish Pilot setup is tailored to the existing situation in Denmark, where the large penetration of the fluctuating wind power often leads to balancing problems. Such problems are handled by the large thermal loads of the District Heating (DH) systems. The main characteristic of the Pilot is a large thermal capacity represented by the water in the pool of the summer houses. The Danish Pilot benefits from the use of price-based indirect mechanism to control the set-points of thermostats of swimming pools in rental summer houses, alleviating many of the issues arising in both T-D grids.

In the price-based indirect mechanism, Distributed Energy Resources (DERs), i.e., swimming pools, after receiving the price signals, calculate: i) the optimal consumption profile within the forecast horizon in dependence from the present price signal coming from the market, and, consequently, ii) the set-point for the thermostat of each summer house. This price signal is based on the grid load forecasts, the price forecasts, the weather forecasts, and the booking information (whether the summer house is presently rent or not). Measurements from the summer houses are afterwards collected and used, along with other data, to feed price-responsiveness information in the price response model which is used in turn in order to establish the price signal itself. The heterogeneous and stochastic nature of the responses of the DERs calls for new procedures for i) predicting how to invoke the needed flexibility, and ii) characterizing and describing the relationship between control signals and the resulting electricity load.

Testing the field of the proposed setup involves a small but a representative number of summer houses. For this Pilot, it has been decided that 30 houses, located in Blokhus and Blåvand in Denmark,

would be enough proof-of-concept for the estimation of the potential of summer houses in the provision of ancillary services.

Additionally, the report introduces some further Hardware-In-the-Loop (HIL) simulation tests which were carried out by employing both the Simulation platform developed in the SmartNet project and the specific setup of Danish Pilot [1].

1 Introduction

The Danish power system is characterized by a high penetration of Renewable Energy Sources (RES), wind, but, increasingly, also solar Photovoltaic (PV) systems. Other highly-flexible DERs, such as Combined Heat and Power (CHP), waste treatment plants, as well as Electric Vehicle (EV) and heat pumps are also expected to have a significant role in the mid-term. Figure 1.1 shows the share of electricity originating from RES in Denmark during a specific period. In 2017 in Denmark, it was observed that 44% of the electricity load were covered by the fluctuating and partly unpredictable wind power generation. This large penetration of the stochastic wind power often leads to balancing problems. Nowadays, these balancing problems are to some extend handled by the large thermal loads of the DH systems.

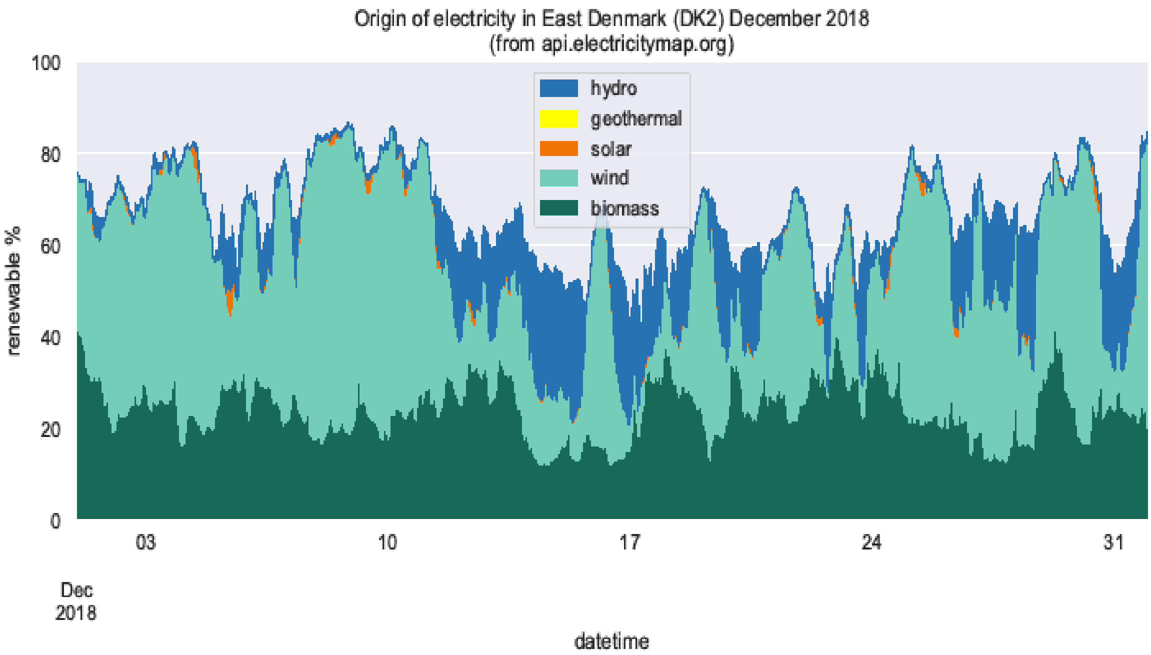

Figure 1.1 share of electricity originating from RES in Denmark during a specific period

Danish Pilot's main purpose is to assess the opportunity of making use of predictable demand to contribute to T-D grid operation. The main characteristic of the Pilot is a large thermal capacity represented by the water in the pools of the summer houses. Therefore, the primary focus of this Pilot is to demonstrate how the pilot set up including the models, technologies and algorithms can be used to provide the next generation of balancing services. The summer houses are in areas where the T-D grid is weak in terms of voltage control. It is important to notice that this deliverable describes the "living lab" or physical implementation of the system in 30 summer houses with swimming pool. This setup is aligned with existing situations in Denmark coupled with the existing balancing market. It is aimed at presenting the use of price signals to control the set-points of thermostats of swimming pools in rental summer

houses. Such price-based control is capable of handling many of the issues arising in both T-D grids, as well as balancing wind power generation.

2 Overview of Activities and Responsible Partners

An important technological advancement incorporated into Danish Pilot in SmartNet is the field test and proof-of-concept of DERs using unidirectional communications. In such unidirectional context, two different control mechanisms, i.e., direct and indirect, can be implemented. The former is a direct control signal requesting the DERs to turn on/off based on the optimization done at the aggregator's side while the latter, which is adapted to Danish Pilot, allows DERs to perform economic optimizations and leaves to the DER themselves the ultimate decision to get activated. Note that the Pilot considers only the SmartNet ancillary services market and completely disregards previous energy markets (Day-Ahead and Intraday). In Danish Pilot, the aggregator acts also as the Balance Responsible Party (BRP).

The following reviews the main activities done in the Danish Pilot followed by the description of the involved partners and their main responsibilities. The operation of Danish Pilot is materialized by addressing three main challenges:

1. **TSO-Aggregator-DSO-Interactions:** It addresses the engagement of coordination schemes, relevant setup, and the market principles. The main actors are ENERGINET, ONE, Nyfors, DTU, and ENFOR.
2. **IT Infrastructure and Cloud Services:** It points to the Information Technology (IT) infrastructure, communication protocols, cloud computing setup, and the Internet of Things (IoT) solutions implemented and used in the Danish Pilot setup. The main actors are EURISCO, Nyfors, NOVASOL, ENFOR, DTU, and ONE.
3. **Smart House Models and Controllers:** The price-based indirect control mechanism and models developed for the design of the Model Predictive Control (MPC) in the lower part of the Pilot are the main drivers of Danish Pilot. The main actors are DTU and ENFOR.

Here the actions carried out by the partners are involved in the Pilot:

- **DTU** develops mathematical models for the heating dynamics of the summer houses. Furthermore, it coordinates the Pilot and the interactions with other partners to utilize the models and software for aggregation/disaggregation and market clearing developed in the project.
- **ENERGINET** provides specifications on the requirements in terms of ancillary services at the TSO level (e.g., balancing needs and congestion management requirements). Furthermore, **ENERGINET** supports data analysis and brings experience in the management and control of power systems.
- **Nyfors** brings ability in the management of the relevant distribution grid issues for the case study, as well as provides information on the requirements in terms of local ancillary services (voltage regulation).

- **NOVASOL**, as the summer house rental company, provides data on its summer houses included in the field tests (e.g., historical time series on consumption and occupancy of the summer houses). **NOVASOL** acts as an intermediate between house owners and house renters.
- **EURISCO** delivers knowledge and hardware while taking care of the installation of communication systems based on widely used International Electrotechnical Commission (IEC) standards. Furthermore, **EURISCO** ensures that the specifications and standards decided in the project to use are respected. **EURISCO** also acts as the Market Operator (MO) in the Danish Pilot developing flexibility bidding and market clearing procedures.
- **ONE** serves the Danish Pilot with its expertise within the aggregation of DERs and knowledge on the modalities for market interaction. **ONE** also creates the price signals to be broadcasted to DER units, which act as the Economical Aggregator in the Danish Pilot.
- **ENFOR** presents a WEB-based forecasting of prices for DK1 (western part of Denmark), power load of the summer houses, and wind power generation in DK1. It also works closely with **DTU Compute** in setting up the Data Management System (DMS) for the lower level of the Danish Pilot, and for implementing the cloud-based solutions for predictive model control. **ENFOR** is on a subcontract with **DTU** in the project. **ENFOR** also provides HPC facilities for the calculations, and the hardware for the cloud solution used for forecasting and control. Therefore, **ENFOR** jointly with **DTU** acts as the Technical Aggregator in the Danish Pilot.

The following section describes the system model of the Pilot and supplies some background related to the price-based control used at the lower level of the Pilot.

3 Architecture of the Danish Pilot

Summer houses with swimming pools consume substantial amounts of electricity for heating water and humidity control. The electricity demand from summer houses is particularly flexible. For example, swimming pools have a large thermal capacity thus, the load to heat pool water can be disconnected or shifted with little consequences on the comfort of the occupants within given intervals that depend on the size of the heated environment and other factors. The Danish Pilot is aimed at assessing and demonstrating to which extent flexibility of summer houses can be exploited to provide both T-D grid levels with ancillary services.

NOVASOL is a rental company that operates about 900 summer houses with an indoor pool in Denmark, holding an average annual power consumption of about 30.000 kWh per house. They also do pool inspections 55.000 times a year – this includes heating adjustment tasks prior and after arrivals/departures. Figure 3.1 demonstrates geographical locations of summer houses in Denmark, which are participating in Danish Pilot. Although the summer houses are not occupied permanently, they have a year-round base load, e.g., to guarantee that the pool water temperature does not fall below a certain threshold, should a customer wish to rent the house with short notice. The location of the houses, coupled with their thermal inertia, make their load a suitable candidate for the provision of grid services. Indeed, many are in coastal areas of northern Jutland (in the DK1 control area of NordPool), where the distribution grid is weak. At the same time, a large capacity for wind power production is installed in the area, making summer houses a suitable candidate for the provision of congestion management services.

NOVASOL joined the SmartNet project in order to be able to offer lower energy cost for house owners with pool and thereby attract more owners, while at the same time ease their pool handling services. Figure 3.1 demonstrates geographical locations of summer houses in Denmark, which are participating in Danish Pilot.

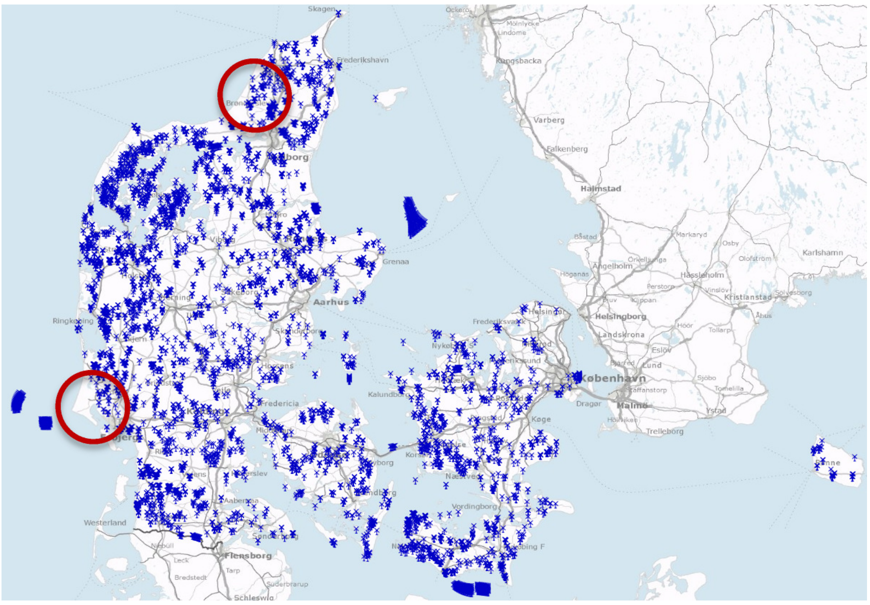

Figure 3.1 Geographical locations of summer houses in Denmark.

Exploiting a small but representative sample of the summer houses operated by the summer house rental company, the Danish Pilot demonstrates swimming pools' value in providing ancillary services both at local level to the DSO, and transmission level to the TSO. The ***Aggregator*** which is referred to as an ***Economical Aggregator*** in this document acts as the aggregator of the summer houses and oversees their flexibility offering into the local or national markets, where relevant. The necessary Information and Communication Technology (ICT) required to establish the coordination between the Economical Aggregator and other actors through the physical facilities is also provided falling under the responsibility of the automatic control algorithms which is also referred to as a ***Technical Aggregator*** in this document.

3.1 Current Situation in Denmark

The uniform taxation scheme, currently in Denmark, results in flat electricity prices for residential consumption, which in turn has discouraged investments in smart energy management systems. Further the house owner is personally taxed from both rental income as well as for the utility cost that guests in the house consume.

Figure 3.2 demonstrates the economic effect of a market where kWh prices are not flat during the day, which keeps the overall amount of kWh consumption steady. In order to do this, accurate and timely meter measurements are needed. Furthermore, it is expected but not incorporated in this calculation that the total kWh consumption will be less due to optimal heating of pool using the algorithms developed by SmartNet. Note that house renters pay for the electricity for the period they rent the summer houses. House owners pay for the electricity of the remaining available periods.

House owners economic effect of kWh consumption	
Rental income	200.000
Energy consumption (kWh)	60.000
Total Owner gross income	**260.000**
Fixed Deduction (2018)	-40.000
Total Owner net income	**220.000**
40% deduction (tax free)	-88.000
Tax base	132.000
Tax amount (34%)	**44.880**
Current scenario:	
Owner income after tax - DKK	**215.120**
Utility cost	-60.000
Net effect - income to owner after energy cost	155.120
Alternative scenario:	
Owner income after tax - DKK	**215.120**
Utility cost 20% lower due to demand response	-48.000
Net effect - income to owner after energy cost	167.120

Figure 3.2 The economic effect of a market where kWh prices are not flat during the day for a typical Danish summer house with an indoor swimming pool (NOVASOL)

Today, electricity consumption in summer houses is managed through simple algorithms that do not envisage any interaction with the grid operators. For example, pool water is warmed through standard thermostats that switch heaters on and off when the temperature reaches some preset thresholds. The DSO currently has electricity meters placed in the distribution grid. These meters are placed on the 150/60 kV and 60/10 kV transformer stations to monitor the power consumption/production. Furthermore, DSO has points of monitoring units like voltage, current, power, and reactive power, for daily management of the distribution grid.

3.2 Ancillary Services

This Pilot aims at assessing to what extent flexible summer houses can provide ancillary services of the following types:

- **Balancing:** Given that summer houses are equipped with appropriate infrastructure for remote data acquisition and control, they can be an important provider of manual reserves and balancing power. Indeed, control signals can be implemented in a short time. Furthermore, the large inertia of pools allows for a shift of electricity consumption (and thus of the "rebound" in load) by several hours, also depending on the occupancy state of the house.
- **Voltage regulation:** Summer houses are typically located at the periphery of radial distribution grids. The Economical Aggregator can support voltage stability by sending appropriate control signals to summer houses located below a critical node of the distribution network. Since summer houses are often located in clusters, holiday periods tend to result in particularly large consumption in these geographical areas as many summer houses are rented out. This is a

situation, in which, the active coordination of these flexible sources through the Economical Aggregator has an importance for grid stability.

- **Congestion management:** Many Danish summer houses are in areas with large installed wind power production capacity. Hence, they may play a role within congestion management as required by the TSO to achieve an optimal routing of the renewable power output.

This Pilot primary focus is on **balancing services** and **voltage regulation**.

3.3 Field Testing

Field testing of the proposed setup involves a small but representative number of summer houses. For this Pilot, it has been decided that a set of 30 houses, representing 3% of the assets of same type operated by NOVASOL, would be enough proof-of-concept for the estimation of the potential of summer houses in the provision of ancillary services in Denmark. In addition, NOVASOL has also provided historical data on the energy consumptions of other summer houses for further analysis to enable NOVASOL to utilize the results in facilitating the rollout of a similar set up in their existing summer houses in the future. The field testing is conducted under the existing regulatory conditions in Denmark, which reflects the issues often faced by a large BRP in the existing balancing market. The SmartNet solution then provides a proof-of-concept of a solution, which might be relevant in other existing cases with large thermal loads, which today mostly is the DH networks. A secondary purpose of the field tests is also to provide data making it possible to establish models and controllers for simulating a large number of houses aiming at taking full advantage of SmartNet Simulation Platform for testing future scenarios.

3.4 Intelligence and Software Solutions

The intelligence base (models, forecasts, controllers, and system architecture) of the Pilot is drawn from the models devised in [2], [3], [4], [5], [6] [7]. Mathematical models for the dynamics of summer houses, aggregation/disaggregation as well as market clearing models and the resulting software implementation are of utmost importance for the materialization of the Danish Pilot. However, in some cases, it was not possible to use the models and methods devised in [2], [3], and [4]. The reason is that the Danish Pilot is served as a proof-of-concept. Thus, to implement theoretical developments in real-life, where real-life as an unpredictable phenomenon, includes numerous probabilities and uncertainties, models developed over the course of project had to be updated to be useable within the Pilot. As a result, this document describes the models used for the simulation of the summer houses with a pool, as well as the models and methods used for the price-based MPC of the heating systems.

3.4.1 Smart-Energy Operating System: Hierarchical Optimization for Control Problems

The Smart Energy Operating System (SE-OS) is a framework for implementing flexible energy solutions [8]. It consists of both direct and indirect (mostly price-based) control of the electricity load. It contains methods to implement solutions for handling ancillary service problems. Most importantly for the SmartNet project, the concept is equipped with, for instance, a methodology for price-based control of electricity load in future electric and integrated energy systems.

The SE-OS, as shown in Figure 3.3, is built as a hierarchy of four nested stochastic optimization layers representing aggregated consumption on various spatial and temporal scales [8]. Within for instance the CITIES project (see [9]), SE-OS has been used to implement flexible and smart grid enabled solutions for waste-water treatment plants, interactions between power and heat, smart energy control of supermarket cooling systems, new solutions for control of heat pumps, and methodologies for using thermal mass in buildings as well as DH systems as an energy storage [5]. Price-based control is an important part of the SE-OS framework. This concept for price-based control was used first in the FlexPower project; see for instance [10] and [11]. Danish Pilot has benefited from SE-OS by implementing the top-down one-way communication from aggregators to DERs using price-based control method.

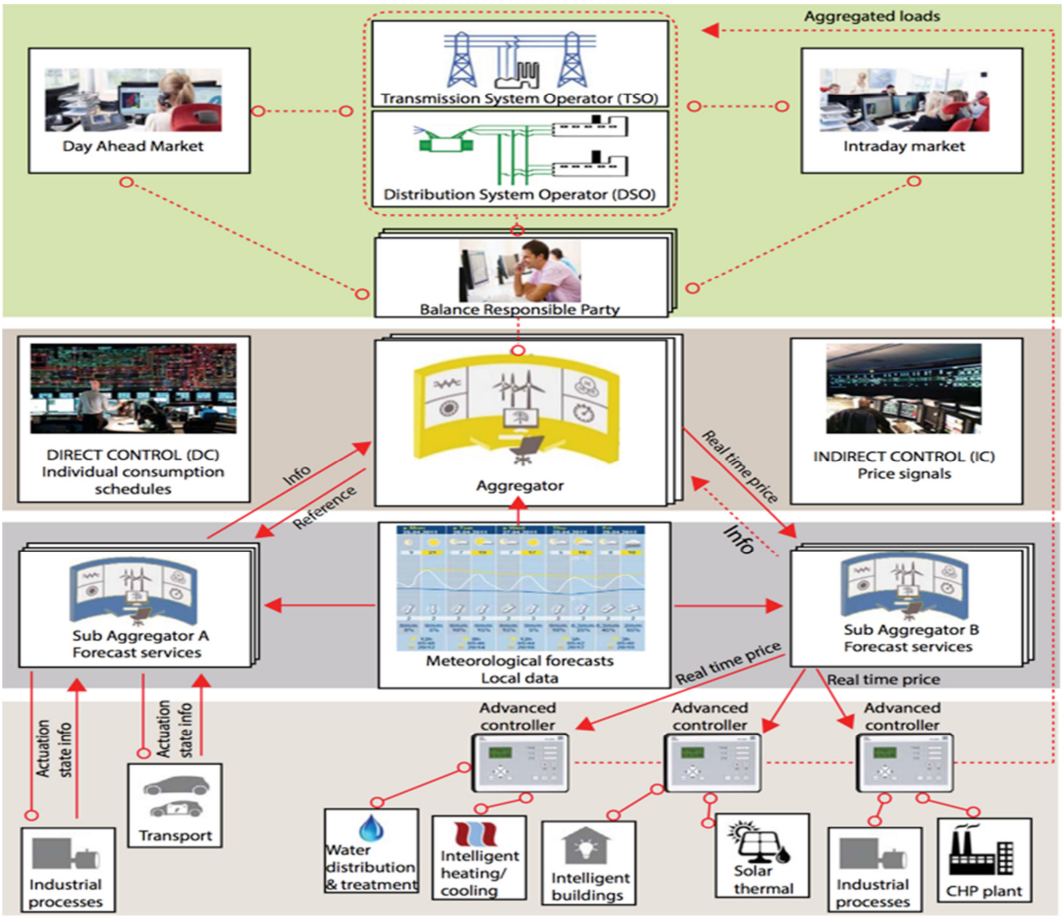

Figure 3.3 The SE-OS framework.

3.5 Information Flow

Figure 3.4 represents the *main* signals (red lines) exchanged among the partners participating in the Pilot [12]. Figure 3.5 also illustrates the functionalities, communications, and ICT interfaces in the Danish Pilot divided into two ***Lower*** and ***Upper*** Levels. The Pilot, which focuses on balancing and voltage regulation, is characterized by a bidding and clearing procedure operated by the MO. It receives grid status from the TSO and the DSO (line 1 in Figure 3.4) and interacts with Commercial Market Player (CMP) to gather the required flexibility. A flexibility model predicts the electricity demand as a function of prices (line 2 in Figure 3.4). The CMP sends out both prices and price forecasts (line 6 in Figure 3.4). Such communication intends to create a balanced situation for the relevant MO for the next hours. Actual prices and price forecasts are received by the Technical Aggregator. Based on the latter, weather forecasts, and booking information, it calculates the optimal set-point for the thermostats of all the summer houses. Measurements from the summer houses are collected (line 7 in Figure 3.4) and used to feed price-responsiveness information in the flexibility model.

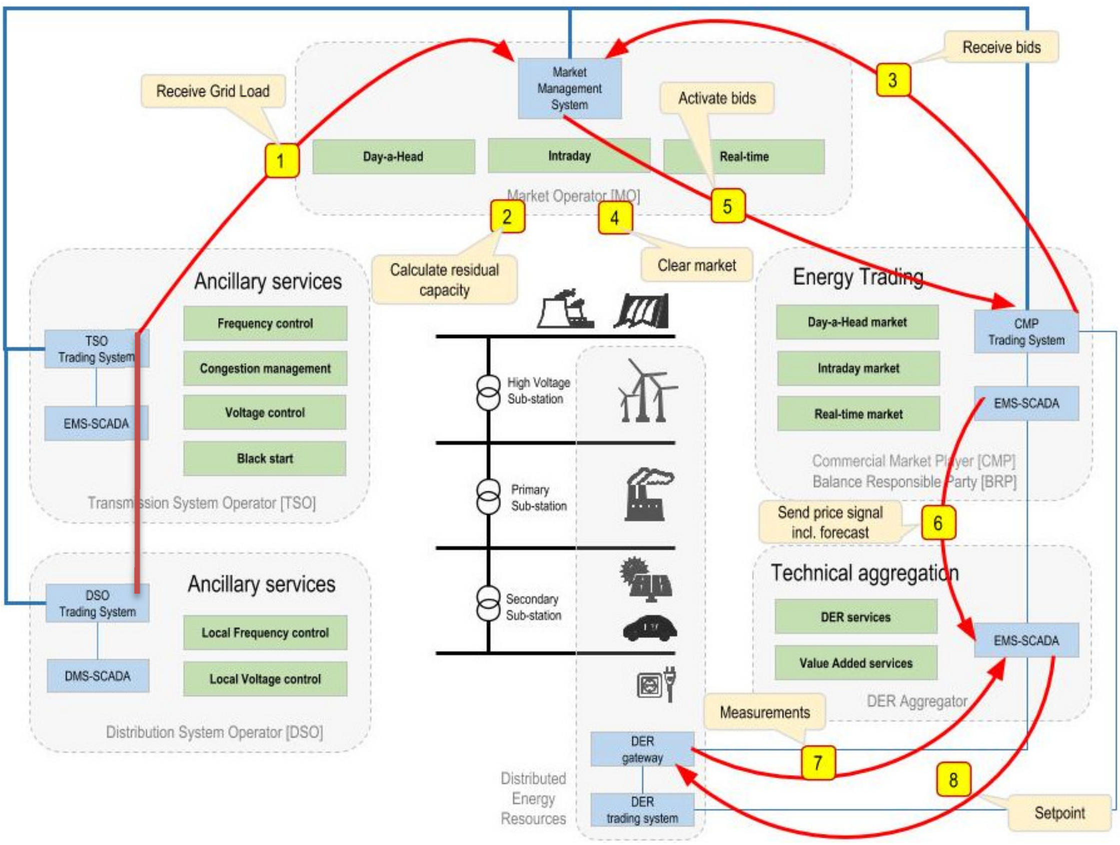

Figure 3.4 Information Flow (see [12] for more information).

The implementation of the Pilot has been made in a step-wise manner: the laboratory tests; the first demonstrative implementations were completed in late 2016. The laboratory tests were carried out using a water tank as a small representation of a swimming pool installed in Eurisco's lab that had sensors and actuators connected to it and was also connected to ENFOR platform for the remote control purposes. Upon completing the lab experiments, a full field test has been conducted on selected summer houses during 2017 and 2018. The selection has been based on the summer house characteristics, stability of their communication network and their booking status.

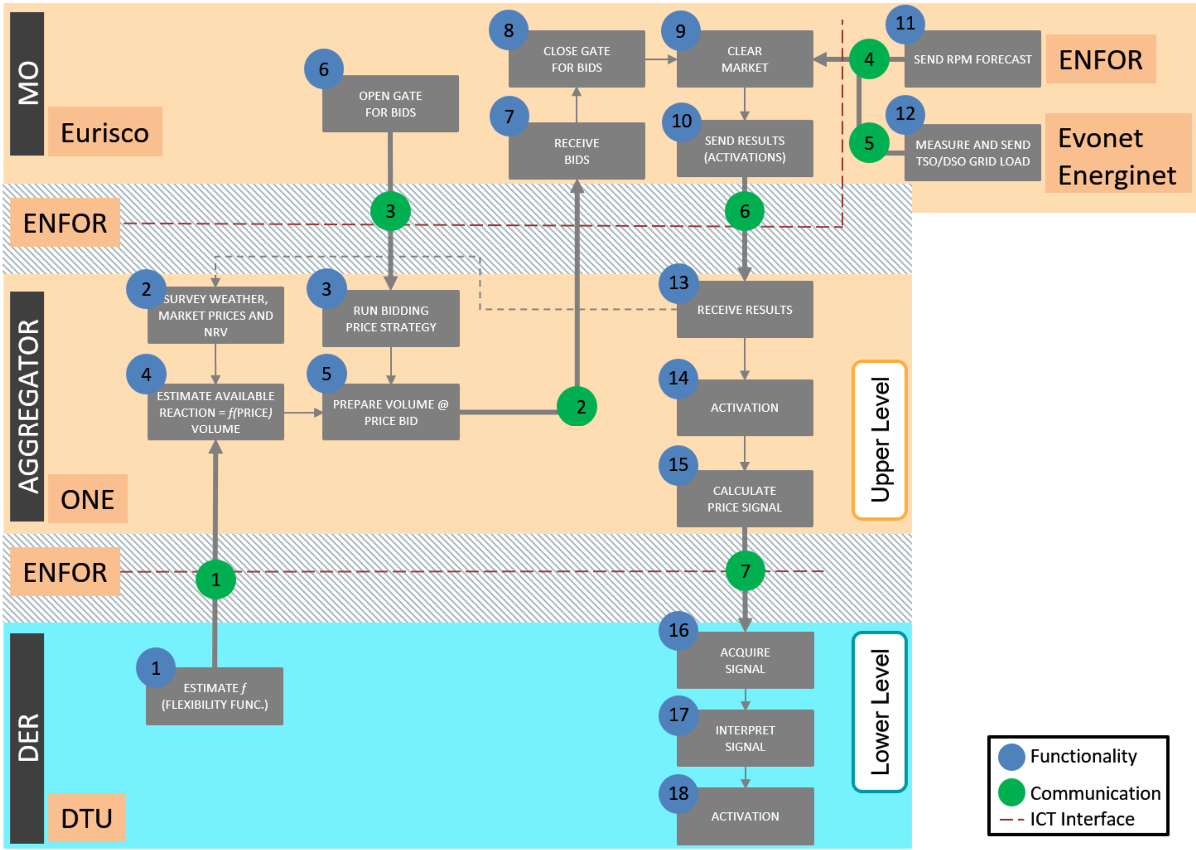

Figure 3.5 Functionalities, communications, and ICT interfaces in the Danish Pilot divided into lower and upper levels.

3.6 Cloud Platform

The ***Technical Aggregator*** has been developed based on a cloud platform for aggregating the data receiving from SN-10 gateways, which have been installed in summer houses and running the controller model. The data flow to the cloud platform is shown in Figure 3.6. All data communication with SN-10s

and the summer houses (and the rental company to receive booking information) is done using a REpresentational State Transfer full (RESTful)[1] Application Programming Interface (API).

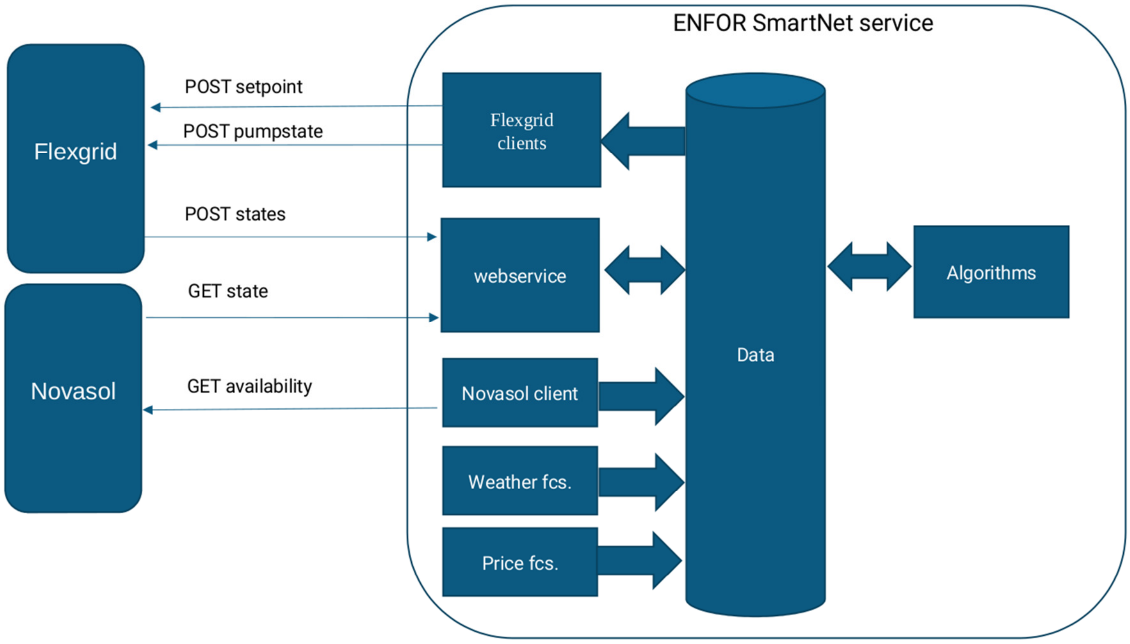

Figure 3.6 Data flow to and from the cloud platform.

The Cloud platform provides a Web-based Graphical User Interface (WebGUI) for monitoring the system that has been developed for this pilot, see Figure 3.7. The WebGUI shows the data for all houses and related forecasts making it possible to inspect historical data. The system is used by the summer house rental company for entering the temperature requirements for each pool.

[1] Representational State Transfer (REST) is a software architectural style that defines a set of constraints to be used for creating Web services. Web services that conform to the REST architectural style, termed RESTful Web services (RWS), provide interoperability between computer systems on the Internet.

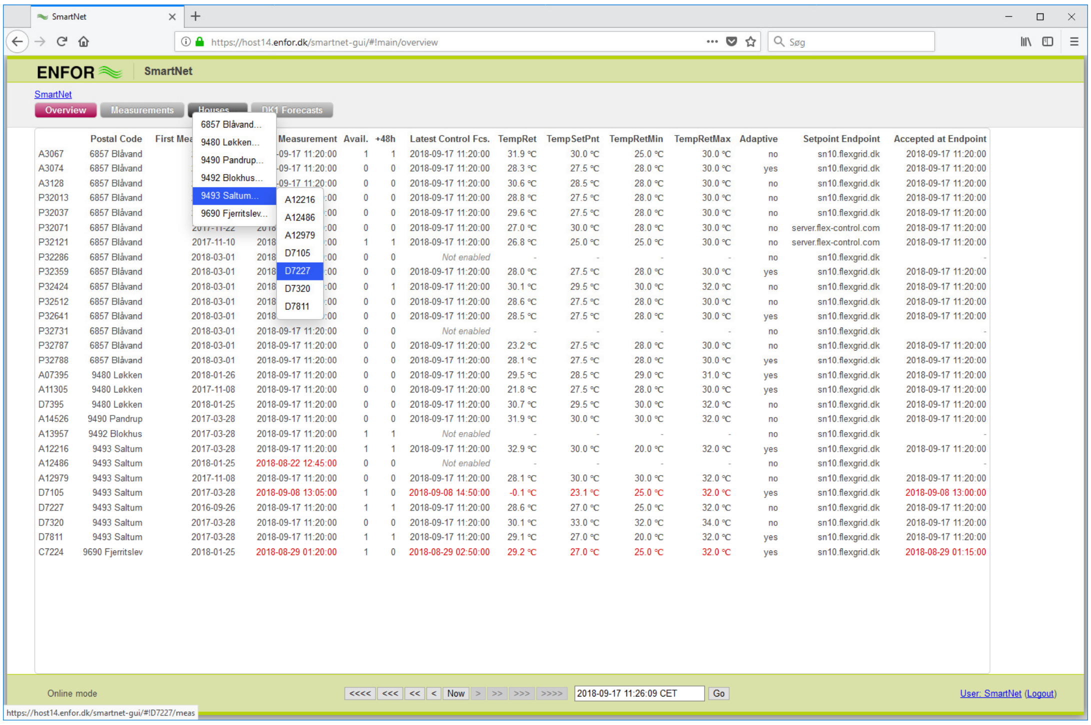

Figure 3.7 Web-based graphical user interface for monitoring the system.

The Cloud platform provides online monitoring of the entire system in a number of forms. Email alerts are sent to the Technical Aggregator in case of any missing data, and specially designed alerts are sent to the rental company in case of missing house data or violations of temperature requirements.

3.7 Forecasting Methodology

Methods for probabilistic price forecasts, as well as probabilistic load forecasts for all the summer houses, beside hourly weather forecasts for houses, wind power forecast, power load forecast, spot price forecast (wind and load forecasts are used for the spot price forecast), and an imbalance price consumption forecast have been provided. Online connections to providers of meteorological forecasts, as well as nearby real time measures (when available) have also been established. To support the switch to 5-minute control, an imbalance price consumption forecast in 5-minute time resolution 24 hours ahead is also provided. The method developed to provide such 5-minute prices is explained in Section 5.7.

4 Concepts of Market Design and Control Strategies

The Danish Pilot aims at performing in-depth analysis and test of control of DERs. There are several solutions for activation of flexibility from DERs both on the market and aggregation levels, which are defined in the following.

4.1 Indirect Control and Market Design Mechanisms

This part briefly describes the Indirect Control through the Economical Aggregator, and the MO followed by a comparison table explaining the advantages and challenges of different concepts of market design. Each of the two mechanisms holds advantages and challenges. Danish Pilot employs the second mechanism, which is the control-based approach using an indirect control method requiring just unidirectional signals from the Economical Aggregator towards the flexible DERs ending up in a stochastic control for the DER assets. Such adaption turns the power system operation problem into a control problem where model of the system, devices, and services can be nonlinear, dynamic, and stochastic.

The Economical Aggregator issues prices to control the electricity consumption in the summer houses in a way, which is defined by specific cost functions. These cost functions can be constructed in several ways. One obvious choice is to define a cost function in which the load (partly) matches the wind and solar power production for the controller algorithm to control the power consumption. Another possibility is to define a cost function such that peak power consumption is reduced.

The total price broadcasted to the summer houses might also partly consist of a grid-control related price, such that the TSO by altering the price, can avoid grid congestion and partly control the power load in various areas of the grid [13]. For the summer houses, the control of the set-point of the thermostats is typically an economically-related cost function like those related to E-MPC (Economic MPC).

On the other hand, from the Economical Aggregator's perspective, the aim is to test the feasibility of aggregation models in an indirect-control environment, aiming to schedule decentralized assets potentially by the thousands or millions through broadcasting signals. There are two main approaches to implement this technology: via price signals (adapted by the Danish Pilot) or scalar signals. These two alternatives, although based on the same principle and sharing many advantages worth experimenting in Danish Pilot, present significant differences in terms of operation, implementation and potential application in future scenarios. Figure 4.1 highlights the main features of each method along with their conceptual differences. Table 4.1 also compares price-based signals with scalar signals from the aggregation's point of view.

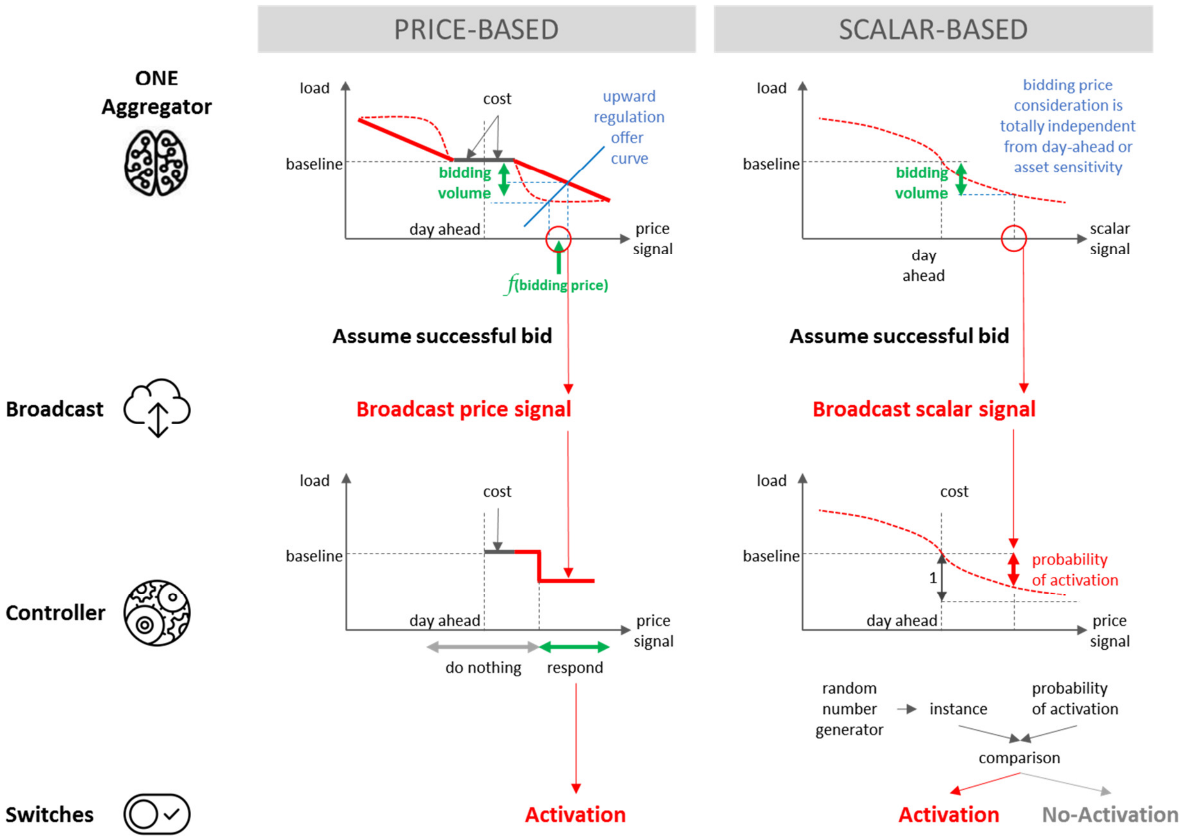

Figure 4.1 Main features of two main ways to implement the indirect control through the Economical Aggregator along with their conceptual differences

Table 4.1 Comparison table for scalar and price based signaling

	Price-based signal	**Scalar-based Signal**
Economical Aggregator bidding	Economical Aggregator has an 'accurate' model of price elasticity of DERs.	Economical Aggregator has an 'accurate' model of the reaction for each scalar.
Economical Aggregator clearing	Economical Aggregator acquires firm commitment for a given volume and a given price towards the DSO and TSO.	
Economical Aggregator delivering	Depends upon price elasticity model	Controlled by the strength of the scalar. Scalar parameter
Economical Aggregator-DER communication	Energy price for the reactive energy	Scalar

DER control	Interprets Prices to decide	Interprets a Scalar to decide
Stochastic control	Elasticity of reaction to only '*interesting prices*' batches (possible approach)	Elasticity of reaction to the scalar
PROS	DER participates actively to the market	Simpler and straight forward (from communication's perspective). It offers a more understandable product to the end user.
CONS	- Requires a baseline for reactions - Settlement process requires a replica of direct control for reactive observation asset by asset Two price logics: one at Economical Aggregator to bid as the MO, and another decentralized one for acceptance of the signal from Aggregator	- Consumer is not in control of the price. Settlement can only be through either activations or capacity prices (incentive schemes), as the price signal does not arrive to the end user.

4.1.1 Indirect control through the Economical Aggregator

Figure 4.2 shows the communications among the actors defined in this concept. The price-based approach implements an indirect control consisting of one-way communication from the Economical Aggregator to the DERs, where the price signal is used to influence the whole load of the DER during the activation period. After clearing the market, the MO sends the market clearing information to the Economical Aggregator. In turn, the Economical Aggregator calculates the price-based control signal estimating the flexibility function. The flexibility function predicts the electricity demand dynamically as a function of a time series of prices. The purpose is to activate the flexibility of the DERs in a way, which creates the most value for the DERs and the Economical Aggregator during the next hours. Then, it broadcasts control signals to the DERs, prompting a certain electricity consumption profile of the summer houses. These signals and the induced response may serve to reduce peak power consumption or to increase power consumption in case of available power surplus. This approach requires no feedback since it operates in an open-loop scheme.

After receiving the signals within a specific time resolution (for example 15 minutes), each DER uses the information to plan the optimal consumption profile, which results in the lowest electricity bill while

staying within the boundary conditions, such as the pool temperature. Before reaching the next time step, the price for the next time step is sent from the Economical Aggregator including an updated price forecast. Each DER updates its consumption profile for each time step. This results in a quite simple unidirectional communication system, which does not require the commitment of the DERs. It lets the DERs optimize their consumption continuously. One challenge is, however, for the Economical Aggregator to predict the response from the DERs at a given price signal.

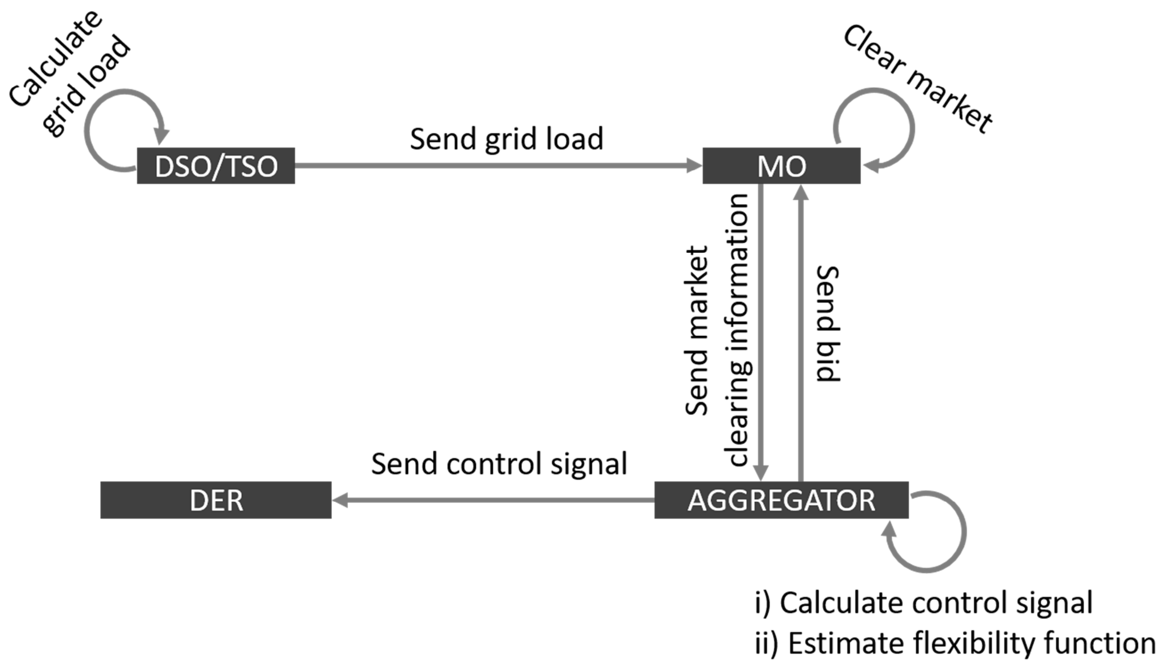

Figure 4.2 The main communications in controlling DERs indirectly through the Economical Aggregator.

By establishing a price generation mechanism, the Economical Aggregator, described in Section 4.2, determines the optimal real-time price signal based on the estimations of the Aggregated response; the so-called Flexibility Function. Such estimations are based on the historical data, and the characteristics of the response can be tailored to specific needs. In International Energy Agency (IEA) Annex 67 "Energy Flexible Buildings," [14], for characterizing the aggregated flexibility response on a step-change in price, the authors use a step-response function as illustrated in Figure 4.3. The Aggregated response in electricity demand for a particular type of DERs showing six characteristics of the Demand Response (DR) to a step increase in electricity price. τ: The delay from adjusting the electricity price and seeing an effect on the electricity demand, equal to approximately 0.5s here. Δ: The maximum change in demand following the price change, in this case, close to 0.2. α: The time it takes from the shift in demand starts until it reaches the lowest level, approximately equal to 0.5s here. β: The total time of decreased electricity demand, roughly equal to 2s here. A: The total amount of decreased energy demand, given by the green-shaded area. B: The total amount of increased energy demand, given by the grey-shaded area.

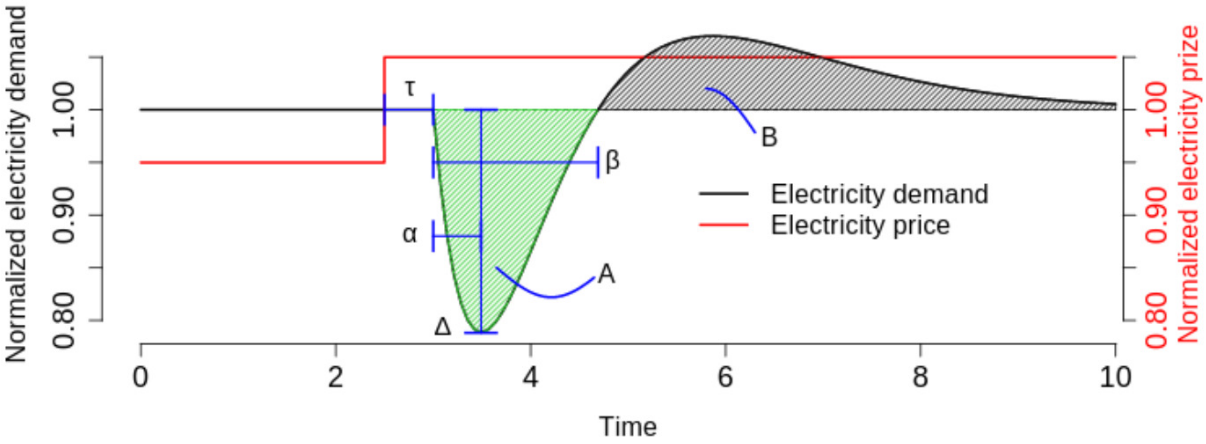

Figure 4.3 Example of a flexibility function.

4.1.2 Indirect control from the MO

In the current Regulating Power Market (RPM) up- or down-regulation is activated from a merit order list of bids. The price of the most expensive activated bid is the marginal price as in the Day-Ahead Market. The marginal price will be paid for the activation of all the selected bids. This price is currently not published until after time of operation. Yet if a large market player has put many bids on the RPM, it is able to guess the market clearing price. This creates an inequality of information, which gives the large market players an advantage over the small ones. To publish the cost of imbalance from before the time of operation would even out this inequality.

An alternative to control of DERs through an Economical Aggregator is to have the MO publish the clearing cost of imbalance before the time of operation and thereby let the DERs react on it, as Figure 4.4 illustrates its main communications. One challenge in the price-based indirect control from MO solution could be that market players will have less incentive to bid in the RPM because they could wait and react to the imbalance cost afterwards. Therefore, this could remove liquidity from the RPM.

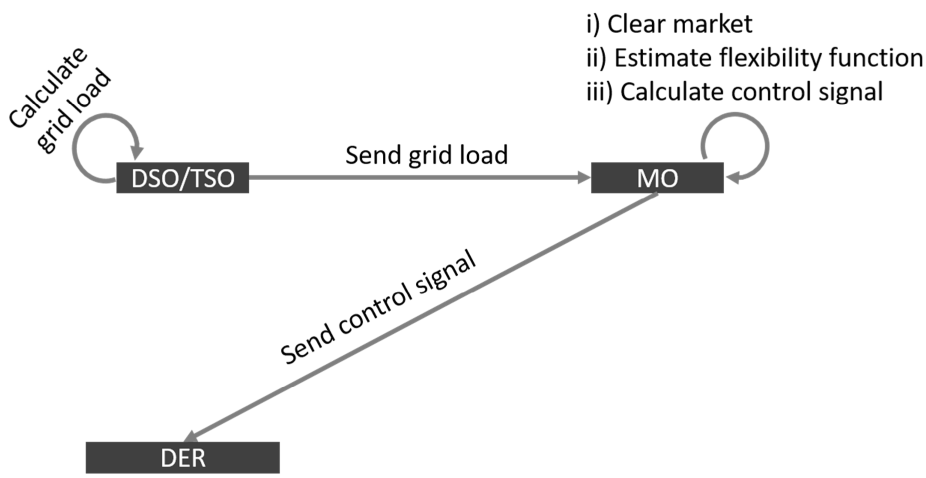

Figure 4.4 The main communications in controlling DERs indirectly through the MO.

Instead, the MO could replace the RPM by an indirect control system and publish a price and a forecast designed to obtain balance. The price is set and frequently updated such that the system is in balance. To furthermore let DERs be settled directly at this price would give them the opportunity to optimize according to this price. This solution is similar to the solution proposed in Section 4.1.1. Nevertheless, the MO is broadcasting the price signal instead of the Economical Aggregator. One advantage is that the MO has more system information available and hence should be better at estimating the response to a price. Furthermore, the relative prediction error is smaller for a large population of DERs. One challenge is that it is an entirely different market design which could show some unexpected responses and that it leaves the balance responsibility at the MO.

4.1.3 Comparison between Indirect Control through the Economical Aggregator vs. from the MO

Table 4.2 shows Comparison between advantages and challenges of different concepts of market design.

Table 4.2 Comparison between advantages and challenges of different concepts of market design

Mediator	Advantages	Possible Challenges
Economical Aggregator	• Communication is simple and fast (requires neither a two-way communication, nor a computationally expensive market operation) • Low control requirements for the DERs • The risks can be calculated (since probabilistic statements about the response are provided) • Low entry barrier • Scalable to millions of DERs • Economic optimum for every single flexible DER in relation to the price signal. • Data privacy • Harvest the full flexibility • Offers a cheaper solution in terms of implementation/regular maintenance costs DERs participate actively in the market	• Exact response to prices is unknown Estimation of the flexibility curve might be difficult
MO	• Full use of flexibility potential • Directly available same price for all DERs • No contract needed • No need to go through Economical Aggregators or BRPs • The risks can be calculated • Closer market-consumer connection • Incredibly low transaction costs	• Exact response to price is unknown • Less information about near future load compared to current RPM (MO) Only suitable for

	Data privacy	close to real-time markets

4.1.4 Discussion and Conclusion on Two Indirect Control-based Approaches

As full real-time feedback is not required, the computational load and time decline considerably, thus, allowing to broadcast signals from thousands or even millions of assets. For this very same reason, indirect price-based control from the Economical Aggregator approach simplifies the communication scheme between parties. Once the communication among the parties is simplified, the next step should consider the regulatory concerns in which if the parties do not fulfil their commitments who should be responsible. This pilot has only investigated the technical aspects of the operations and the feasibility of applying the methodologies in larger scales. It has also been discussed and analyzed that sending price signals by the MO instead of the Economical Aggregator is technically feasible. However, it requires a fundamental redefinition of the role of MO. Moreover, the following challenges can arise: flexibility value loss, incomplete price information in price signals, and flexibility estimation and system balancing by MO (outside of its responsibility). Furthermore, adding an external commercial forecast provider can bring more transparency and forecast reliability even though it increases the complexity of DER participation in the market.

The main advantage of the price-based control through the Economical Aggregator is its simplicity in handling the situations, where it leaves the choice to the final consumer. From an economic perspective, indirect control better suits committed DERs, since it avoids bidirectional communication and allows them to maximize their revenue. As a final note, historical data in indirect price-based control approach is necessary either to calculate control signals or to estimate flexibility function. This has required the SmartNet to orchestrate an experimental period in Danish Pilot to get the necessary amount of historical data.

To have a mutual understanding of definitions, indirect control is enabled when incentives (e.g., price signals) are provided to DERs, but the decision is made locally. The price being broadcasted is linked to the imbalance cost. Therefore, a DER can choose to be out of balance and for instance consume more than planned at this price or consume less than planned while selling the extra energy at this price. This price, according to the TSO/DSO coordination schemes, takes DSO requirements and grid constraints into account.

4.2 Price Generation Mechanism by Economical Aggregator

The main technological advancement incorporated by Danish Pilot is the field test and proof of concept of the control of DR units (DERs). This is done through indirect control set-up using broadcasted

price signal in the lower level but participating in the existing market mechanism of bidding/clearing in the upper part of the set-up.

The translating party role is assumed by the Economical Aggregator, who is an active market agent in the day-ahead, intraday and real-time markets (as well as a supplier of the DERs) and also develops the capability and aggregates flexibility of heterogeneous nature and even stochastic nature, developing the risk management tools to let this flexibility participate in the market.

The overall process is described in Figure 4.5 along with main interfaces with other agents such as MO and Technical Aggregator.

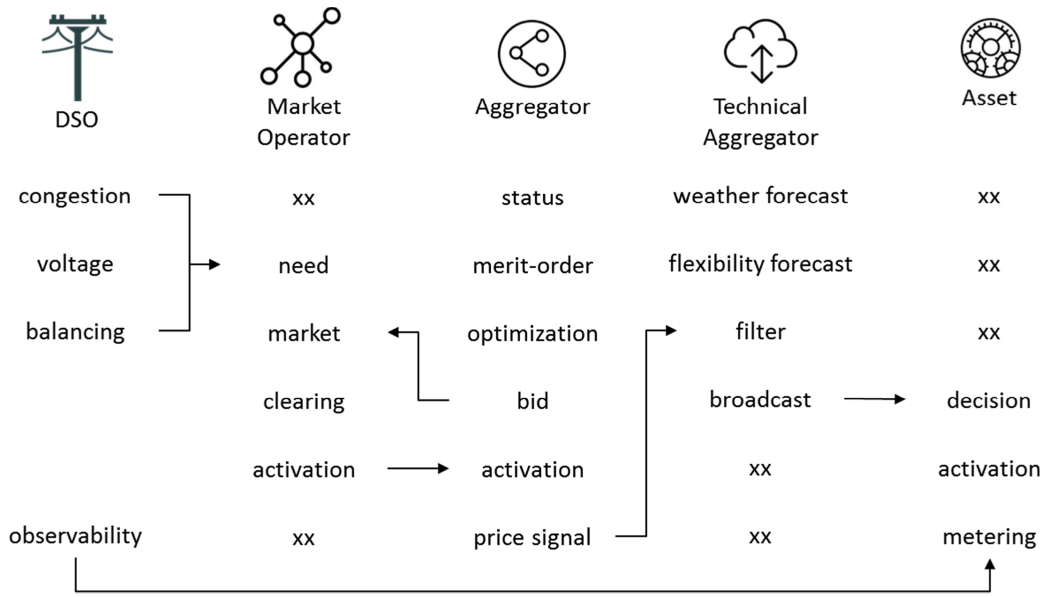

Figure 4.5 Diagram for the Danish Pilot from the (Economical) Aggregator's point of view.

In Figure 4.5, all different participants and tasks are represented in a short form. In the left side, the balance and the Market are represented, with its representative entity, the MO. The MO is a non-discriminatory platform in which agents can post bids for up and down regulating the flexibilities in the manner explained in Section 5.3. The MO will accept bids based on their merit order and locational adequacy. This MO should be cleared within the range of balancing incentive otherwise, one would be incentivized to go out of balance to bid into the MO market (see [15]).

In the middle column, the aggregation algorithm is briefly presented. This is one of the main features of the Danish Pilot, where the Economical Aggregator serves as a translator between "transactional" ancillary services and price-based control. This process involves a degree of understanding of the nature of the underlying flexibility, a method to price uncertainty and a platform to communicate with these decentralized DERs. In the real market set-up, market agents such as the Economical Aggregator face cascading market options across time, from day-ahead spot auction, followed by intraday markets, after gate closure counting on SmartNet market (MO) or Ancillary Services and the last chance in real time participating to balancing markets.

On top of the above, the complexity increases when there might be additional opportunities such as deviations from a stochastic load, non-responsive activations, and etc. within the Economical Aggregator's portfolio. Hence, in order to not only maximize the value for the customer but also enhance the functioning of energy markets, the Economical Aggregator must consider all options and produce the merit order list to his flexibility at hand. This creates additional complexity as one must produce estimates of all these markets since they have different time deadlines. Therefore, it is produced based upon the estimates and has an inherent risk premium attached to it.

Once the merit order locates the target market to participate in, along with the characterization of the reaction (including constraints, rebound effects, etc.) the optimization is performed to match how much volume at which price can be placed into the SmartNet market bid. It can also happen that one successful bid in a one-time step generates an incentive / a constraint to bid in a future time-step.

5 Upper Level of the Danish Pilot

The purpose of this part is to describe the upper level setup of the Danish Pilot and market perspectives of control based (price signal based) activation of DR, as shown in Figure 5.1. The Upper Level of Danish Pilot includes market clearing at the MO and the interactions among MO, Economical Aggregator, DSO, and TSO. The Pilot considers two ancillary services namely balancing and grid congestion management in 5-minute time steps, which are handled in the SmartNet Reserve Market, which is a refinement of the current RPM. Both conceptual and practical setup are described separately.

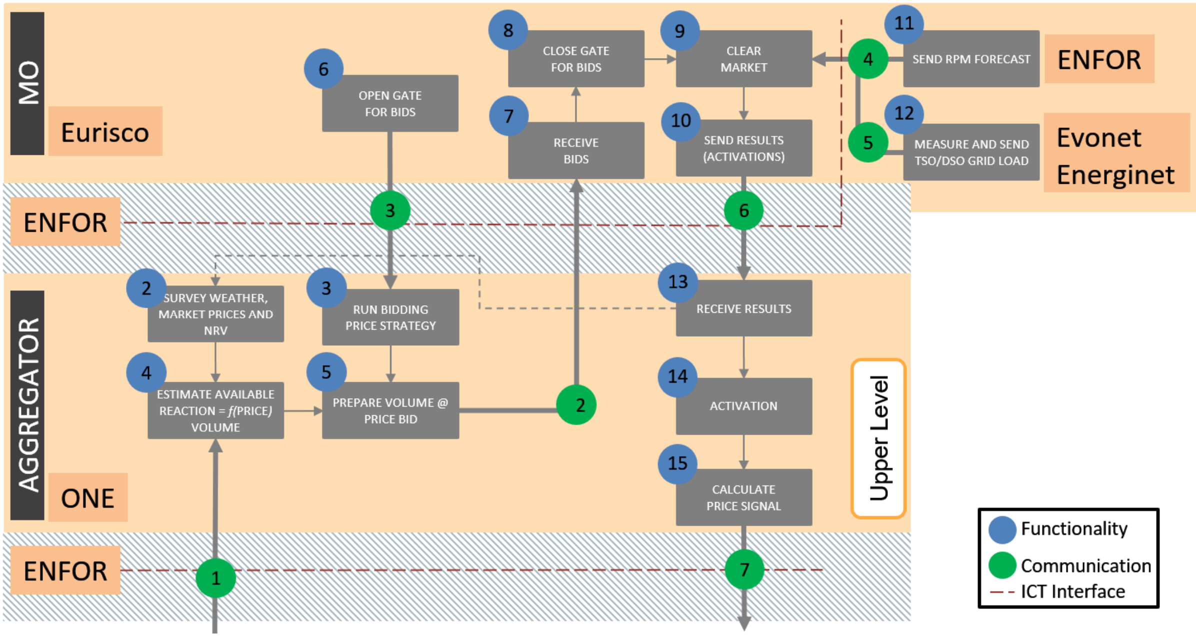

Figure 5.1 Conceptual setup of the upper level of Danish Pilot (see Figure 3.5 for the whole setup).

The Economical Aggregator estimates available flexibility and cost, decides on a bid strategy, and sends the bids to the MO **(2)**. The bids contain price, quantity, and location of the bid. The latter is included to enable the option of using the bids for grid congestion management on distribution level. It is possible to place the bids for the coming 12 time-steps, which equals 60 minutes. Furthermore, the bid can be more advanced including intertemporal constraints as described in [16]. Meanwhile, the grid operators, DSO and TSO, measure the grid load and send the data to the MO **(5)** along with the updates of the available grid capacities in case there are changes.

The SmartNet Reserve Market uses 5-minute time steps with a rolling horizon optimization, meaning that Economical Aggregator sends the bids for the following 60 minutes in a 5-minute resolution. The MO calculates the optimal dispatch **(9)** and sends activation for the following 5-minute time step and non-binding activations for the following 11 time-steps equal to 55 minutes **(6)**. However, in some occasions, bids can be binding further ahead than the coming time step, for example, in case of some advanced intertemporal bid types, such as block bids. The bids are updated every 5 minutes by the Economical

Aggregator and the MO updates the activations accordingly. The MO has a model of the grid (at T-D levels). Along with the real time grid load data from the DSO and TSO, they are used to estimate grid congestions and remaining grid capacity. The MO estimates the need for balancing and grid congestion management on the T-D levels and solves it all in one step. In this way, it is possible to manage grid congestions at level at once while activating the cheapest balancing resources.

The Technical Aggregator in the practical setup sends bids **(2)** to the MO for the next 60 minutes in 5-minute resolution and with a frequency of 5 minutes as described above. More specifically, the bids contain at a minimum the following parameters: (BID_ISSUER_ID, BID_ID, NETWORK_NODE_ID, UNIT_BID, PWL, CURTAILABLE, P, Q). Furthermore, the bids can contain more advanced parameters such as intertemporal dependencies as described in [16]. Meanwhile, the DSO measures the grid load on the transformer stations and reports the loads to the MO every 5 minutes **(4)**. In Danish Pilot, summer houses only on two 400 V feeders are considered as flexibility assets. Therefore, the DSO only monitors the load on the 10/0.4 kV stations and 60/10 kV stations directly above these summer houses, as shown in Figure 5.2.

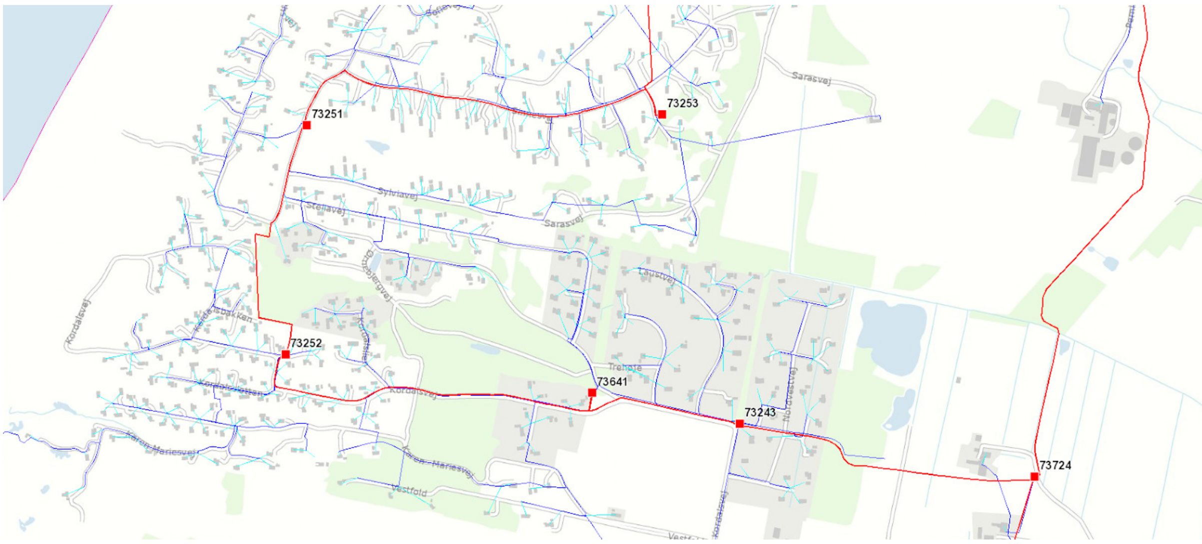

Figure 5.2 The T-D grid, with 10/0.4 kV and 60/10 kV stations, considered in the practical setup of Danish Pilot.

EURISCO hosts the MO platform since it is not possible to implement it in the TSO's IT-system for security reasons. The SmartNet Reserve Market clearing algorithm and price formation is not actually implemented in Danish Pilot since it would be far too complicated compared to the added value. The SmartNet Reserve Market is simulated by using the same time steps, types of bids, and sending the same types of activations/market results.

The price formation is simulated from forecasts of the RPM-price in the following hour. The Technical Aggregator forecasts the RPM-price for Western Denmark for the following two hours with an update for every hour and sends it to the MO **(5)**. The forecasted prices are converted to 5-minute prices to fit the

temporal resolution of the SmartNet Reserve Market. This price is considered the market clearing price. The market clearing is simulated by comparing this market price to the incoming bids from the Economical Aggregator. Bids with a lower price than the market price are activated whereas bids with a higher price than the market price are not activated. The market result sent from the MO to the Economical Aggregator **(6)** is a binding activation of the next time step and 11 non-binding activations for the following 11 time-steps, representing the rolling horizon optimization in the SmartNet Reserve Market. These 11 non-binding market results are updated every 5 minutes with adjusted bids received from the Economical Aggregator and market prices adjusted from the Technical Aggregator's conversion algorithm.

If there are no congestions in the distribution grid, the price at the distribution level is equal to the transmission level price. However, if there is a congestion in the distribution network, a different price is formed behind the congestion. Since no real congestions are expected, lower capacities of the stations are anticipated to provoke and demonstrate congestion management on distribution level in the Pilot.

5.1 Market Perspectives of Control-based Activation of DR

The control based (price signal based) activation approach ensures that the grid operates within its physical constraints based on a dynamic real time market. Compared to the existing market solution in Denmark, the SmartNet solution enables small consumers to participate in balancing the system and solving local problems. The Danish distribution grids are experiencing an increased strain as an increased amount of heat pumps and electric cars are implemented and the need for a solution that solves local problems efficiently is necessary to avoid or postpone expensive grid reinforcements.

In contrast to local and static tariff adjustment schemes, the control based (price signal based) approach ensures that the consumption is adjusted in close to real time depended on the actual available grid capacity and electricity price. This is a key feature for integrating the largest possible amount of solar and wind bound production which is expected to be the primary electricity sources in Denmark. In 2017 the total Danish wind power production corresponded to 43.6% of the total Danish electricity consumption.

To achieve economic efficiency markets should allow all participants to offer their production or consumption in a form that ensure the optimal use of the available resources. By reflecting the current, physical grid state and enabling participation of small and local units, the control based (price signal based) approach has the possibility to bring the electricity market closer to its optimum and ensure the best use of the existing grid and distributed resources.

In the SmartNet project, the solution developed was tested and found technically possible to implement. If the tested method was to be fully implemented in Denmark, a series of related consequences and the scalability would have to be evaluated carefully. Managing real time price formation and response would be of increased complexity compared to the current market solutions. The

socioeconomic distribution of total costs and gains related to implementation of a control based (price signal based) solution as well as the consequences for the security of supply would have to be further analyzed and developed.

The control based (price signal based) approach could work as a supplement to the existing regulation power market applied in Denmark and even though it is not fully ready for implementation the learning gained from the SmartNet project is an important step towards identifying the best solution for both the customers, the DSOs, and the TSO.

5.2 TSO-Aggregator-DSO Interaction

This section describes interactions being taken place in the simulation of the SmartNet market in the second phase with 30 houses, i.e., after the installation of all 30 houses. The first phase uses prices from NordPool and scales these prices to reflect a like future scenario for the regulatory conditions, including the taxes. The interactions between the TSO, DSO, and Aggregators are shown in Figure 3.4. The following explains how the MO is engaged with such interactions:

1. The MO has information about the grid topology and the capacities of each line and transformer station of the T-D grid. This information is not updated regularly but only when necessary, for example, in case of grid expansion or fall-outs. In the specific Pilot project, the grid topology of the distribution grid where the summer houses are connected and all the way up to transmission level including relevant transmission grid are delivered from the DSO and TSO.
2. The MO has information from the previous markets (day-ahead and intra-day) about the time steps, quantities, and locations of the traded energy, which gives a forecast of the load of the grid.
3. The DSO and TSO measure the load of each station in real time and send it to the MO.
4. The MO uses this information to assess the need for balancing and congestion management on T-D level.
5. The Economical Aggregator sends bids of up- and/or down regulation to the MO (time steps, prices, quantities, locations, etc.). The exact bid design depends on the specific market considered, for example, current manual Frequency Restoration Reserve (mFRR) or SmartNet Reserve Market.
6. The MO activates the cheapest bids to balance the system and handle the possible congestion.

5.3 Upward and Downward Regulation

For the current mFRR market, the market participant can submit bids for upward and/or downward regulation in the hour of operation. The bids can be submitted until 45 minutes before the hour of operation. The bids must be minimum +/- 10 MW.

The MO activates the necessary bids within the hour of operation. The price payed to the market participant are calculated as the marginal price within the hour. The mFRR bids can be activated for less

than one hour, however, the market participants are guaranteed with an activation time of at least 30 minutes. The MO pays the market participant for the activated energy, such that the compensation is consistent with the actual delivery.

For the SmartNet Reserve Market, the market uses the market model, which is developed and tested in SmartNet Simulation Platform. Here, the market participants can submit bids for upward and/or downward regulation until 5 minutes before the operation time. Since there is no minimum bid size, the flexibility is bid directly into the market by the Economical Aggregator. The market and the resulting prices are used to simulate the SmartNet Reserve Market in the Pilot under the assumption that the swimming pools do not affect the price formation.

5.4 Grid Tariffs

The current grid tariffs in Denmark are designed as a flat rate per kWh. This rate is higher than the marginal costs of transporting electricity. In this Pilot project, the grid tariffs are divided in fixed and variable tariffs. The variables tariff is set to cover the marginal cost of transporting the electricity. A fee covers the fixed tariffs not related to the energy consumption. The fixed fee does not affect the consumption, and hence is not included in the market model nor the simulations. The variable tariff is included in the market clearing such that an optimal dispatch is achieved including the variable costs of using the grid.

The distribution grid in the Pilot project is characterized by consumption on the lowest voltage level (summer houses) and variable production from wind power on the medium voltage level. Most of the wind power is exported to the transmission level but some are consumed at the lowest voltage level. When the wind is not blowing the power is supplied from transmission level. There grid loss varies a lot depending on the wind power production, but the local consumption has currently no incentive to consume when there is local production available, even though it would lead to lower grid loss and hence lower cost of operating the grid.

For this Pilot project, it is assumed that there is no production on the lower level. The production, therefore, takes place on the middle level and the higher level. The electricity always flows from the middle level to the lower level. For the higher level, the electricity either flows from the higher level to the middle level, if production primary takes place on the higher level, see Figure 5.3.

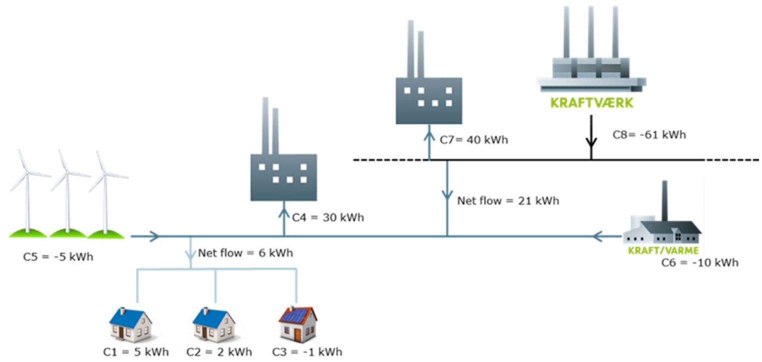

Figure 5.3 Tariff Model 1.

When the power flows from the higher level to the middle level, the production (the wind turbines), reduces the overall grid loss. Hence, they have a negative tariff (receive tariff). The electricity flows from the middle level to the higher level, if production primary takes place on the middle level, see Figure 5.4.

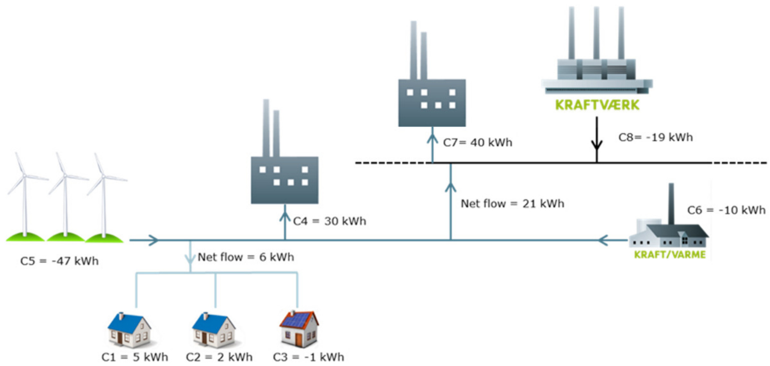

Figure 5.4 Tariff Model 2.

When the power flows from the middle level to the higher level, the production (the wind mills), leads to an increase in grid loss and, hence, they have a positive tariff (pay tariff). The tariff is included in the market clearing process, such that the actual price of their bid includes the tariffs. This makes the actual bid size either higher or lower depending on whether the wind turbines causes higher or lower grid loss. The same rules apply to the summer houses giving them incentive to consume when there is local production available and lowering the overall costs.

5.5 Time-Line for Bids and Activation

Clearing and activation of Aggregated flexibility bids is based on the predicted imbalance price which is simulated as explained in section 5.7(dotted yellow curve shown in Figure 5.5) and actual bids submitted by the Economical Aggregator at the time T-4 (four minutes before the next operation period). At the time T-1 (one minute before the next operating hour) relevant bids are activated based on the result of the price/bid clearing as seen in Figure 5.5. The simulated imbalance price (red curve shown in Figure 5.5) is used for billing in the actual operating period. The price/bid clearing is executed every five minutes for the following operation period (five minutes).

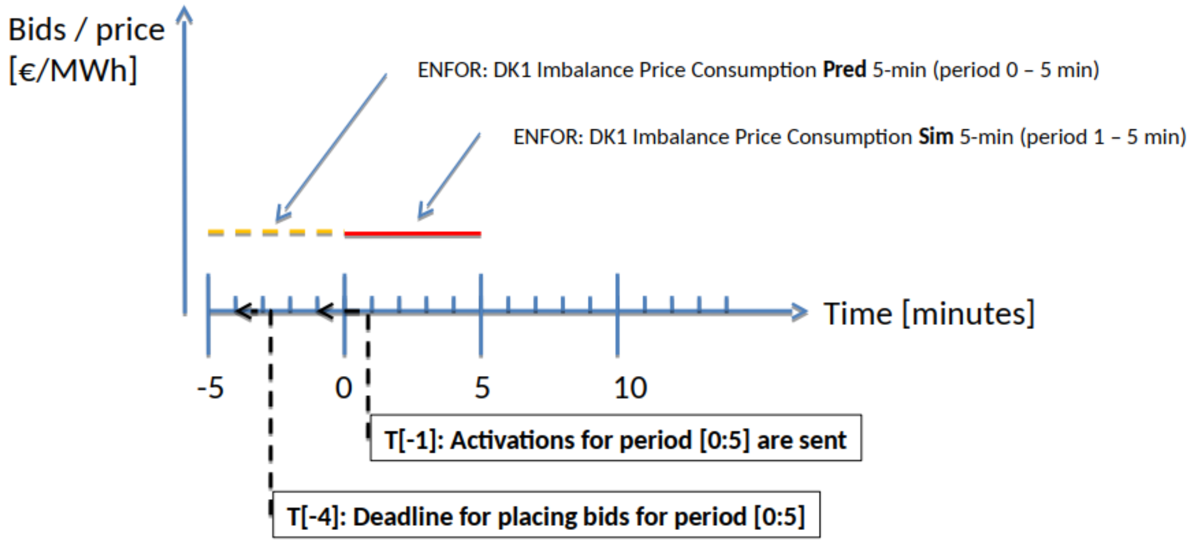

Figure 5.5 Time-line for bids and activations

5.6 Data Management System and Protocols

The specialized Technical Aggregator has been developed and hosted at the Pilot DMS, which is a cloud solution. The DMS is based on REST and JavaScript Object Notation (JSON) data structures. The summer house rental company provides information about the booking status. To generate the initial dynamical models, it also supplies information about the main characteristics of the summer houses; the pool and the heating systems.

5.7 Generation of 5-Minute Electricity Prices based on 1-Hour Data

This part describes a method for simulating and generating 5-minute electricity prices based on real-time hourly spot price forecasts. The concept of a Brownian Bridge is employed, which is an embedded stochastic process derived from standard Brownian motion. We, then, describe the data used to simulate 5-minute prices followed by providing the simulations result. Finally, the operational setup used for demonstration purposes is briefly described.

The focus is on materializing the concept of model-based control principles for activation of flexibility from swimming pools to provide system balancing and grid congestion services at TSO and DSO levels. That is, it presents a stochastic method for generation of 5-minute electricity prices during each time step, which enables two ancillary services in Danish Pilot, namely energy balancing and grid congestion management, accordingly. Since such 5-minute prices data is unavailable, this report considers the real-time hourly spot price forecasts to be converted into 5-minute prices in order to fit the temporal resolution of the SmartNet Reserve Market. The Brownian Bridge is a continuous-time stochastic process, whose probability distribution is the conditional probability distribution of a Wiener process (a mathematical model of Brownian Motion).

5.7.1 Data

To enable a Brownian Bridge to simulate 5-minute prices between each two consecutive hours, real-time hourly spot price forecasts from the Technical Aggregator are used.

5.7.2 Simulation

To simulate 5-minute prices, Sim.DiffProc package [17] including its all dependent packages are used. A generic function of Brownian Bridge as follows:

$$BB(N, M, x0, y, t0, T, Dt) \tag{1}$$

with arguments:

N	number of simulation steps
M	number of trajectories
$x0$	initial value of the process at time $t = 0$
y	terminal value of the process at time T
$t0$	initial time
T	final time
Dt	time step of the simulation (discretization). Default is $\frac{T-t0}{N}$.

BB returns $M = 1$ trajectory of the standard Brownian Bridge starting at $x0$ at time $t0 = 0$ and ending at y at time $T = 1$. Number of simulation steps is indeed $N = 11$. To get variation on the same scale as the input data, the forecasts are standardized as follows:

$$x0 = \frac{P_\tau - \overline{P}}{\hat{P}}, \tag{2}$$

$$y = \frac{P_{\tau+1} - \overline{P}}{\hat{P}}, \tag{3}$$

where $P_\tau, P_{\tau+1}$ are price forecasts for the current and next hours while $\overline{P}, \hat{P}$ are the mean and the standard deviation error of the day-ahead prices. In this case, to engage some stochasticity with the prices, only one simulation trajectory is generated. As a result, Equation (1) changes to:

$$\left(BB\left(11,1,\frac{P_\tau - \overline{P}}{\hat{P}},\frac{P_{\tau+1} - \overline{P}}{\hat{P}},0,1,\frac{1}{12}\right) \times \hat{P}\right) + P_\tau, \tag{4}$$

where the simulation is transformed back to the correct scale. As an example, a Brownian Bridge with arguments $P_\tau = 356.7$ DKK/MWh (16:00 on October 19, 2017), $P_{\tau+1} = 403.98$ DKK/MWh (17:00 on October 19, 2017), $\overline{P} = 378.02$ DKK/MWh, and $\hat{P} = 47.87$ DKK/MWh returns a trajectory (including boundary prices), as Figure 5.6 illustrates.

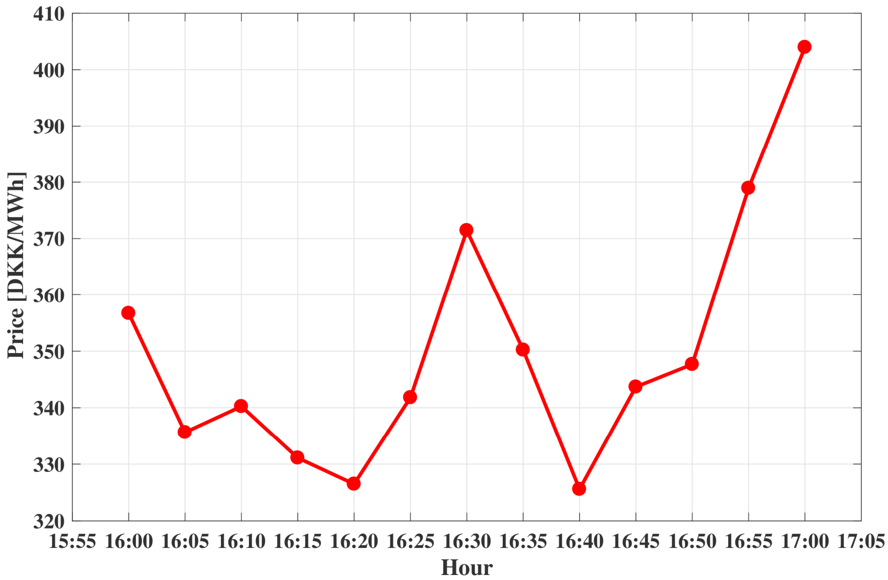

Figure 5.6 : Example of the output trajectory of a Brownian Bridge including current and next hour's spot price forecasts.

5.7.3 Operational Implementation

Simulation of 5-minute prices follows real-time hourly spot price forecasts. Therefore, in order to perform the simulation operationally it is required that the predicted prices are downloaded online. The prices are delivered to the MO to use for activation in the next 5-minute time step while providing price forecast for the next 12 time-steps (in 5-minute time resolution). The MO of the SmartNet requires the 5-minute prices to be available in the beginning of each 5-minute time interval. The operational setup is outlined in Figure 5.7.

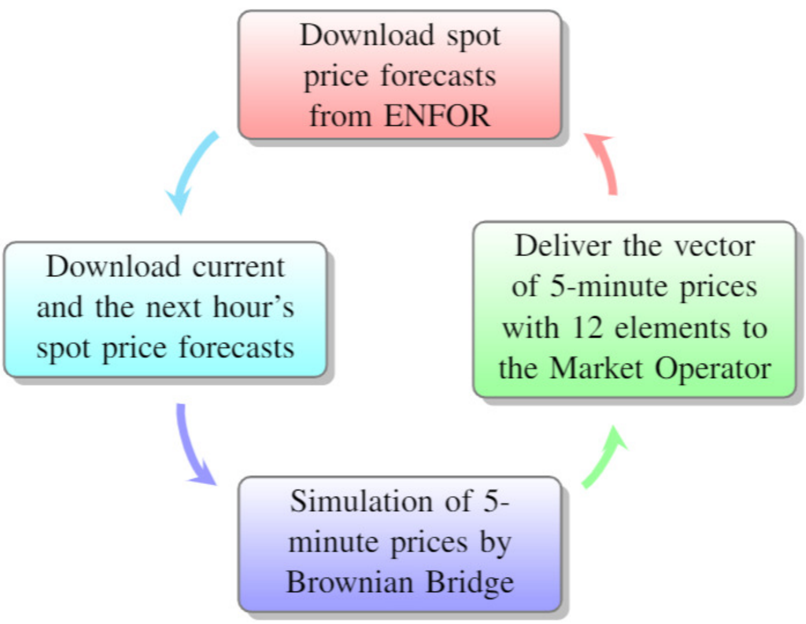

Figure 5.7 Outline of the operational procedure applied to simulate 5-minute prices.

6 Lower Level of the Danish Pilot

The main focus of the lower level of the Pilot, as shown in Figure 6.1, is to receive price signals (16), compute optimal heating schedules according to these (17), and actuate the computed heating schedule for the swimming pools (18). In this Pilot a secondary focus was to estimate a flexibility function for the Economical Aggregator, that explains the expected amount of electricity usage as a dynamic function of penalty. The most common example of penalty is simply price, when it is assumed that the controllers minimize the total costs of heating the swimming pools in terms of money. However, penalty can also be any other quantity, that one wants to minimize, such as the CO_2-intensity of the production of the electricity. In general, the penalty is simply a signal, that for each point in time, describes the desire to reduce consumption.

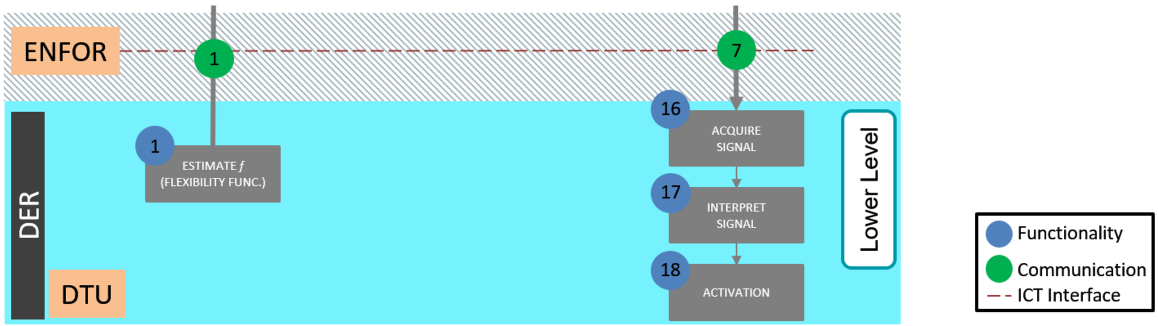

Figure 6.1 Conceptual setup of the lower level of Danish Pilot (see Figure 3.5 for the whole setup).

6.1 Modelling

In order to facilitate model predictive control, models had to be developed of the temperature of the swimming pools, and the impact of the heating. Grey-box models were chosen since they utilize the physical relations that are known to govern the system. At the same time, they can easily be applied for control.

6.1.1 Greybox Modelling and Stochastic Differential Equations

Models describing the thermal dynamics of the summer houses with a focus on the pools have been developed. Since these models are used for controlling the water temperature of the pools, the focus is on building a precise but simple relation between the water temperature and the controlled variables. Initially, the only controlled variable is the valve position determining whether the pool is being heated, and thus the effect of the valve position is the most important part of the modelling process.

The physical nature of pools makes them ideal for grey-box modelling, where the structure of the models is based on physical realizations, while unexplainable things like human activity, model approximations, and measurement errors are incorporated through stochastic terms. The grey-box modelling is carried out with stochastic differential equations, which are identical to ordinary differential

equations except that they include a random term, in the form of Brownian motion. Moreover, subtle mathematical details enable us to express stochastic differential equations, but instead one uses stochastic integration equations.

Let T_t^w denote the temperature of the pool at time t, then a possible stochastic integration equation governing T_t^w could be

$$T_t^w - T_0^w = \frac{1}{C_w}\left(\int_0^t \frac{1}{R_a}(T_s^a - T_s^w)ds + \int_0^t f(T_s^a, T_s^w)ds + Q\int_0^t u_s\, ds\right) + \sigma B_s \quad (1)$$

where C_w is the heat capacity of the water, R_a is the resistance describing how easily heat is transferred between the air and the water, T_s^a is the temperature of the air in the pool room at time s, f is a function describing how much heat is lost due to evaporation, Q is the rate with which the pool can be heated, u_s is whether the pool is being heated at time s or not, σ is the parameter describing how much uncertainty goes into the temperature of the pool, and B_s is the state of Brownian motion at time s. Since everything is being integrated from time 0 to time t, the following short hand notion is used:

$$dT_t^w = \frac{1}{C_w}\left(\frac{1}{R_a}(T_t^a - T_t^w) + f(T_t^a, T_t^w) + Q\,u_t\right)dt + \sigma\, dB_t \quad (2)$$

where the first term of the equation is a deterministic function of the water and air temperatures and whether the pool is being heated or not. This part comes from physical considerations and by itself is referred to as a white-box model. On the other hand, the second term is purely stochastic and is referred to as the black box model. Combining the two is referred as a grey-box model.

More stochastic differential equations, for example for describing the air temperature, are required. This can be done without further complications. The last addition to the model which would typically be made is the notion of an observation equation. The purpose of this equation is to describe the uncertainty in the measurements of the pool water. Such an equation could be given by

$$Y_t = T_t^w + \epsilon_t, \quad (3)$$

where $\epsilon_t \sim N(0, \sigma_m^2)$. This equation simply describes how on average one assumes to get the right measurements, but there is always an error to the measurement, and the typical size of the error is given by σ_m.

6.1.2 Models used for MPC

MPC uses model of the plant for prediction calculation. The linear models are preferable due to relative simplicity of solving the corresponding linear program. In this part, a linear parameter-varying model of the swimming pool heating system, which can be further used for MPC controller design, is described. Figure 6.2 shows the ground plan of a typical summer house with indoor swimming pool and Table 6.1 describes of the corresponding parameters. The swimming pool is filled with blue color; the pool area is filled with green color.

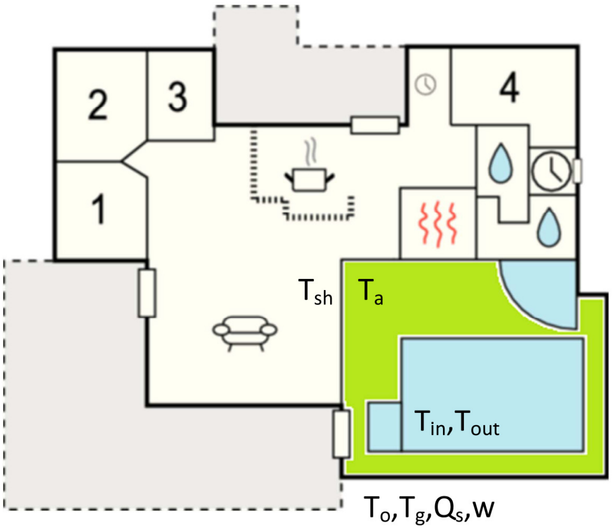

Figure 6.2 Ground plan of the summer house.

Table 6.1 Description of the parameters.

Par.	Units	Description
T_{in}	$°C$	Water temperature into the pool
T_{out}	$°C$	Water temperature out of the pool
T_a	$°C$	Pool area air temperature
T_{sh}	$°C$	Summer house air temperature
T_o	$°C$	Outdoor temperature
T_g	$°C$	Ground temperature
w	m/s	Wind speed
Q_s	kW	Solar heat gain

Heating system of a swimming pool (e.g., heat pump), which is a part of summer house heating system, supplies hot water into the swimming pool. The inflow is controlled by the valve (see Figure 6.3).

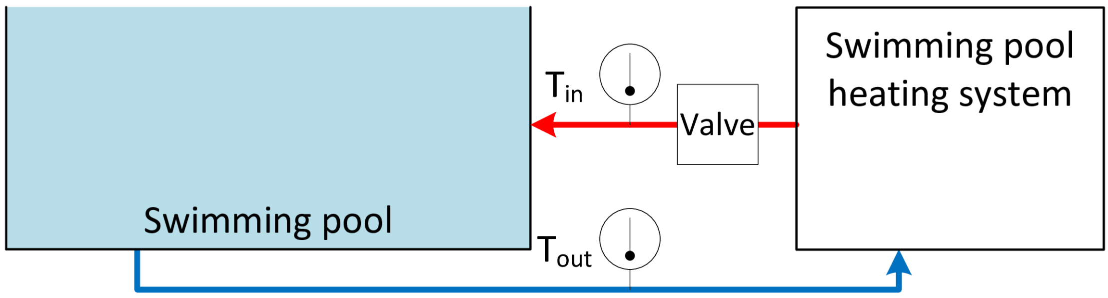

Figure 6.3 Swimming pool heating system.

It is assumed that all heat losses can be lumped to heat loss to the ground. Figure 6.4 illustrates Energy Technology Perspectives (ETP) model of the system. Here, H_o is the thermal conductance of the pool area envelope; H_{sh} is the thermal conductance between the pool area and the summer house; H_g is the thermal conductance of the swimming pool isolation; H_{sh} is the thermal conductance between the swimming pool and the pool area; H_w is the thermal conductance of the swimming pool; C_{out}, C_{in} and C_a are the corresponding thermal capacitance; Q_a is the heat gain from the pool area heating system; Q_{in} is the heat gain from the swimming pool heating system.

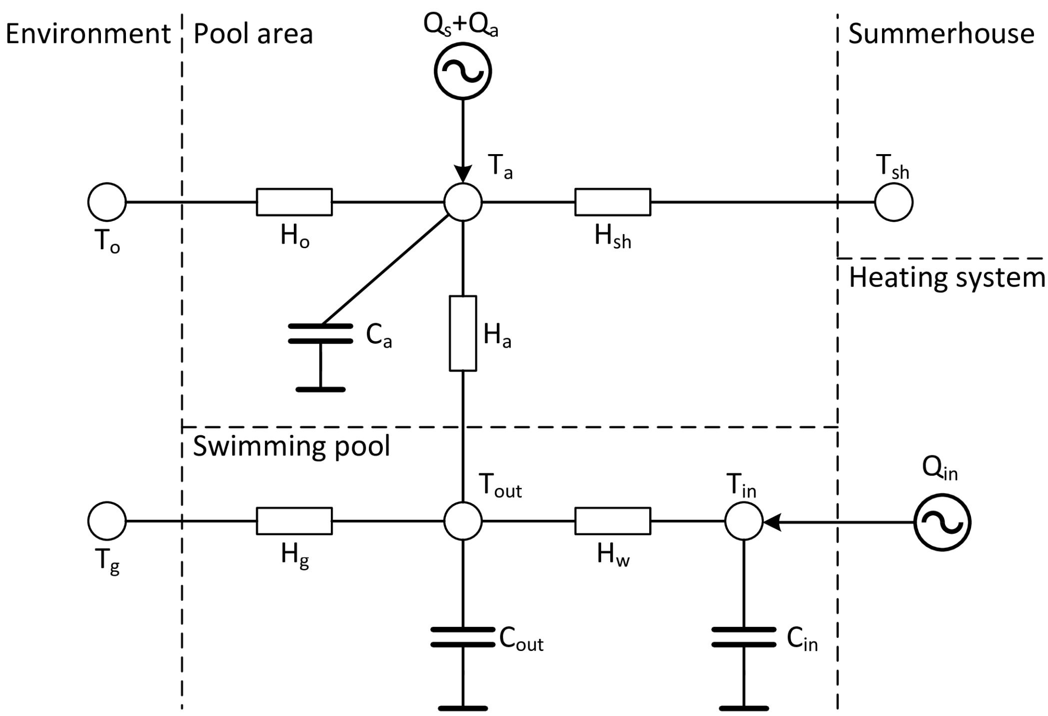

Figure 6.4 ETP model.

The wind speed influences H_o as follows:

$$H_o = H_{on} + k_w w, \tag{4}$$

where H_{on} is the nominal thermal conductance of the pool area envelope; k_w is the coefficient defining wind speed influence. The heat gain from the swimming pool heating system depends on the valve position:

$$Q_{in} = V \; COP_h \; P_{nh}, \tag{5}$$

where V is the valve position, COP_h is the coefficient of performance of the heating system, P_{nh} is the nominal power of the heating system.

The output temperature is thermostatically controlled, the valve position is defined as follows:

$$V = \begin{cases} 0, \text{ if } T_{out} \geq T_{st} + \Delta T, \\ 1, \text{ if } T_{out} \leq T_{st} - \Delta T \end{cases} \tag{6}$$

where T_{st} is the temperature set-point, ΔT is the hysteresis band. The following equations describe dynamics of the ETP model:

$$\dot{T}_{in} = \frac{1}{C_{in}} \left(H_w(T_{out} - T_{in}) + Q_{in}\right) \tag{7a}$$

$$\dot{T}_{out} = \frac{1}{C_{out}} \left(H_w(T_{in} - T_{out}) + H_g\left(T_g - T_{out}\right) + H_a(T_a - T_{out})\right) \tag{7b}$$

$$\dot{T}_a = \frac{1}{C_a} \left(H_o(T_o - T_a) + H_a(T_{out} - T_a) + H_{sh}(T_{sh} - T_a) + Q_s + Q_a\right) \tag{7c}$$

6.2 Characterizing the Energy Flexibility

The goal of the Pilot is to utilize Energy Flexibility, but since the Economical Aggregator does not have a direct control over the energy usage, it is instead needed to have a characterization of the energy flexibility in terms of the penalty signals sent to the summer houses. Figure 6.5 represents the conceptual dependency between a penalty generator and a potential DER including flexibility function. The characterization method used here is described more in detail in [6].

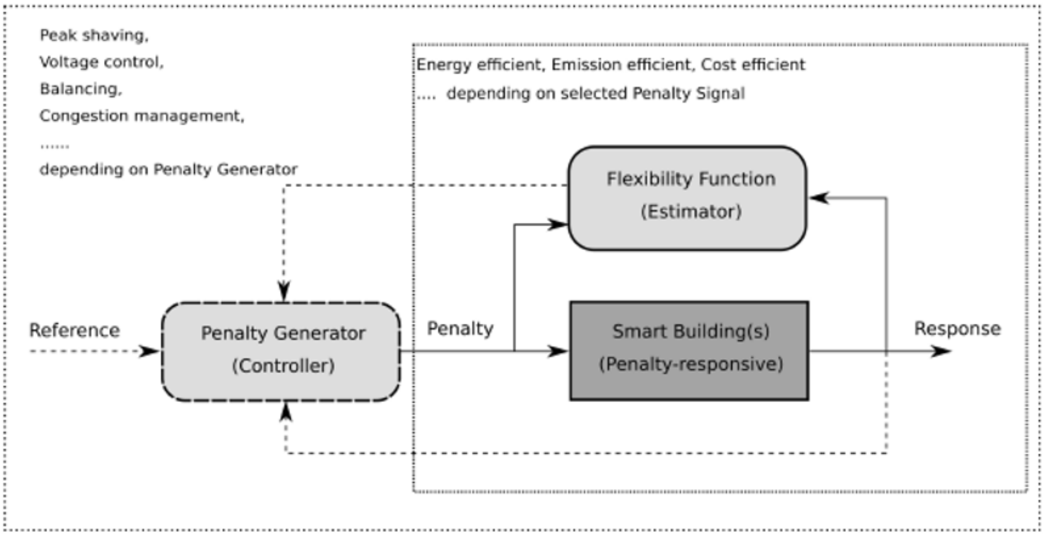

Figure 6.5 Dependency between a penalty generator and a potential DER including flexibility function

6.2.1 Methodology

If the relation between penalty and energy consumption is considered to be linear and time-invariant, then, it is uniquely characterized through the step response [18]. Since the Economical Aggregator does not measure the energy consumption in real time (time resolution is set to 5-minute), a model without this requirement has been chosen, namely the finite impulse response model:

$$y_t = \mu_t + \sum_{k=0}^{N} h_k \lambda_{t-k} + \varepsilon_t \tag{8}$$

where y_t is the consumption, μ_t is the average consumption if penalties are 0, λ_t is the penalty, while ε_t is the error. All of them are at time t. μ_t and h_k are the parameters that need to be estimated, and

$$FF(n) = \sum_{k=0}^{n} h_k \tag{9}$$

is the flexibility function.

6.2.2 Example for swimming pool

An estimated flexibility function can be seen on Figure 6.6. This flexibility function is estimated from October 2017, when the swimming pools were operated according to a penalty signal based on CO_2-intensity in the electricity mix. It is seen that the response to an increase in penalty is slow, with the full effect taking approximately 10 hours to be reached. This extremely slow response is due to two things. Firstly, the heat pumps used to heat the swimming pools are not designed to be turned on and off frequently, and thus the MPC has been designed to limit of often this happens, to prevent damaging them. This meant that the MPC often chose not to react immediately to changes in penalties. Secondly, technical

issues with the hardware meant that the SN-10 was often unresponsive to MPC, and so also to the penalty signals.

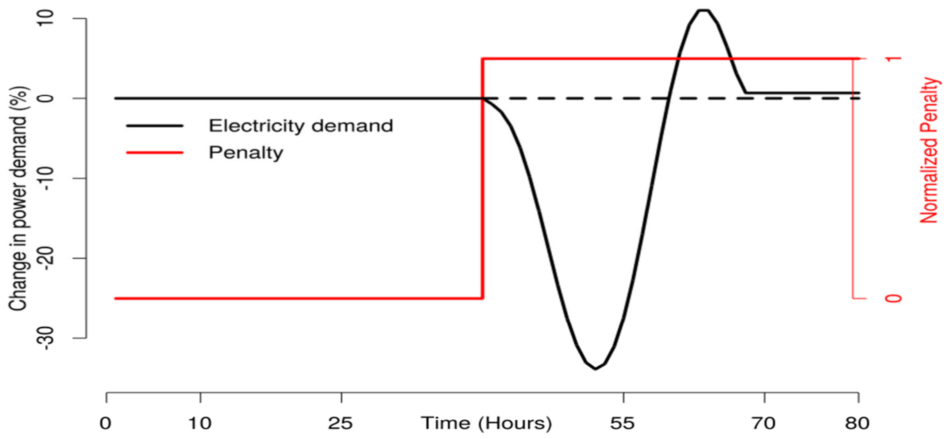

Figure 6.6 Estimated step-response, based on data from October 2017, where the penalty was based on CO_2-intensity.

6.3 Smart House Controller (SN-10)

Data communication from the Technical Aggregator to the summer house, is exchanged by the SN-10 controller, as Figure 6.7 shows. A device was made specially for the SmartNet project, because no existing commercial products could meet the requirement specification. This Smart House Controller (SN-10) is a component inside the system installed at the summer houses. The system also includes 5V/12V DC power supply, 230V switch and sensors for temperature measurements. The SN-10 also has an interface to the energy meter installed in the summer house.

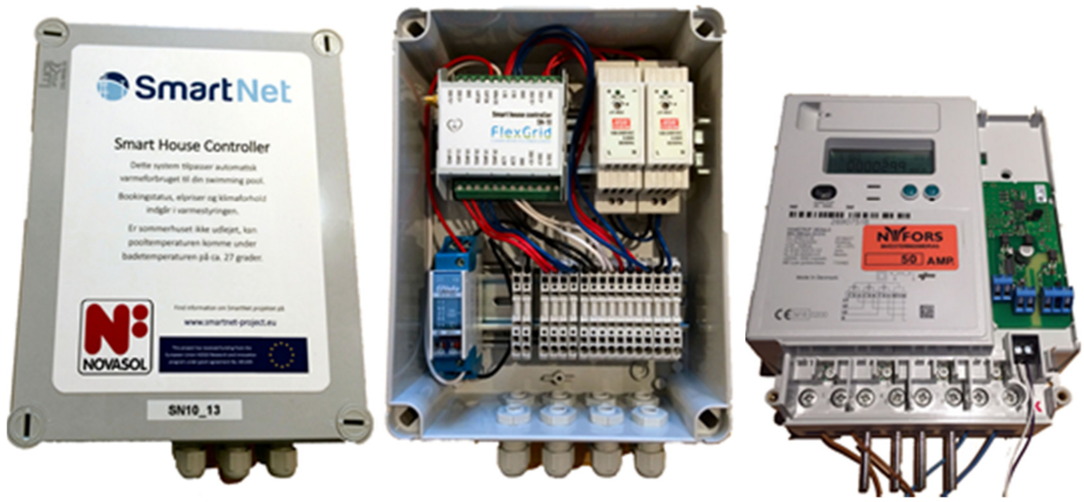

Figure 6.7 SN-10

6.3.1 Setup

The Actuator in Figure 6.8 is a controllable thermostat, which opens or closes depending on a Pulse Modulated Signal (24VDC) from the SN-10 controller. Water temperature are measured for the pool water going in and out of the pool and the air temperature sensor measures the heat from the pool room.

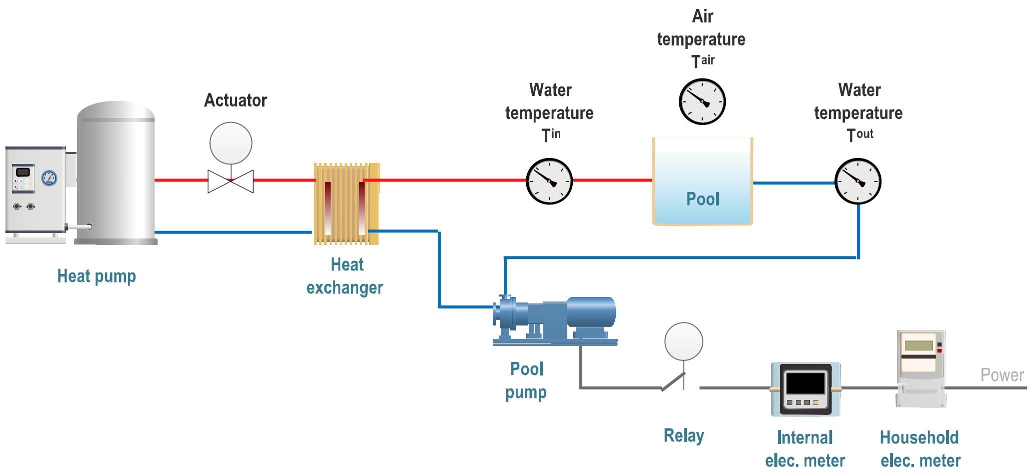

Figure 6.8 Test setup.

The pool pump can be switched off during high energy price periods, but only for a limited period due to constraints on the water cleaning process. The power consumption is measured with an internal electricity meter (sub-meter) and with the house hold revenue meter.

The SN-10 unit in Figure 6.9, including sensors, meters, and the actuator is installed in each summer house. The controller is an IoT unit, which is connected to the internet and can perform the measurement and controlling. The main part in the controller is a "Particle Electron" (http://www.particle.io), which is connected to the internet via a 2G/3G communication. Every 5 minutes, the SN-10 sends data to a cloud server, and then relays to the DMS. Control signals are calculated and sent to the SN-10 unit on a 5-minute basis. The control signal is a temperature set-point which the SN-10 controller will regulate the water temperature after. If the SN-10 is installed with an electrical boiler it will activate the relay when heating is needed and deactivate when the set-point is reached, in order to prevent fast switches a 1 degree Celsius hysteresis is used. If the SN-10 instead is installed in a house with a central heating system, a thermal actuator is used instead of the relay.

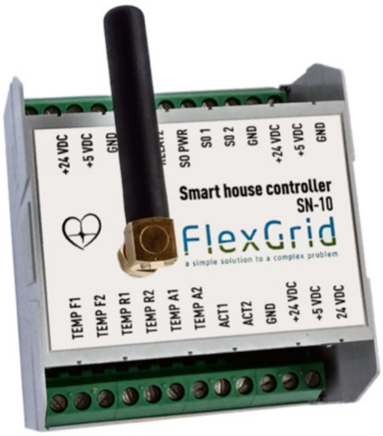

Figure 6.9 SN-10 local controller.

Figure 6.10 shows how SN-10 performs according to data measurement and information gatherings. Moreover, SN-10 actuates the relay in summer houses according to the information gathered with respect to the running price-based control, as shows in Figure 6.11.

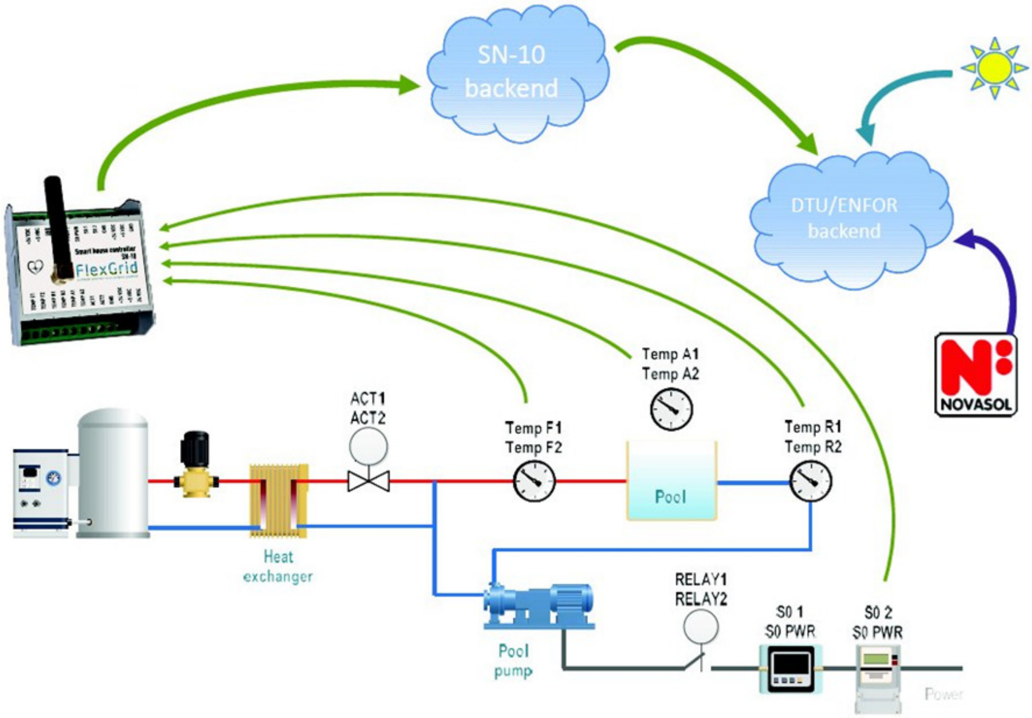

Figure 6.10 Data measurement and information gathering by SN-10.

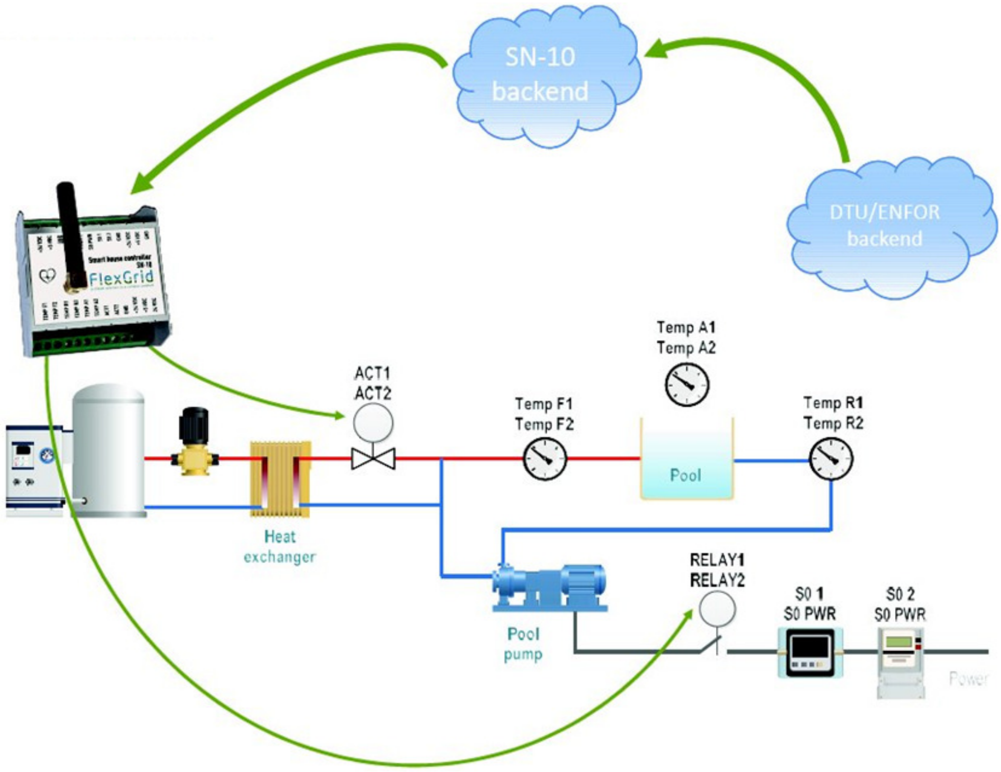

Figure 6.11 Relay actuation according to the information gathered with respect to the running price-based control.

6.3.2 Pre-Testing the Installations

In order to make sure that the installations are working, a pre-testing is done. This is basically multiple step responses which is carried out manually. The pool temperature is first raised by setting the set-point manually to around 1 degree Celsius higher than the actual temperature. The day after the reading of the temperature is watched to ensure that the new set point has been reached and that the installation has been able to hold the temperature. Then the set-point is set to 2 degrees Celsius lower and again this is checked the day after. The temperature is then set back to the highest set-point and is checked later again. If the installation is responding as expected it is ready to be assigned a controller and if not, the installation must be checked. If the installation seems good at test cycle it is carried out once more to give the controller a better view on the dynamics of the pool.

6.3.3 Controlling Approach

Smart house controllers generate optimal temperature set-points for the summer houses, which are then sent to the local controllers. This part describes the principle of smart house controllers for an individual summer house, which is the same for all houses. Figure 6.12 shows the structure of the control system.

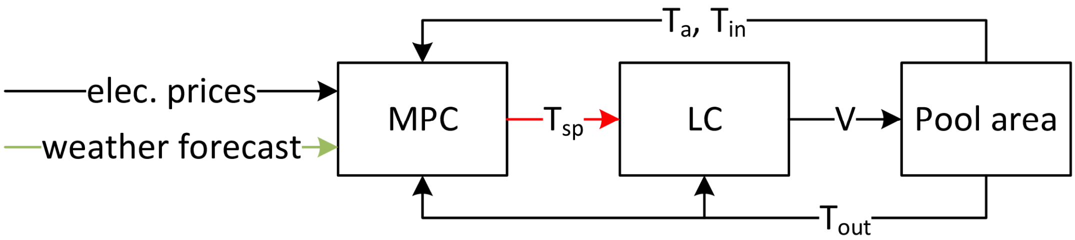

Figure 6.12 Control system.

The controller aims at minimizing the operational cost of the swimming pool heating system installed in the summer house using measurements, booking status, electricity, and weather forecasts. Recall that the heating system has two states: ON (open valve) and OFF (closed valve). This status directly influences electricity consumption of the system. Consequently, the algorithm for finding optimal temperature set-point is divided into two stages: first, an E-MPC calculates the optimal valve position; then, the optimal temperature set-point is defined such that the obtained valve position is held during sampling time of the controller (t_s).

Linear parameter-varying model (7) can be converted to a discrete-time state space model using zero-order-hold sampling of the input signal

$$x_{k+1} = A(\theta_k)\, x_k + B(\theta_k)\, u_k + E(\theta_k)\, d_k \tag{8a}$$

$$y_k = C\,(\theta_k)\, x_k \tag{8b}$$

where A, B, E and C are the discrete state space matrices; $\theta = [T_o\ w\ s\ ]^T$ is the vector of parameters influencing the state space matrices; x is the state vector; $u = V$ is the manipulated variable; $y = [T_{in}\ T_{out}\ T_a\ ]^T$ is the measured output vector; and $d = [T_o\ w\ ]^T$ is the measured disturbance vector.

E-MPC uses model (8) for calculating the prediction and solves the following optimization problem:

$$\min_{U_k, V_k} \sum_{j=0}^{N-1} c_{k+j|k}\, u_{k+j|k} + \rho_v v_{j|k} \tag{9a}$$

$$s.t. \quad x_{k+j+1|k} = A(\theta_k)\, x_{k+j|k} + B(\theta_k) u_{k+j|k} + E(\theta_k) d_{k+j|k} \tag{9b}$$

$$y_{k+j+1|k} = C(\theta_k)\, x_{k+j+1|k} \tag{9c}$$

$$y_{min,k+j+1|k} - v_{j|k} \le y_{k+j+1|k} \le y_{max,k+j+1|k} + v_{j|k} \tag{9d}$$

$$U_k \in \{0,1\} \tag{9e}$$

where N is the predictive horizon; c is the cost coefficient (electricity price); v is the slack variable relaxing the optimization problem with corresponding penalty cost ρ_v; and y_{min} and y_{max} are the minimum and maximum output constraints, respectively.

Problem (9) can be converted to a standard MILP optimization model with binary constraints:

$$\min_{x_{LP|k}} f_{LP|k}^T\, x_{LP|k} \tag{10a}$$

$$s.t. \quad A_{LP|k}\, x_{LP|k} \le b_{LP|k} \tag{10b}$$

$$l_{LP|k} \le x_{LP|k} \le u_{LP|k} \tag{10c}$$

Calculation of output predictions for linear parameter varying model (8) is derived in [7]. Further, the following presents the obtained in the paper results using notations listed in Table 6.2.

Table 6.2 Description of the parameters.

Parameter	Description
$\boldsymbol{U_k = [u_{k\|k} u_{k+1\|k} \dots u_{k+N-1\|k}]^T}$	Vector of future inputs
$\boldsymbol{Y_k = [y_{k+1\|k} y_{k+2\|k} \cdots y_{k+N\|k}]^T}$	Vector of predicted inputs
$\boldsymbol{D_k = [d_{k\|k} d_{k+1\|k} \dots d_{k+N-1\|k}]^T}$	Measured disturbances (weather forecast)
$\boldsymbol{C_k = [c_{k\|k} c_{k+1\|k} \dots c_{k+N-1\|k}]^T}$	Electricity price forecast
$\boldsymbol{\Upsilon_k = [v_{0\|k}\ v_{1\|k} \dots v_{N-1\|k}]^T}$	Slack variables
$\boldsymbol{P = [\rho_v\ \rho_v \dots \rho_v]^T}$	Penalty cost
$\boldsymbol{Y_{min,k} = [y_{min,k+1\|k} y_{min,k+2\|k} \cdots y_{min,k+N\|k}]^T}$	Minimum output constraints
$\boldsymbol{Y_{max,k} = [y_{max,k+1\|k} y_{max,k+2\|k} \cdots y_{max,k+N\|k}]^T}$	Maximum output constraints

$$Y_k = \Phi_k x_{k|k} + \Gamma_{u|k} U_k + \Gamma_{d|k} D_k \tag{11a}$$

$$\Phi_k = \begin{bmatrix} O_{1|k} \\ O_{2|k} \\ \cdots \\ O_{N|k} \end{bmatrix} \tag{11b}$$

$$O_{j|k} = C(\theta_{k+j|k})\left(\prod_{i=k}^{k+j+1} A(\theta_{i|k}) \right), j \in \{1,2,\dots,N\} \tag{11c}$$

$$\Gamma_{u|k} = \begin{bmatrix} H_{u,1,0|k} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ H_{u,N,0|k} & \cdots & H_{u,N,N-1|k} \end{bmatrix} \tag{11d}$$

$$H_{u,i,j|k} = C(\theta_{k+j|k})\left(\prod_{l=k+i-1}^{k+j+1} A(\theta_{l|k}) \right) B(\theta_{k+j}), i \in \{1,2,\dots,N\},, j \in \{0,1,\dots,N-1\} \tag{11e}$$

$$\Gamma_{d|k} = \begin{bmatrix} H_{d,1,0|k} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ H_{d,N,0|k} & \cdots & H_{d,N,N-1|k} \end{bmatrix} \tag{11f}$$

$$H_{d,i,j|k} = C(\theta_{k+i|k})\left(\prod_{l=k+i-1}^{k+j+1} A(\theta_{l|k}) \right) E(\theta_{k+j|k}), i \in \{1,2,\dots,N\},, j \in \{0,1,\dots,N-1\} \tag{11g}$$

The parameters of the linear optimization problem (10) are defined as follows:

$$x_{LP|k} = \begin{bmatrix} U_k \\ \Upsilon_k \end{bmatrix} \tag{12a}$$

$$f_{LP|k} = \begin{bmatrix} C_k \\ P_k \end{bmatrix} \tag{12b}$$

$$A_{LP|k} = \begin{bmatrix} \Gamma_{u|k} & -I \\ -\Gamma_{u|k} & -I \\ 0 & -I \end{bmatrix} \tag{12c}$$

$$b_{LP|k} = \begin{bmatrix} \Upsilon_{max\,|k} - \Phi_k x_{k|k} - \Gamma_{d|k} D_k \\ -\Upsilon_{min\,|k} + \Phi_k x_{k|k} + \Gamma_{d|k} D_k \\ 0 \end{bmatrix} \tag{12d}$$

where I is the identity matrix; input constraints $l_{LP|k}$ and $u_{LP|k}$ are defined such that $U_k \in \{0,1\}, \Upsilon_k \geq 0$; initial states $x_{k|k}$ can be estimated using Kalman filter. E-MPC provides the optimal profile of future valve positions ($U_{opt|k} = \left[u_{opt|N-1}\right]^T$) solving optimization problem (9) at each sampling time. As it is mentioned above, optimal temperature set-point $\Gamma_{sp|k}$ is found such that the local controller keeps $V_{opt|k} = u_{opt|k}$ during the sampling time of the controller:

$$T_{sp|k} = \begin{cases} T_{out|k} - \Delta T \ \text{ if } V_{opt|k} = 0 \\ T_{out|k} + \Delta T \ \text{ if } V_{opt|k} = 1 \end{cases} \tag{13}$$

H is the hysteresis width of the local controller.

As a demonstrative example, a three-day scenario has been simulated. Figure 6.13 shows the obtained results. It is assumed that the summer house is rented out on the second day, therefore, the temperature constraints are narrower during this time. The results demonstrate that the system works at economically optimal regime: the water temperature (T_{out}) is kept as close as possible to the lower temperature limit; the valve is open during low-price periods and closed during high-price periods.

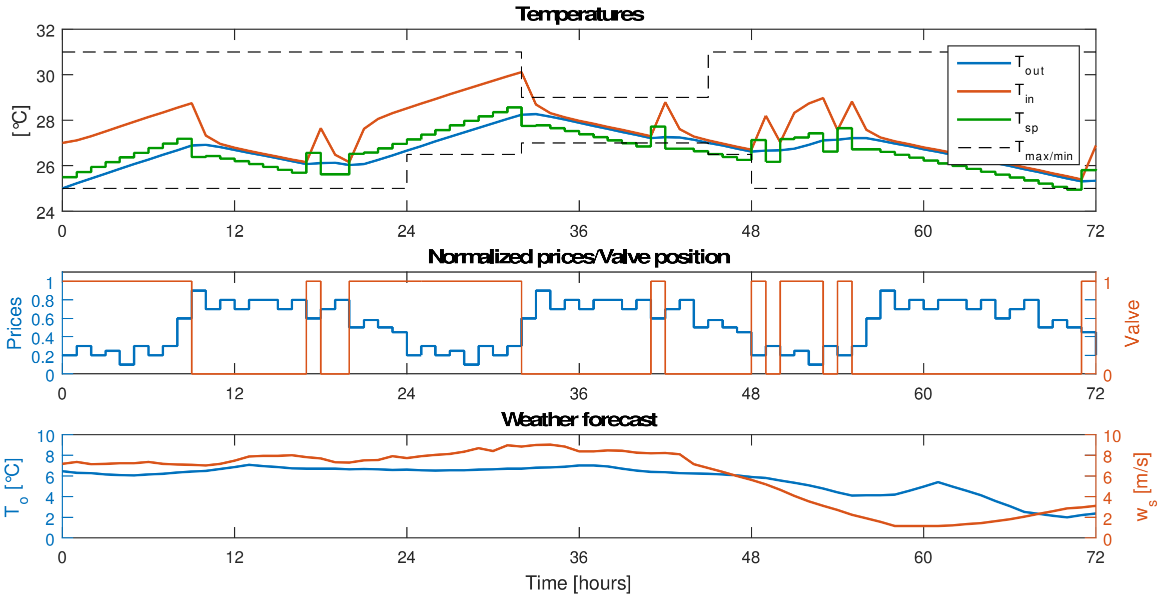

Figure 6.13 Simulation results.

7 Results, Discussions, and Disseminations

The flexibility of the summer houses has been estimated based on some selected test periods during Winter 2017/18 using the current market. To achieve a situation with redesigned regulatory conditions, the NordPool prices have been considered, which have simply been scaled them up to an average price corresponding to the average prices as seen by ordinary households. Furthermore, the flexibility has been estimated on the available power measurements.

The second phase takes advantage of the SmartNet Simulation Platform and implements the SmartNet market using simulations and set-up developed in [1]. Here, (a number of) summer houses potentially act as the HIL in the simulation.

7.1 Installation of SmartNet Controllers

There is a total of 30 summer houses in the control system. 28 of the summer houses are installed with a SN-10 control unit with a GSM module including an external antenna and 2 summer houses with a FlexControl system that communicates via the Internet.

In the Blåvand area, there are 15 summer houses with a SN-10 system installed and 2 summer houses with FlexControl system. All 17 summer houses have an electric heater that heats the swimming pool. All 17 summer houses are supplied from 60 kV station Oksby via the 10 kV lines Horns Bjerge, Hvidbjerg and Heksebjerg, see map below. From the map shown in Figure 7.1, it can be seen that 6 summer houses are connected to Horns Bjerge (purple), 6 summer houses are connected to Hvidbjerg (green) and the remaining 5 summer houses are connected to Heksebjerg (light blue). The summer houses are marked with a blue circle.

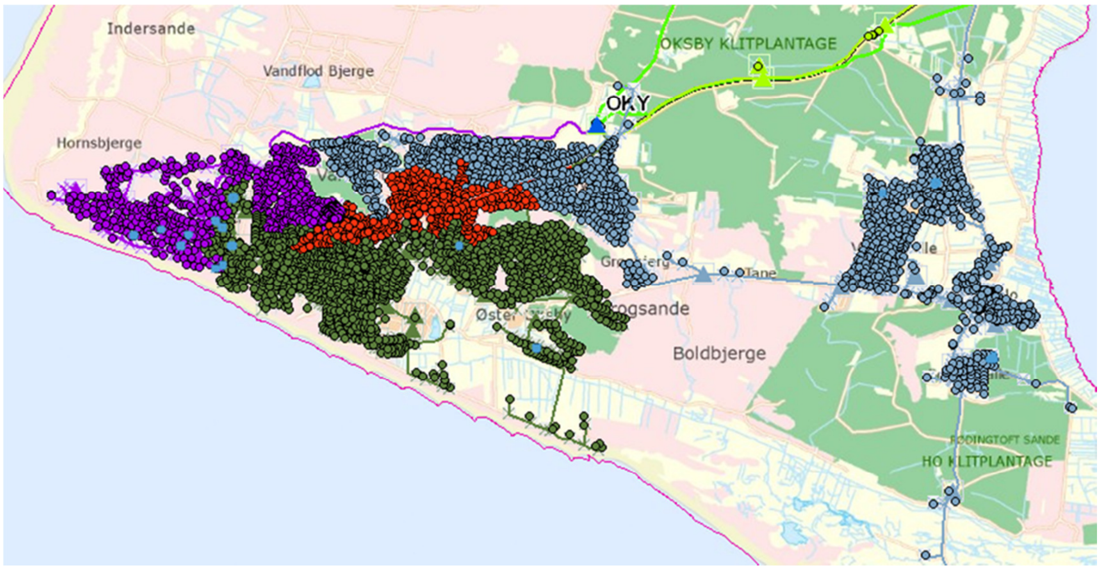

Figure 7.1 Geographical locations of summer houses

In Saltum, Løkkenn and Blokhus, there are 13 summer houses with a SN-10 system installed. 7 of the summer houses have a heat pump installed for heating the swimming pool. In the remaining 6 summer houses the swimming pool is heated with an electric cartridge. The summer houses are supplied from 60 kV station Ingstrup, 60 kV station Pandrup and 60 kV station Fjerritslev. Figure 7.2 shows where different summer houses are located.

Figure 7.2 Geographical location of a number of summer houses

As the summer houses are spread on different 10 kV lines and at different 10 / 0.4 kV substations, no changes in power flow due to the control has been seen. To show the influence of a management, a small village, where the houses today are mainly heated by natural gas, is selected. Electricity consumption in the houses is therefore classic electricity consumption, for example: electricity for washing machine, refrigerator, freezer, TV, stove, light, etc. An extraction of electricity consumption (hours) from the houses under a 15 / 0.4 kV station (31189) has been made. Figure 7.3 exhibits the electricity consumption for a year. The seasonal variation of the classic electricity consumption is clearly seen.

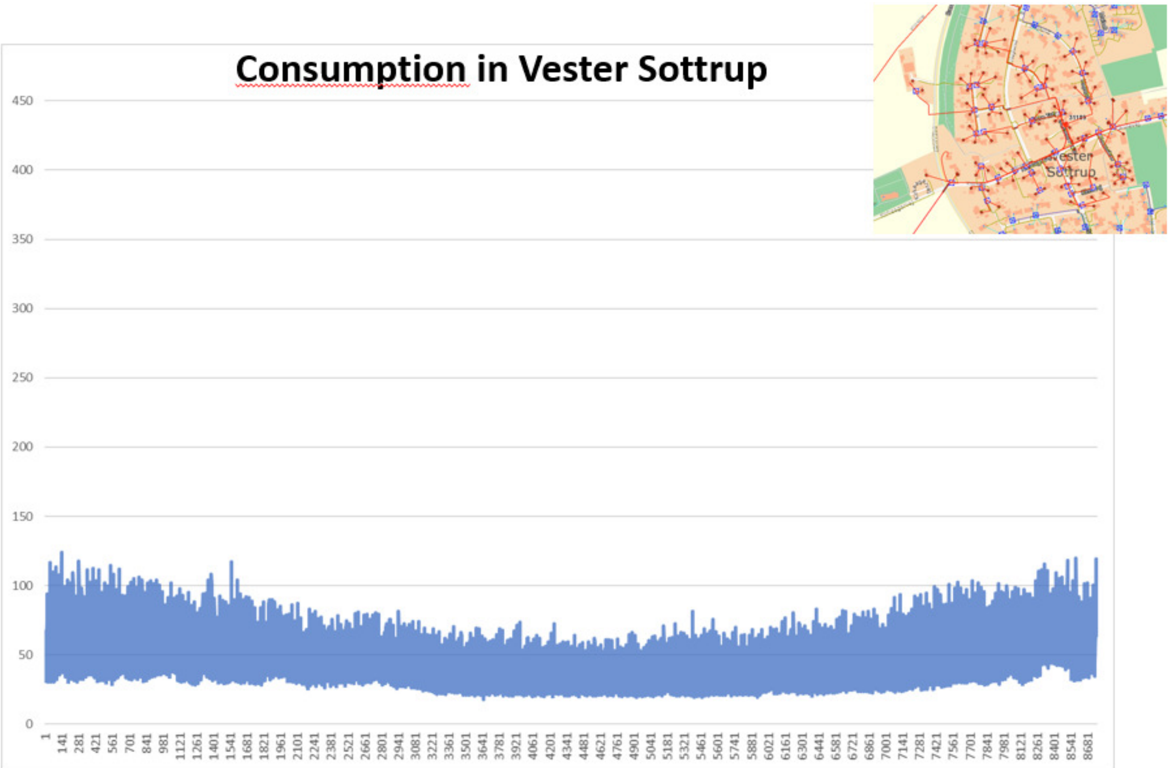

Figure 7.3 Consumption in Vester Sottrup

To give an overview of the maximum load of the 15 / 0.4 kV station, all houses are converted into a consumption profile where the house is heated by a heat pump. Consumption profiles of the houses heated by heat pump are randomly selected throughout the whole of DSO's supply area. This ensures that the heat patterns of the heat pumps are random. The selected houses currently have a normal tariff which means there is no incentive to move with the heat pump operation. Figure 7.4 shows that with a 100% conversion from gas to heat pump, annual energy consumption will increase by a factor of 2.3 and the maximum power peak will increase by a factor of 3.

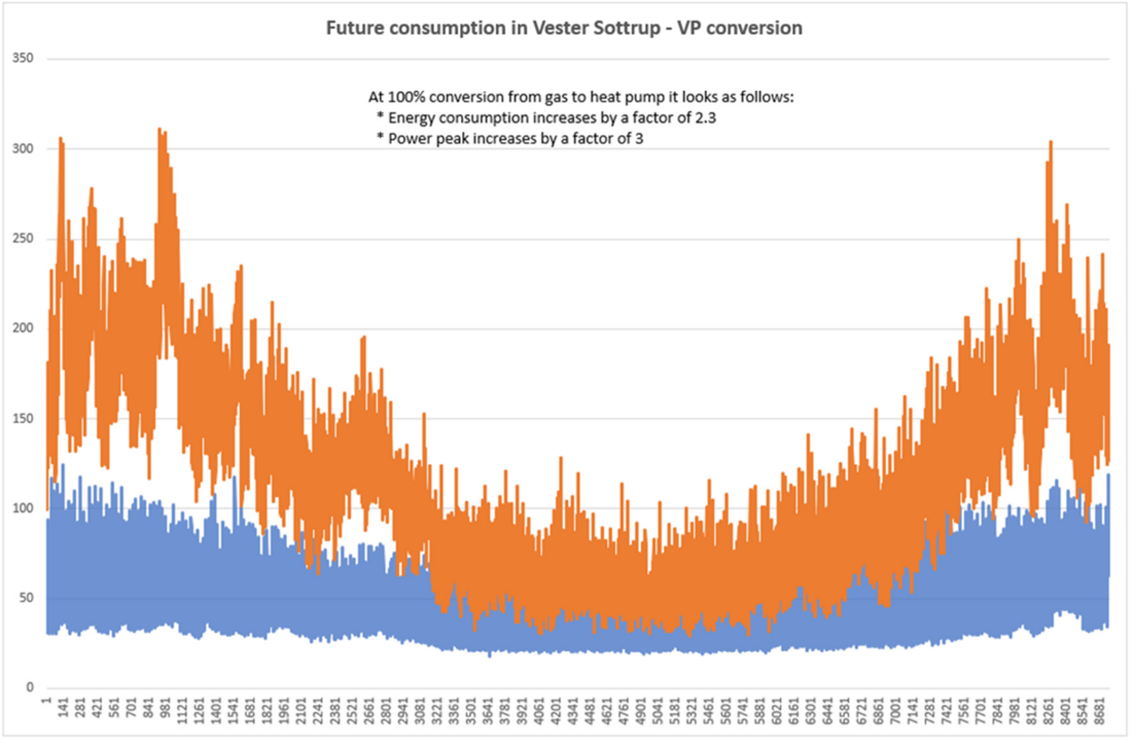

Figure 7.4 Future consumption in Vester Sottrup - VP conversion

The Danish pilot set-up proof of concept could benefit both the transport sector and the heating district where similar models, algorithms and technologies can be implemented. In the future, the transportation is expected to be solved by EV. Charging of EV's must therefore be added to the above power diagram to provide a correct picture of the future energy consumption and the maximum load of the existing grid. In this survey, it is chosen that 10% of households in the future will buy an EV. An average driving requirement of 75 km per day is calculated.

Figure 7.5 shows that with a 100% conversion from gas to heat pump and 10% of the houses buying an electric car, the annual energy consumption will increase by a factor of 2.5 and the maximum power will increase by a factor of 4.

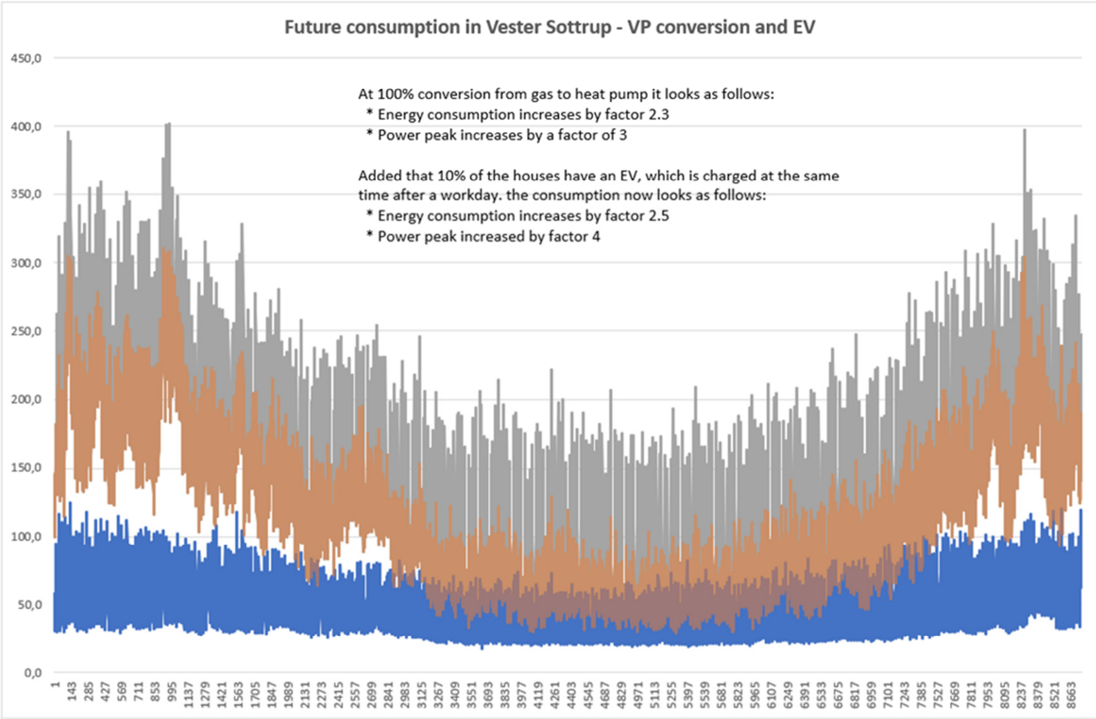

Figure 7.5 Future consumption in Vester Sottrup - VP conversion and EV

To show the influence of an intelligent charging of EV on the power peak, the time has been shifted by one hour, as seen in Figure 7.6. It now eliminates almost entirely the power peak in relation to existing charts. If the heat pumps also are more flexible, there will be a reduction here too. This is not included here. An intelligent control of power consumption seems that much more energy consumption can be absorbed into existing grid without the need for reinforcements.

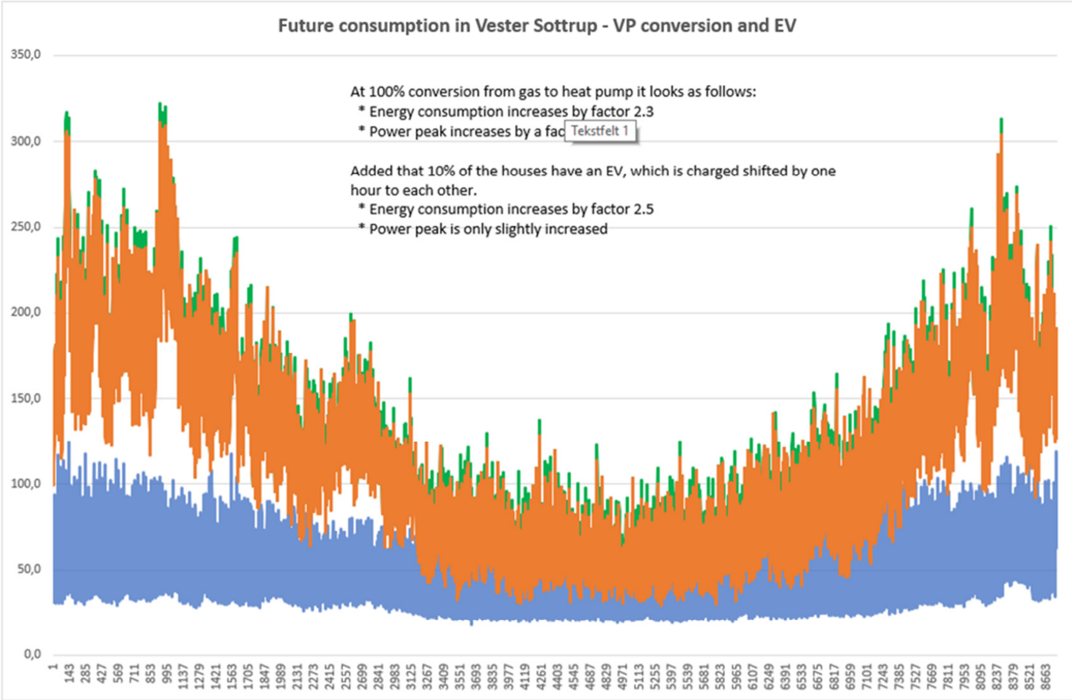

Figure 7.6 Future consumption in Vester Sottrup - VP conversion and EV (shifted by one hour)

7.2 Pilot Operation Results under Indirect Price-based Control

In this section the operation of the lower level is shown through snapshots from the control interface. For all of the figures the top plot illustrates the past and predicted temperatures of the pool in dark blue and light blue, respectively. The temperature limits are shown in teal, while green represents the temperature set point. The bottom plot shows the predicted penalty in black and scheduled heating in purple. Figure 7.7 is a typical example where the summer house goes from occupied to not occupied, resulting in the lower temperature limit being reduced. As can be seen, the MPC makes sure to heat the pool just enough to keep the temperature above the limits before the evacuation of the summer house and doing so during the time with the smallest predicted penalty.

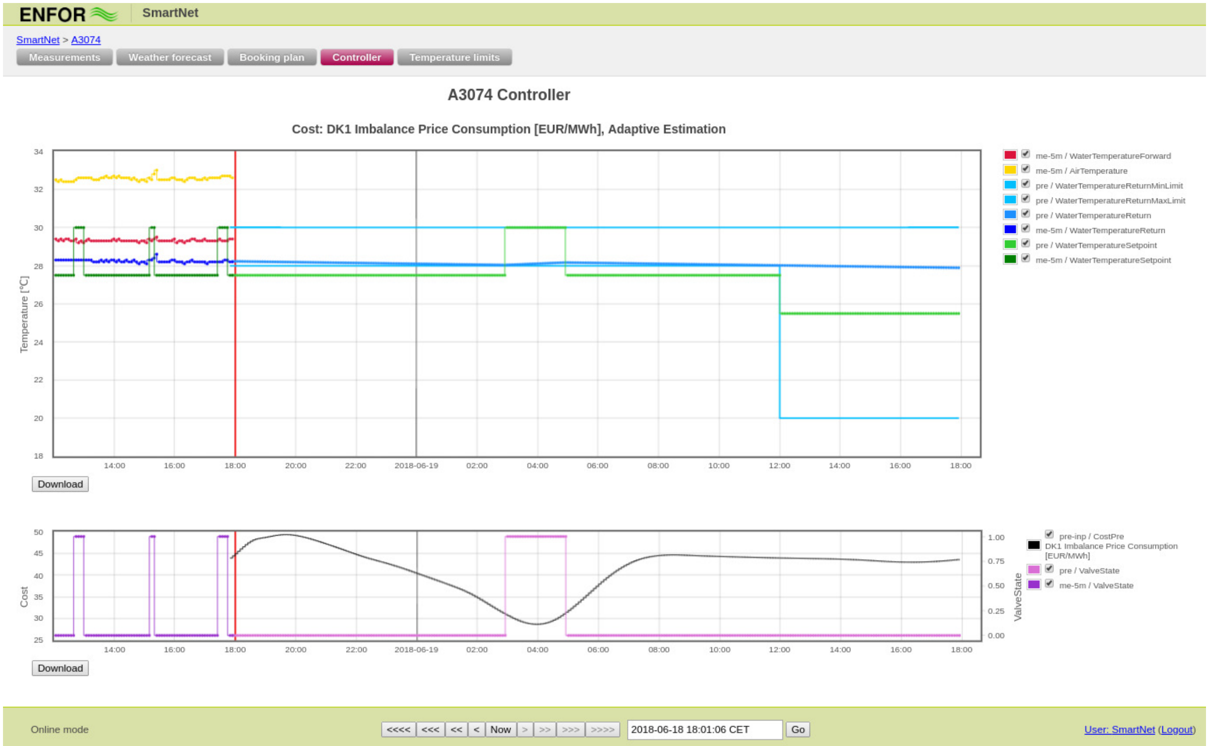

Figure 7.7 Summer house going from occupied to not occupied

Figure 7.8 shows the opposite case, where the summer house goes from not occupied to occupied, and thus the lower temperature limit increases. Since it might take more than the look ahead time of 24 hours to increase the temperature sufficiently, the lower temperature limit increases gradually 24 hours prior to the summer house being booked, giving the MPC 48 hours to react. Since the increase in temperature is continuous, it is still possible for the MPC to utilize the flexibility to some extent. If the temperature limits were raised instantly, then the MPC would heat constantly until the limit was reached, resulting in it being completely inflexible.

Figure 7.9 shows a day where Danish wind turbines were producing large amounts of electricity resulting in negative regulation prices. The result of this was that all swimming pools were heated as much as possible, until they reached the upper temperature limit.

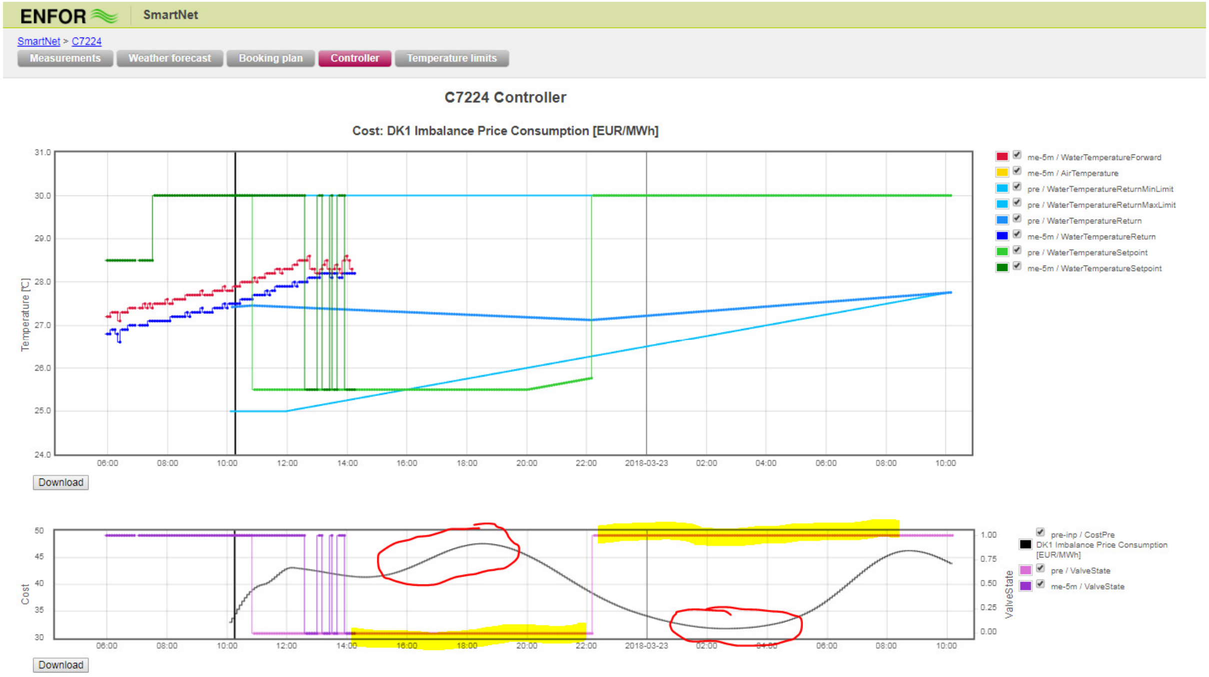

Figure 7.8 Summer house going from being not occupied to occupied

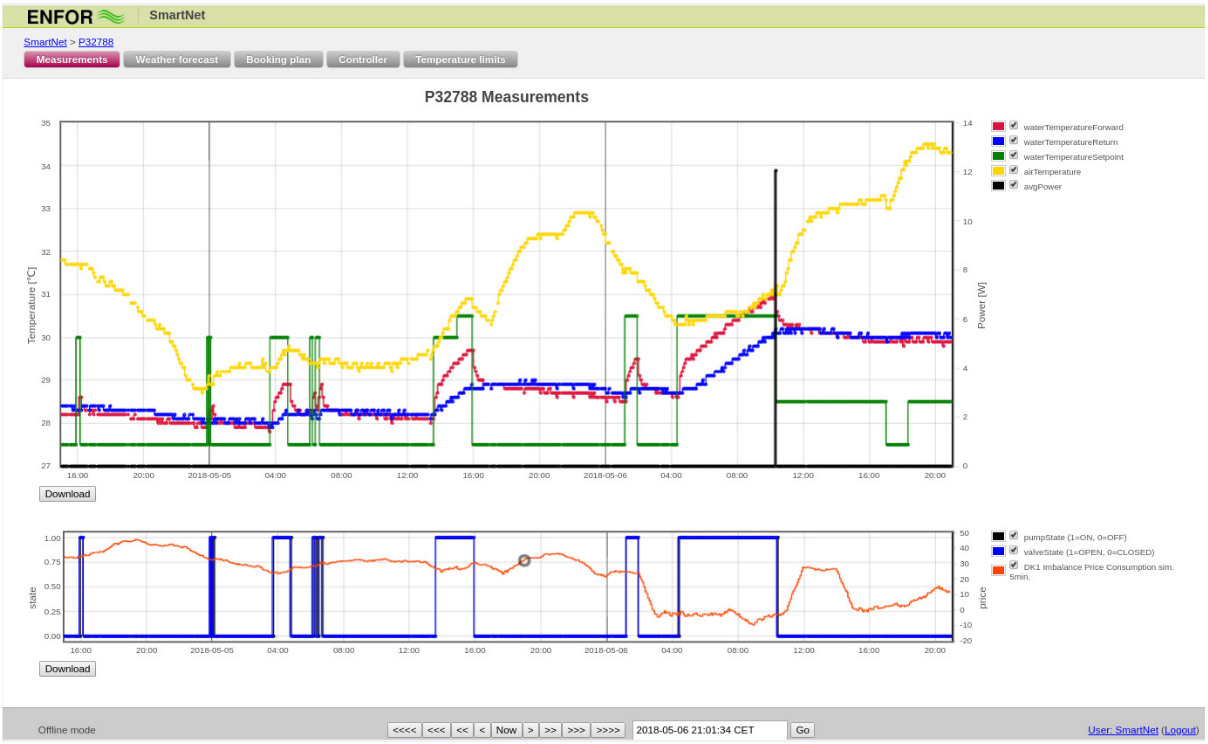

Figure 7.9 A day where Danish wind turbines were producing large amounts of electricity resulting in negative regulation prices

To quantify the potential savings, when using penalty-based control, summer house D7811 was analyzed for three weeks during October 2017, where it was being controlled such as to minimize CO_2 emission. This period is shown in Figure 7.10, where the top plot shows the temperature in blue and the state of the heating in red (1 if on, 0 if off). The bottom plot shows the CO_2 intensity for the same period. It is evident that the heating tends to be turned on when the CO_2 intensity is low and off when it is high. To figure out the extent to which this was possible, the average CO_2 intensity while the heating was on can be compared to the overall average CO_2 intensity. If no extra energy consumption was caused by the MPC, the ratio between these two averages gives the saved fraction of CO_2 emission. In this case, the average CO_2 intensity during heating was 201.8 gCO_2/kWh, while the overall average was 223.1 gCO_2/kWh. This means that the CO_2 emission was reduced by 9.6% compared to normal operation.

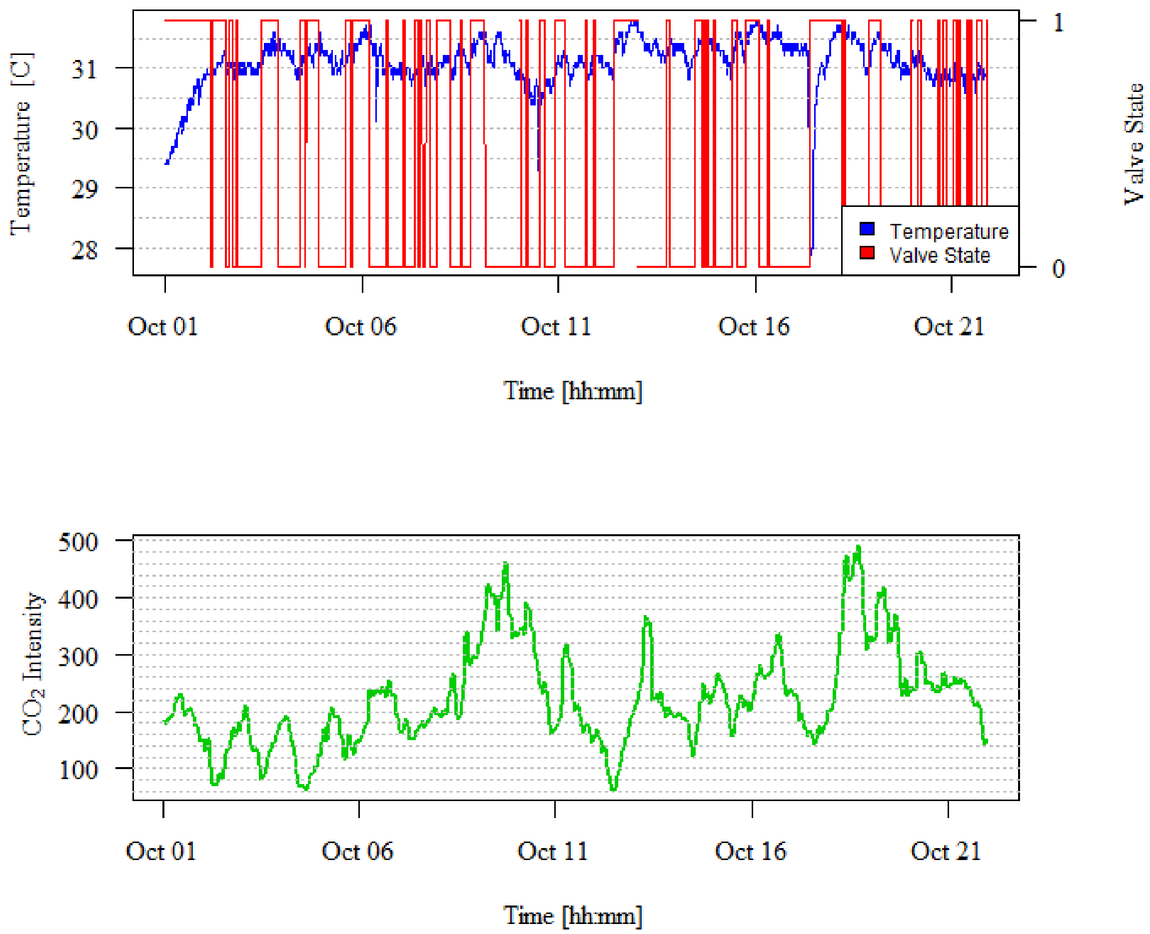

Figure 7.10 *21 days of CO_2 based control in October 2017. The top plot shows the temperature of the swimming pool in blue and the state of the heating in red (1 for on and 0 for off). The bottom plot shows the CO_2 intensity of the electricity for the same period*

7.3 Hardware in the Loop Simulation in the Lab Environment

In order to test and validate the findings within the SmartNet project, beside collecting real Pilot results, Danish Pilot was chosen to participate in a laboratory test, which was intended to accompany and

extend the validation and tests made in the Pilots. The laboratory tests are dedicated to replicate and test a number of functionalities as well as to anticipate some potential issues and troubles before they are implemented in a real scenario. In addition to that, laboratory tests can add further possibilities for testing new functions that cannot be tested in a Pilot, such as situations where the current regulatory framework is blocking.

Having these goals in mind, the laboratory tests focused on evaluating certain equipment that were conceived for purpose of the Pilots. This was done by combining the capabilities of AIT SmartEST laboratory[2] with SmartNet simulator. In other words, the laboratory validations were based on HIL setups, avoiding relying only on software simulations. Furthermore, the use of the SmartNet simulator in a HIL setup also provides further possibilities for validation of the SmartNet simulator, especially considering real-time aspects. The following presents how these laboratory tests were specified, executed, and what the main results of these tests were. These tests were also presented in [12].

7.3.1 Price Based Controls in Combination with SmartNet Coordination Schemes

The Danish Pilot uses a priced-based control from the Economical Aggregator down to the heaters of the swimming pools. Since these price-based controllers are different than the controllers initially considered during the design of the coordination schemes, a laboratory test combining the price-based controllers with a simulation of the SmartNet coordination schemes provides an interesting validation case. Besides providing answers about the general setup of such a system, it might also be possible to validate how the different coordination schemes perform in combination with price-based controller. Of course, this is also studied in the Danish Pilot, but a laboratory test brings more flexibility when it comes to testing scenarios that may not be comfortable for the residents of the Danish summer houses. Since the price-based controllers should be tested they need to be integrated into the laboratory environment.

For the integration, the laboratory was connected to the physical swimming pools located at the summer houses in Denmark. A simple possibility to achieve this kind of setup is to reuse the Danish system as much as possible; i.e., the local controllers for the swimming pool heaters and the Economical Aggregator entity. Furthermore, since real-time measurements of the active power consumption are available for the summer houses the reaction of the swimming pool heaters can be monitored and the measurements feed back to the network simulator. The concept for this option is seen in Figure 7.11.

[2] https://www.ait.ac.at/en/research-fields/smart-grids/power-system-technologies-development-validation/smart-electricity-systems-and-technology-services/

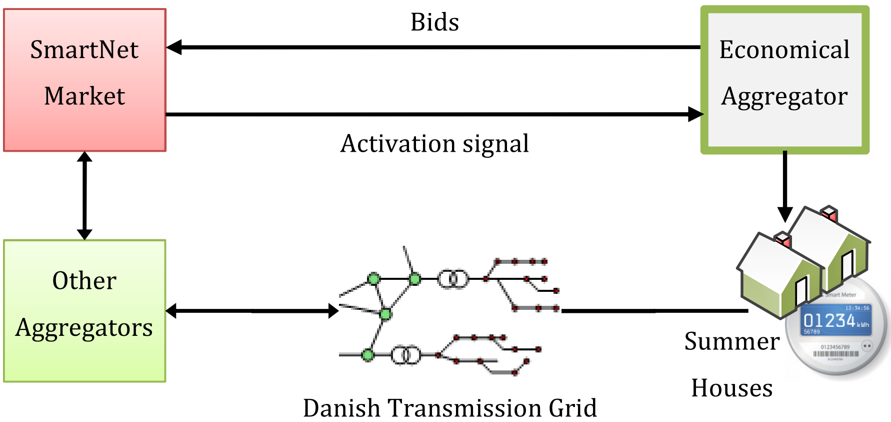

Figure 7.11: Conceptual setup for the HIL test case: Price Based Controls in Combination with SmartNet Coordination Schemes

An advantage with this setup is that the real swimming pools, used by real people, would be used. The main issue with this option is that the tests cannot be run in parallel with the Danish Pilot. Since the Economical Aggregator for the Danish Pilot can only connect to one market at the time (i.e., either the market used in the Danish Pilot or the simulated market for the laboratory tests), this needs to be coordinated between the Danish Pilot and the laboratory tests.

Based on the concept shown in Figure 7.11, a more detailed test case can be formulated. The main idea with this test is to connect the laboratory to the summer houses located on site in Denmark. Thus, not only the local controllers for the swimming pool heaters at the summer houses, but also the Economical Aggregator is used as intended for the Danish Pilot. Furthermore, since real-time measurements of the active power consumption are available for the summer houses, the reaction of the swimming pool heaters can be monitored and used for the evaluation of the test. For the laboratory test case two summer houses were integrated. An overview of this test case is seen in Figure 7.12.

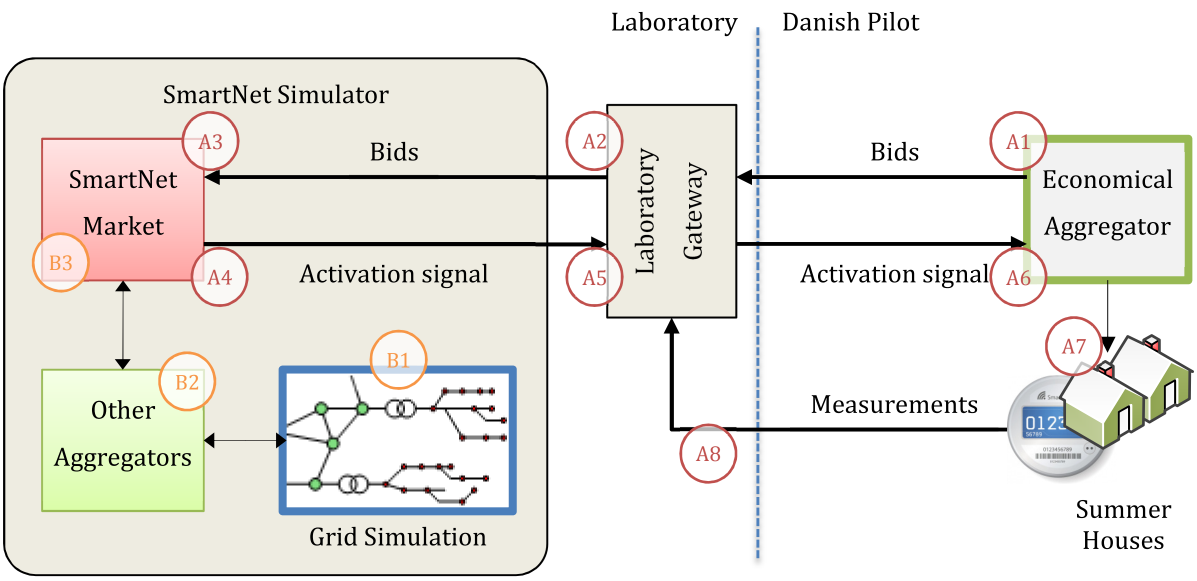

Figure 7.12 Overview of Test Case

The setup of this test case uses the SmartNet simulator, where a scenario based on the Danish Pilot is simulated. Together with the simulation of the transmission grid, the SmartNet simulator also simulates the market and any other aggregators. In the market simulation different coordination schemes developed in the SmartNet project can be used. Since the Economical Aggregator only acts for two summer houses, other aggregators are also needed to be able to simulate a proper market. The SmartNet simulator is running on the Amazon Web Services (AWS).

In order to integrate the components from the Danish Pilot, three main connections are needed. First of all, bids sent from the Economical Aggregator must be forwarded and integrated into the SmartNet market simulation. Secondly, once the market has cleared activation signals are created for all accepted bids and sent back to the aggregators. Thus, the Economical Aggregator must be also able to receive these activation signals. Thirdly, the reaction of the summer houses needs to be monitored. These three connections are seen on the right-hand side of Figure 7.12. To interface the SmartNet simulator running on the AWS with the components running in the Danish field, a gateway installed in the SmartEST laboratory was used. Besides forwarding bidding and activation signals between the Economical Aggregator and the SmartNet market simulation, the gateway was also responsible for recording the response of the summer houses.

The test case has one main sequence and one sub-sequence within the simulator. The main sequence A is depicted with A1-A8 in Figure 7.12 and is described as below:

A1. Bids are calculated by the Economical Aggregator and sent to the laboratory gateway every 15 minutes.

A2. When the laboratory gateway receives a bid from the Economical Aggregator this is automatically forwarded to the SmartNet simulation platform.

A3. When the bids from the Economical Aggregator are received by the market simulation, they are included into the clearing process.
A4. After the clearing process for the next market period is finished the activation signals are sent by the market simulation to the laboratory gateway.
A5. The laboratory gateway forwards the activation signals to the Economical Aggregator.
A6. Based on the activation signal (bid accepted or not), the Economical Aggregator calculates a new price signal and sends it to the summer house controllers.
A7. Based on the current situation in the summer houses (swimming pool water temperature, occupancy of the summer house, etc.), the received price signal is reacted upon or not.
A8. In the last step, the reaction of the summer houses is monitored.

Sequence B is executed partly in parallel with sequence A and is seen as steps B1-B3 in Figure 7.12. The steps are the following:

B1. Simulation of the Danish transmission system.
B2. Calculation of bids for the other simulated aggregators.

In the third step the bids from all aggregators (simulated and real) are integrated into the market simulation, where a market clearing is calculated. This step is synchronized with step A3 and A4 in sequence A.

The expected outcome for this test case focuses on the following points:

- *Connection setup between the Danish aggregator and the market operator:* The goal is to find any connection issues and resolve these before the same setup is used in the pilot.
- *Integration of price-based control with the SmartNet coordination schemes:* The SmartNet coordination schemes were originally not designed to work directly with price-based control schemes. Using the SmartNet simulator the integration between the price-based control and the SmartNet coordination schemes can be further tested.

7.3.2 Validation Environment and Setup

The following parts describe the simulation scenario, setup as well as performed experiments and results.

7.3.2.1 Simulation Scenario and Setup

The simulation time of the Danish scenario is not limited by the size of the transmission network. The main limitation in this case is represented by the high number of devices. In order to reduce the simulation time and make it compatible with the lab, only the transmission network is considered, neglecting all the distribution networks. All the devices connected to distribution networks were not deleted, but their exchange of power was assigned to the corresponding transmission node. Only the

individual model of summer houses connected to distribution were maintained so that they could be compared with the bids coming from the lab. Instead, the devices connected to transmission network remain unchanged.

7.3.2.2 Economical Aggregator

As described above, the main goal of the Danish Pilot is the field test and proof of concept of the control of DERs, in particular of DR, within the SmartNet perspective. This is done through indirect control, set-up by means of a broadcasted price signal to the lower-level controllers, but also through participating in the existing market mechanism of bidding/clearing. The translating party role is assumed by the Economical Aggregator, who on one hand is an active market agent in the day-ahead, intraday and real-time balancing markets (as well as a supplier of the DERs) and on the other hand develops the capability and aggregates flexibility of heterogeneous nature and even stochastic nature, developing the risk management tools to let this flexibility participate to the market.

7.3.2.2.1 General Architecture

During the Danish Pilot, the Economical Aggregator infrastructure was hosted on AWS and included the following details:

- Implementation and maintenance of the AWS service.
- Structuring LAMP[3] server into the AWS environment.
- A series of memory increase to deal with the increasing amount of data in the server (partially resolved by daily data extractions).
- Optimization of runtime execution of the scripts for enhanced performance.
- Update to the latest Linux version.
- Implementation of automatic clean-up routines.
- Development of integrations with different APIs (e.g., with the Nord Pool spot market)
- Management of connection errors with the server through Https messages.
- REST server installation for communications with MO

The setup of the Economical Aggregator system is shown in the Figure 7.13.

[3] The acronym was originally popularized from the phrase "Linux, Apache, MySQL, and PHP"

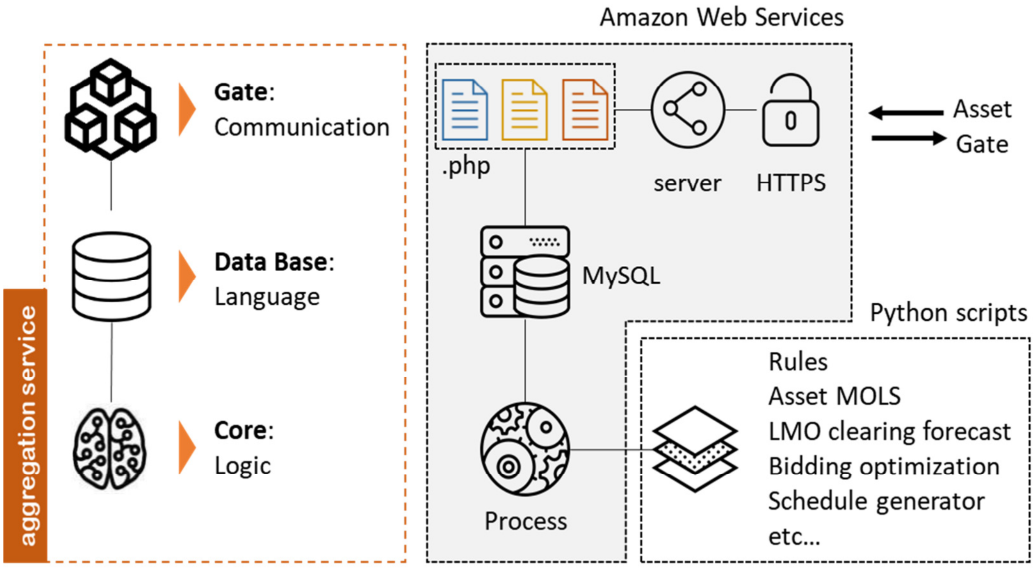

Figure 7.13 Architecture of the different services implemented in the Economical Aggregator system

In order to effectively communicate with other components and partners, the following Python scripts were implemented:

- Creation of 'createOffer.py' script that collects the daily intraday data of Nord Pool through their API and generates a bid (in the eXtensible Markup Language (XML) format) from a bids curve made in our Economical Aggregator.
- Implementation of a new script 'sentOffer.py' that is in charge of generating the requests and Https replies to send the offer to the MO.
- Creation of script 'sentJson.py', which is responsible for collecting the market results accepted in the market, to proceed to operate with the algorithm generated by the Economical Aggregator and send the final price to the Technical Aggregator.

These scripts are necessary to ensure correct communication with all counterparties. All communications through the Economical Aggregator's Asset Gate are made through port 443 over HTTPS. The interpretation of all communications arriving at the server is done through PHP management and HTTPS POST requests and through an encrypted connection. The logical unit R-server executes a series of scripts that result from the implementation of the algorithm of aggregation, management and optimization, shown as the Process in Figure 7.13.

7.3.2.2.2 Software Setup

The software architecture designed for the Economical Aggregator is shown in Figure 7.14

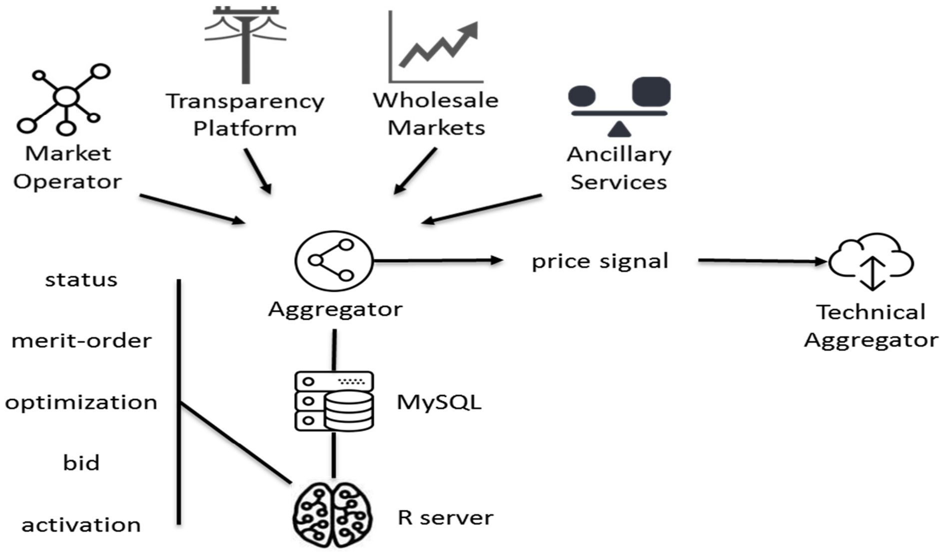

Figure 7.14: Software architecture from the Economical Aggregator's point of view.

For the logical unit, Python was chosen as the development language and it was run from an Ubuntu (Linux) desktop mounted on an AWS server. In Figure 7.15, the timeline of the process is highlighted.

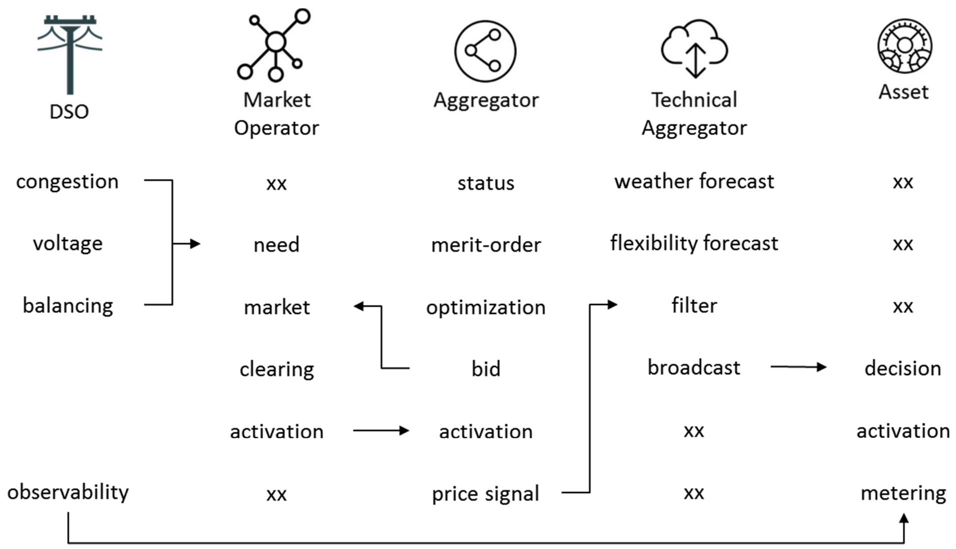

Figure 7.15: Diagram of the timeline for the process from the Economical Aggregator's point of view.

As for the Economical Aggregator's bidding strategy, a global process that consists of the following items has been implemented:

- Acquisition of spot (day-to-day) and intraday prices from the Danish spot market (Nord Pool)
- Calculation and characterization of the difference between these two prices for the current delivery time.

- Based on this characterization two bidding curves are defined: the ascending regulation and the descending regulation.
- Calculation of an appetite layer of "activation" for a given direction (regulation up or down) based on historical activations as well as on the current state of the pools.
    - The bounces from previous activations are analyzed (read the current baseline and, provided there is no activation, what the asset would try to do).
    - This appetite is reflected in the displacement of the bidding curve up or down, so it makes it easier to activate the asset in the "right direction".
- With the two previous levels, an aggregate bid curve is generated that is sent to the market.
- The bid curves are stored with a characterization of which asset is behind each of the individual bid points, so that disaggregation becomes a trivial consideration.
- Continue to listen to market results and activation messages on the Economical Aggregator server.

In case an activation signal is received, the activation is stored, and immediately processed. The rebound effect of these activations that are stored in the baselines for the next market (these rebound effects are added to the previous ones) are calculated, see Figure 7.16 for an overview.

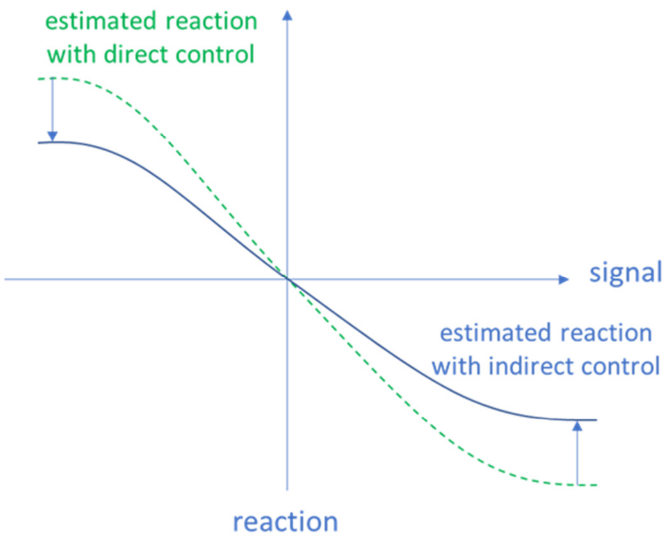

Figure 7.16: Schematic of flexibility activation and associated rebound effect.

Once the bids are sent and the activations made, a price signal must be generated and broadcasted to the Technical Aggregator, i.e., the local controller of the summer houses. This signal is generated considering the economic balance equation for the Economical Aggregator.

In the target setup, the Economical Aggregator is also the supplier of electricity of the DER assets, and it is important to mention the importance of the choice of price control mechanics; as explained above, an opt-out for a price-based signal was made, where the price indicated the price for the whole load of the

DER during the activation period. Different methods would derive different equations and probably different challenges.

Assuming the role of the Economical Aggregator isolated and prior to any considerations for the considered hour, it must be assumed for simplicity that an amount of energy equal to the baseline was bought on the day-ahead market at spot price S. This creates an energy account of L units on the Economical Aggregator account for a cost of L×S monetary units.

Participating to SmartNet market, the Economical Aggregator bids for delivering/receiving additional volume $\hat{A}$ for a price $\hat{E}$. In the same way, E is denoted as the auction clearing price. Furthermore, $\hat{A}$ is denoted the response volume and it is assumed its sign convention is set to match the one for the baseline load L. Hence $\hat{A} > 0$ stands for an increase in consumption and $\hat{A} < 0$ is a reduction of load.

Finally, it is assumed that there is a comfort cost related to the activation of the flexibility C in monetary terms. This term considers not only the amount of flexibility intended to activate, but also the risk premium for rebound effects, availability and complex constraints (e.g. no more than X activations per week).

Hence, the total cost for the Economical Aggregator is:

$$Total\ Cost = \mathrm{L} \cdot \mathrm{S} + \hat{\mathrm{A}} \cdot \mathrm{E} + \mathrm{C}$$

Now, the Economical Aggregator must recover at least this cost from the agreement to procure energy to the DER in the target hour. This is the effective volume

$$\mathrm{L}^* = \mathrm{L} + \hat{\mathrm{A}}$$

and the price of that effective volume P^*, where this P^* is, according to the choice of mechanism, the actual price signal that is aimed to be conveyed to DERs; hence:

$$L^* \cdot P^* = \mathrm{L} \cdot \mathrm{S} + \hat{\mathrm{A}} \cdot \mathrm{E} + \mathrm{C} \rightarrow P^* = \frac{\mathrm{L} \cdot \mathrm{S} + \hat{\mathrm{A}} \cdot E + \mathrm{C}}{L^*}$$

If $L = L^* - \hat{A}$, then

$$P^* = \frac{S \cdot L^* + (E - S) \cdot \hat{\mathrm{A}} + C}{L^*}$$

$$P^* = S + (\mathrm{E} - S) \cdot \frac{\hat{\mathrm{A}}}{L^*} + \frac{C}{L^*}$$

Hence the price signal can be derived from the spot price, adding the spread between the expected MO clearing price and spot, weighted by the share of response in the new load and the response costs per new load energy unit.

Overview of the units used for the equations above:

- L: baseline profile

- *S*: spot price
- *L**: expected profile
- *Â*: expected reaction; L+Â=L*
- *P**: price signal
- *Ê*: expected MO clearing price
- *E*: MO clearing price
- *C*: risks, margins, etc.

7.3.2.3 Laboratory Setup and Configuration

For this test case, the setup of the SmartEST laboratory was reduced to a development and installation of the laboratory gateway. The gateway consists of two main components: a Bid-Platform and a measurement logger, seen in Figure 7.17.

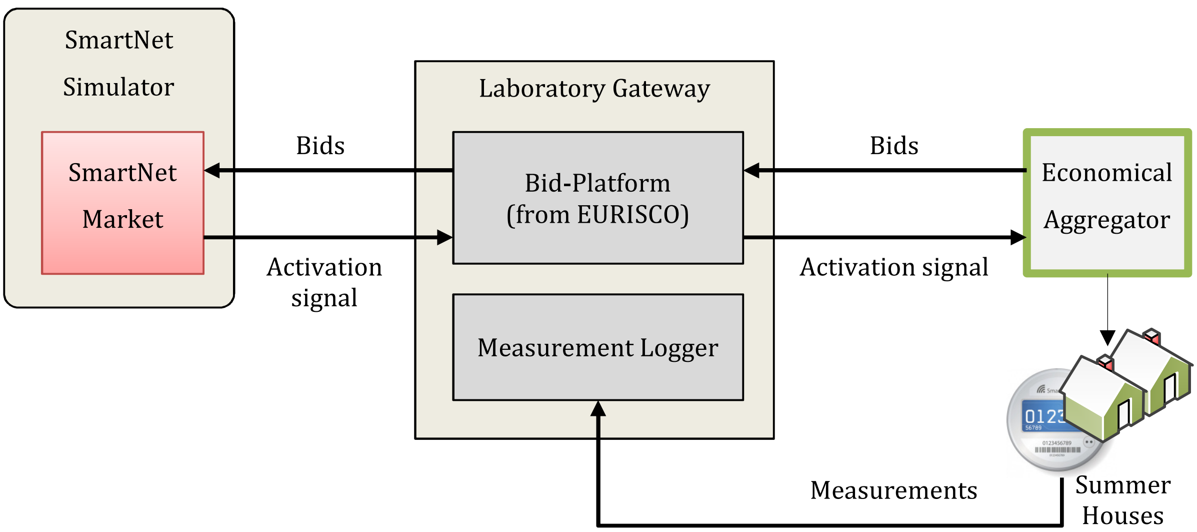

Figure 7.17: Overview of the two main components contained in the laboratory gateway.

The Bid-Platform was originally developed by EURISCO, as the MO, for the Danish Pilot. For this test case it was slightly adapted and reduced to the server where participating aggregators can place bids. This means that for the Economical Aggregator the interface used for bidding (and receiving activation signals) remains the same for both the Pilot and the laboratory test. As an addition to this bidding server, an interface was added for connection to the market simulation running on the AWS server.

The Bid-Platform receives bids from the Economical Aggregator in XML format using an HTTP post. Upon receiving this bid, the platform forwards it to the SmartNet simulator on the AWS platform. This is done by updating an XML-file located on the AWS server. In turn, the SmartNet simulator detects changes to this same XML-file and interprets such a change as a new bid. Consequently, the updated file is read, and the new bid is integrated into the market simulation.

When a new activation signal is calculated by the market simulation, this is also placed in an XML-file located on the AWS server. Once this XML-file is updated, the Bid-Platform detects the change in the gateway and the activation message in the updated XML-file is read and forwarded to the Economical Aggregator.

The second main component of the laboratory gateway is the measurement logger, which reads measurements from the summer houses and logs these for later use. Measurements from the summer houses are available on a web-platform provided by the Technical Aggregator and are updated in real-time every 5 minutes.

7.3.3 Performed Experiments and Results

Based on the test case description and the validation environment and setup two experiments were selected. They are motivated as below:

- *Connection setup between the Economical Aggregator and the MO*: The same bidding-platform is used for both the laboratory test and the pilot. This can be exploited to test the connection between the bid-platform and the Danish aggregator in the laboratory environment, before used in the pilot. This includes sending/receiving bids and sending/receiving activation signals.
- *Integration of price-based controllers for the SmartNet coordination schemes*: Once a successful connection has been achieved between Economical Aggregator and Bid-Platform, longer tests can be performed to validate how well the price-based control scheme of the Danish Pilot integrates with the SmartNet coordination schemes.

The tests done for these two experiments as well as the results are described more in detail in the sections below.

7.3.3.1 Connection Setup between Economical Aggregator and MO

Different types of tests have been established to check the behavior of the developed aggregators, and the tests carried out are as follows:

- HTTPS communication tests between the Technical Aggregator and the MO.
- Communication tests of the REST server between Economical and Technical Aggregators.

7.3.3.1.1 Communication Tests Between the Economical Aggregator and MO

For this test, the HTTP communication was tested between the Economical Aggregator and. Two main tests were made:

- Stability of requests and Http response through port 443 between both parties to check the frequency, with which market results from the market platform are received.

- Check the data structures of the enabled houses (pools), defined and supplied by the MO and adapt them to the system.

In principle, a connection was possible both between the aggregators, the MO, and the SmartEST laboratory. Initially, there were some problems with the wrong XML-format used for the bids by the Economical Aggregator, which resulted in unsuccessful interaction with the market platform. Once the XML-format was corrected the interaction worked.

7.3.3.1.2 Communication Tests between Economical Aggregator and Technical Aggregator

The goal here was to test the connection between the Economical Aggregator and the Technical Aggregator (i.e., the local controller of the summer houses). Three main tests were carried out:

- Stability of the REST connection and execution times in the transfer of information.
- Correct sending of files (json format) to the Technical Aggregator.
- Carry out a complete cycle of communication between Economical Aggregator and technical Aggregator, so that offers, and activations are sent and received by both parties on a continuous basis.

7.3.3.1.3 Market Aggregator Test

Once communication was established between the Economical Aggregator and the other systems, these tests were intended to validate the correct operation of the Economical Aggregator. Four tests were made:

- Input frequency of files (.xml) by MO.
- Execution of all aggregation processes on a continuous basis.
- Check that the available stations are received, the bids are correctly sent, and the market results are captured within the agreed upon period (5 minutes for the Pilot and 15 minutes for the laboratory test).
- Stability and availability of pools available in each market.

During the initial setup of the laboratory tests, it was noticed that the Technical Aggregator received activation signals also when no bids had been sent. This was due to the Bid-Platform run by the MO, which sent “empty” activation signals every 5 minutes when no bids had been received. Since these “empty” activation signals were sent to the same interface as the activation signals provided by the market simulation in the laboratory tests the Economical Aggregator received “real” activation signals every 15 minutes from the laboratory and “empty” activation signals every 5 minutes from the MO. Once this was detected, two interfaces were created for the communication: one for communication with the Pilot system and one for communication with the laboratory.

7.3.3.2 Integrating Price-Based Controls and SmartNet Coordination Schemes

The second experiment was carried out after the initial communication and connection tests finished. The main goal with this test is to see how well the price-based controls of the Danish Pilot interacts with the SmartNet coordination schemes. These coordination schemes have been integrated into the market simulation but were initially not intended to be used directly with price-based controls. Therefore, also the market simulation of the SmartNet simulator was not developed to directly handle such situations.

The main difference of a price-based solution compared to a direct-control solution is that the actual response of the controlled system (i.e., the heater of the swimming pools for the summer houses) is not known when a price signal is sent. Consequently, a control scheme designed for a direct-control solution that is used one to one with a price-base control solution will most certainly not produce the exact same results. Nevertheless, by monitoring a price-based solution over time, it is possible to “learn” how the system will react to certain price signals.

One of the tests is seen in Figure 7.18. The upper plot shows the measured active power for the two summer houses (labeled C7224 and D7105). The middle plot shows the state of the pump for the heater of the swimming pools and the lower plot shows the activate bids from the market simulation.

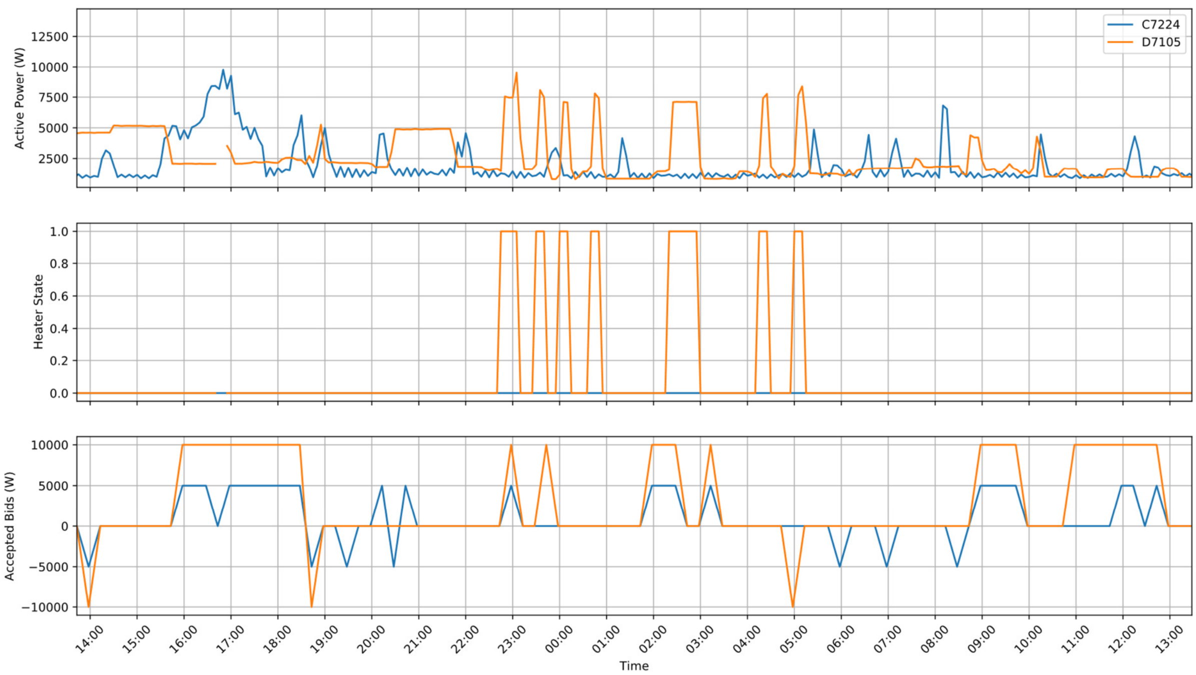

Figure 7.18: Test results for integration of price-based control with the SmartNet coordination schemes; test started 2018-07-25 at 2 pm.

As can be seen in the figure there is a certain mismatch between activated bids and actual activations of the swimming pool heaters. This is because the summer houses have multiple criteria for activating the

heaters. Therefore, the heaters may also be activated without any activation signals coming from the market. Also, the tests were run in the middle of summer, with outside temperatures of around 30° C, so there was not much need for additional heating of the water. This is also the case why the heating of C7224 is never activated during this period. In this case the temperature of the water was high enough, so no heating was needed.

As comparison to the test seen in Figure 7.18, which was made in summer, another test was made in December. The results from this test are shown in Figure 7.19. However, also in this case the activations of the swimming pool heaters do not follow the control signals from the simulation very well. One reason why little response is seen is that both pools were heated in the days prior to the test. Furthermore, summer house P32424 was neither booked for the period before, nor for the period after test. In such cases the setpoint for the water temperature is decreased, which prevents unnecessary heating. In order for the heating to be activated, the price offered by the aggregator must be high enough, which it was not for this test.

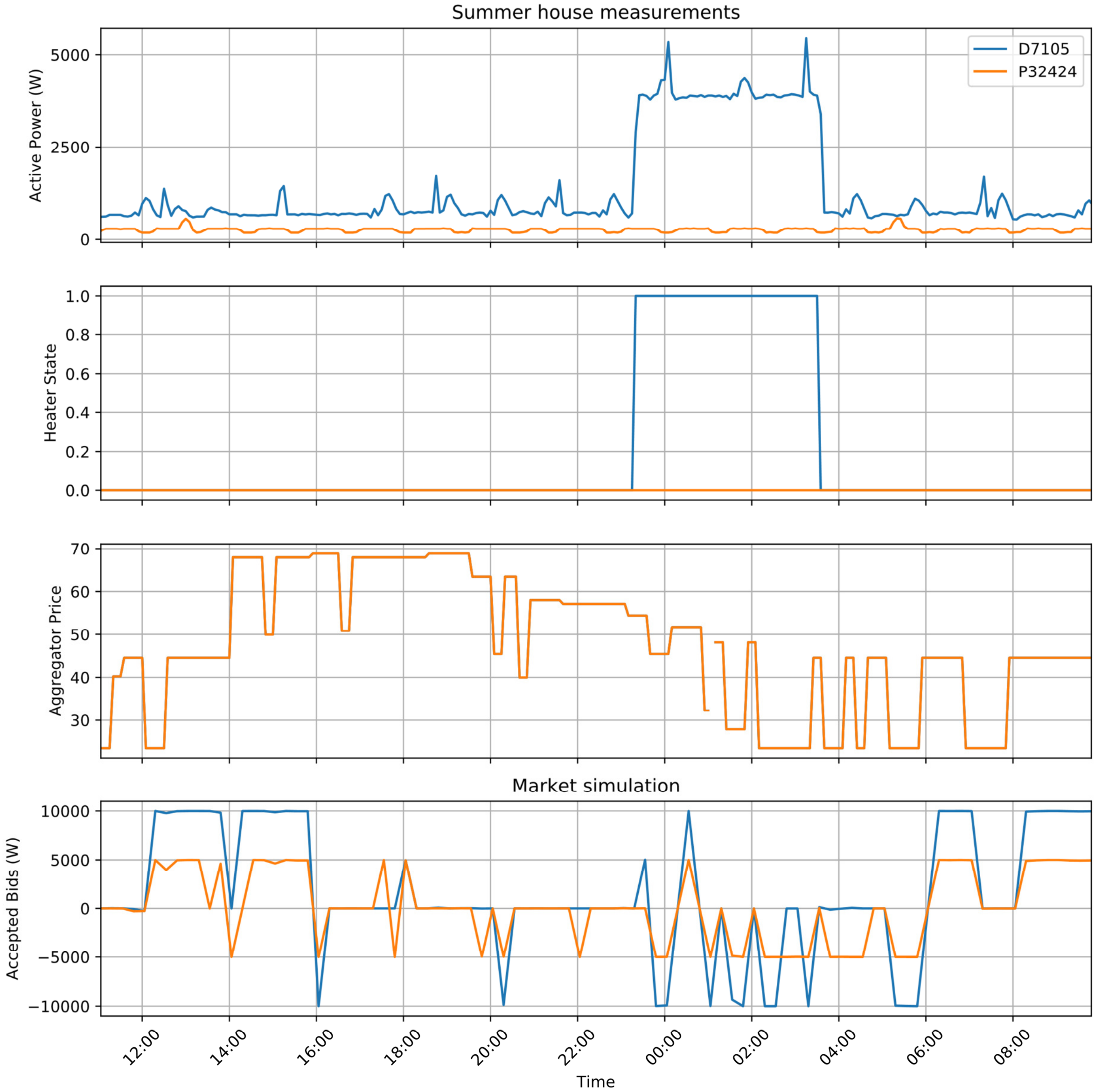

Figure 7.19: Test results for integration of price-based control with the SmartNet coordination schemes; test started 2018-12-17 at 11:03 am CET.

From these results it is clear that the price-based control used in the Danish pilot can technically be integrated into the SmartNet market coordination schemes. This can be validated by looking at the Aggregator Price, which is only sent to the summer houses during a test. However, the results also show that although this is technically feasible the expected results will be something different than with a direct-control solution. It should also be pointed out that these tests were done with only two aggregated summer houses. Therefore, the impact of the price-based control is even more visible. With more houses, there is a higher probability that some of the houses react as expected, which also increases the chances for the aggregator to make accurate bids.

The main added value with HIL test was the possibility to identify issues with the setup and connection of the equipment while using them in the Pilot. Due to the relatively small scale of the laboratory environment compared to the field installation, these issues were soon identified and corrected. Therefore, these issues could be avoided in the pilots, which improved the overall results of the pilot. Besides, using HIL as a validation method allowed the pilot to replicate the setup in a combination of hardware and a simulation platform developed in [1] to use various market strategies to see how the pilot set-up would perform and react. Although, due to various factors including a small number of summer houses used for HIL simulation the full potential of alternative solutions could not be sufficiently achieved.

7.4 Pilot's Challenges and Expected Goals

During the work of connecting the 30 summer houses to the system, several different challenges have appeared. It has been discovered that systems for heating the swimming pool have different control mechanisms and piping. In addition, there have been major problems in maintaining good communication links to the summer house management (SN-10 unit). The chosen communication form is GSM, which in city areas could easily solve the communication task. However, summer houses are located in rural areas where coverage is very unstable. Several communication problems were experienced even with an outside antenna located on a two meters long tube.

Therefore, if electricity consumption is to respond quickly to price signals, more stable communication connections in rural areas are necessary. Considering that in general, heating a summer house with a heat pump is similar to heating an ordinary residential building, some of these approaches developed in the Danish pilot can also be applied to buildings too. Therefore, it is interesting to observe the dynamics and reaction of the occupants of the summer houses to the changes triggered by the controllers; especially to see which parameters are involved when either the electricity consumption is to be started or exposed. An exposure to electricity consumption and knowledge of how long exposure can be without comfort reduction is especially valuable as it ultimately helps to reduce the peak load.

On the other hand, developing and running an operational system of 30 summer houses in the field is quite challenging. Thanks to key technology providers and facilitators of cross-domain solutions among Pilot partners, with the good cooperation in Danish Pilot managed this with good results. Such collaboration also facilitated the test setup and working sessions for the joint activities regarding latency test with IEC61850 protocol payloads to support the requirements specifications in the Pilot.

While supporting the ICT competences and solving the telecommunication issues and contributing to both ICT specifications [12] and lab implementation, the Danish Pilot has also been successful in identifying challenges and presenting robust solutions to the development of the low-level data communication, implementation of the 'Clearing Platform' and actively working on the technology transfer of ICT requirements and knowledge.

Finally, from the Technical Aggregator's point of view, the goal has been to design and run a DMS that supports the projects' aim of running an online system, hereby allowing each of the project participants to fulfill their goals. The DMS has run online for more than a year and has demonstrated the flexibility and robustness of the cloud platform.

7.5 Pilot's Achievements

In general, the pilot's execution has been a great success in a number of ways that have shown the potential for a much more significant contribution to both industry and the research community to harvest energy flexibility. The Danish pilot has demonstrated that energy flexibility could be provided to the grid using new and novel methodologies experimented and deployed in the pilot. A new flexibility function and an economical model predictive control developed by the partners have been implemented, designed and used in a new setup to demonstrate the potential of possible flexibility. Results and analysis obtained from the output of the experiments and test performed in the pilot show that using these new methods could reduce the CO_2 emissions by at least 10%. Besides, the Danish pilot has provided indirect benefits that were not anticipated at the initial stages of the projects, such as remote control of the heating system and the status of property occupancy by the house renters.

From the TSO's point of view, the goal (among others) of the Pilot was to develop and test innovative ICT-solutions supporting activation of flexibility and ancillary services from the demand side to reduce the need of procuring conventional reserves and to secure safe operation of the power system. The Pilot is demonstrating market-based control of customer applications containing energy storage capability (in this case swimming pools) capable of time-shifting their consumption and thereby acting flexible upon price signals. The solution has shown potential to complement existing markets and solution for activation of reserves and ancillary services.

It is believed that collaboration within the project allowed the participants to exchange expert knowledge, valuable research, industry experience, and establishes sustainable research links and networks between main stakeholders on energy systems and energy markets. Discussions about how to solve challenges have been very intense and successful, with a lot of activities ranging from the industrial partners, party installers, and research institutions, to energy stakeholders.

7.6 Lessons Learned

This part describes the lessons learned by Danish Pilot's partners through the challenges faced over the course of the Pilot in, e.g., developing models, prototyping products, implementation, installation, monitoring, and analyzing.

The overall setup has been shown to work, but key elements have experienced issues, that should be considered to improve in future projects. For the Danish Pilot, the goal was to show the utility of energy flexibility in scale. Thus, it was decided to install the setup in 30 summer houses. Major issues within the

Pilot were as follows: connectivity issues, actuation failures, and incorrect sensor measurements. To solve these issues, the responsible partners had to spend large amounts of man hours, with combined costs dwarfing those of quality installations. Moreover, discomfort was caused to occupants of the summer houses, resulting in having to switch off price-based control several times. It is clear that robust installations to reduce the cost of having problems, and more importantly avoid that consumers and partners lose interest in the project, are needed for future projects.

Throughout the Pilot it has also become apparent that energy flexibility must be considered as a dynamic phenomenon. This contrasts with the classical problems related to production, transmission and distribution of power, where everything can be assumed static. Moreover, energy flexibility comes with stochasticity much larger than that experienced for power generators. The dynamics and stochasticity are especially pronounced when zooming in on few buildings and small time-scales, as was done in this Pilot. This means that bidding-clearing approaches are inappropriate for activating energy flexibility, which leaves aggregators in a poor position to participate in the current power markets. Control approaches are currently the only known solution to stochastic and dynamic problems. A restructure of power markets should be undertaken to allow such solutions.

Moreover, it has also been disclosed that for such Pilots, a high time resolution (more than five minutes) has to be chosen to incorporate the energy flexibility on regulation markets. However, the summer houses initially chosen for the Pilot were all heated by heat pumps, where turning them ON and OFF too frequently wears them down. Thus, the frequent flexibility activations requested by the Economical Aggregator were often ignored to protect the heat pumps. For future projects, the time resolution of the energy flexible systems should be chosen, such as to match the requirements of the problems under consideration.

From the DSO's perspective, there is no doubt that the management of the major consumer units in the grid helps reduce power peaks. A new knowledge about the parameters, which are involved when either the electricity consumption is to be started or delayed, was gained. The Pilot shows that it can be achieved with the right market setup.

On the other hand, the TSO has submitted conceptual design input and participated in relevant discussions during the design, implementation, and Piloting phases but has not taken part in the physical implementation and Piloting work. However, by following the process and challenges with the pilot Energinet has obtained valuable knowledge about possible challenges faced by the participants at different levels and in different roles. Understanding the challenges related to integrating DERs in a market structure is important when Energinet everyday together with other TSOs, DSOs and market participants work to improve the current market framework. The process to realize the pilot demonstration and the laboratory test included important discussions of the compatibility between the existing market solutions and the technical capabilities of the DERs.

From a technical perspective, during the uninterrupted operation of the communication and bidding processes implemented in the Economical Aggregator algorithms within the Pilot, various lessons learned have been applied. There have been some anomalies in the processing and adaptation of data at times when data from the NordPool API were not provided. The use of APIs by MOs proves to be really useful in enabling quick, transparent, and non-discriminatory access to market information. Some of the corrective actions were the following:

- Adaptation of the data acquisition and classification method (available pools, bids, activations, loading zones, prices, etc.), to stabilize file transmission times between the Economical and Technical Aggregators as well as the MO.
- Adaptation of the communication protocols has been carried out for the correct resolution of problems, and for alignment with the protocols and specifications manifested during the Pilot's execution period.
- REST Server changes were to the configuration file to establish a stable and continuous communication; the stability of the runtime processes is vital to obtain reliable results for the project.

The Economical Aggregator has also observed the necessity to implement additional code to write temporary extraction files and save the server database (offers, activations, activity logs, etc.) every 24 hours to provide memory optimization solutions on the server in order to feed auxiliary processes and free memory from the server. An optimization of the script to improve the use of memory to solve processing time problems on the server and maximize uptime was also performed. A sound control and understanding of these response functions is a key element for the operation of the Economical Aggregator role when bidding volumes at prices in transactional markets.

The Danish Pilot has been developed by using a unidirectional communication between the upper and lower levels of the Pilot. As a full real-time feedback is not required, the computational load and time declines considerably, thus allowing to broadcast signals from thousands or even millions of assets.

The control for this system is decentralized, as stochastic controllers perform the control duties. Also, this scheme is more secure in case of a certain intrusion, i.e. a hacking attempt into the system. The reason is because it does not allow interference from e.g. the hackers as the Economical Aggregator does not read the available flexibility or bids anywhere; eliminating a significant communication risk.

However, this system makes the Economical Aggregator to implement a new way for the conjugation of the "deterministic" auction/bid/clearing mechanisms necessary at high level, for the "non-deterministic". The exact reaction of the assets is unknown, as just models have been used for this purpose.

During the Danish Pilot, the implementation of the price-based Control, which shares all advantages of unilateral signals as above, presented some theoretical and business-model challenges as follows:

- The decentralized asset makes a price-based decision coupled with the stochastic control.
- The main problem found when working with price-based control from an Economical Aggregator's point of view was its settlement:
    - Which price is the signal referred to? Only for the reaction, or a price signal for the whole set of devices?
    - How to correctly settle exclusively through price-signal a down-regulation from a consumption asset (or up-regulation from a generation asset)?

The use of flexible load control from the domain of residential summer houses is remarkably interesting and particularly challenging. An essential result from the Danish Pilot, has been all the issues related to 24/7 operation of the lower-level equipment and data exchange. Figure 7.20 shows that the data communication to all 30 summer houses are constantly monitored and marked (red), if something needs to be checked manually.

	Postal Code	First Measurement	Latest Measurement	Avail.	+48h	Latest Control Fcs.	TempRet	TempSetPnt	TempRetMin	TempRetMax	Adaptive	Setpoint Endpoint	Accepted at Endpoint
A3067	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0	2018-10-10 13:05:00	32.2 °C	30.0 °C	28.0 °C	30.0 °C	no	sn10.flexgrid.dk	2018-10-10 13:00:00
A3074	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0	2018-10-10 13:05:00	26.6 °C	21.5 °C	20.0 °C	21.0 °C	yes	sn10.flexgrid.dk	2018-10-10 13:00:00
A3128	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0	2018-10-10 13:05:00	30.0 °C	28.5 °C	28.0 °C	30.0 °C	no	sn10.flexgrid.dk	2018-10-10 13:00:00
A3306	6857 Blåvand	2018-09-18	2018-09-25 21:45:00	0	0	Not enabled	-	-	-	-	no	sn10.flexgrid.dk	-
A3763	6857 Blåvand	2018-09-18	2018-10-09 12:25:00	0	0	Not enabled	-	-	-	-	no	sn10.flexgrid.dk	-
P32013	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0	2018-10-10 13:05:00	28.8 °C	27.5 °C	28.0 °C	30.0 °C	no	sn10.flexgrid.dk	2018-10-10 13:00:00
P32037	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0	2018-10-10 13:05:00	28.7 °C	27.5 °C	28.0 °C	30.0 °C	no	sn10.flexgrid.dk	2018-10-10 13:00:00
P32071	6857 Blåvand	2017-11-22	2018-10-10 13:05:00	0	0								
P32121	6857 Blåvand	2017-11-10	2018-10-10 13:05:00	0	0								
P32286	6857 Blåvand	2018-03-01	2018-10-06 17:05:00	0	0								
P32359	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0								
P32424	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0								
P32512	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0								
P32641	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0								
P32731	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0								
P32787	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0								
P32788	6857 Blåvand	2018-03-01	2018-10-10 13:05:00	0	0								
A07395	9480 Løkken	2018-01-26	2018-10-10 13:05:00	0	0								
A11305	9480 Løkken	2017-11-08	2018-10-10 13:05:00	0	0								
D7395	9480 Løkken	2018-01-25	2018-10-10 13:05:00	0	0								
A14526	9490 Pandrup	2017-03-28	2018-10-10 13:05:00	0	0								
A13957	9492 Blokhus	2017-03-28	2018-10-10 13:05:00	0	0								
A12216	9493 Saltum	2017-03-28	2018-10-10 13:05:00	0	0								
A12486	9493 Saltum	2018-01-25	2018-10-10 13:05:00	0	0								
A12979	9493 Saltum	2017-11-08	2018-10-10 13:05:00	0	0								
D7105	9493 Saltum	2017-03-28	2018-10-10 13:05:00	1	0								
D7227	9493 Saltum	2016-09-26	2018-10-10 13:05:00	0	0								
D7320	9493 Saltum	2017-03-28	2018-10-10 13:05:00	0	0								
D7811	9493 Saltum	2017-03-28	2018-10-10 13:05:00	0	0								
C7224	9690 Fjerritslev	2018-01-25	2018-08-29 01:20:00	0	0								

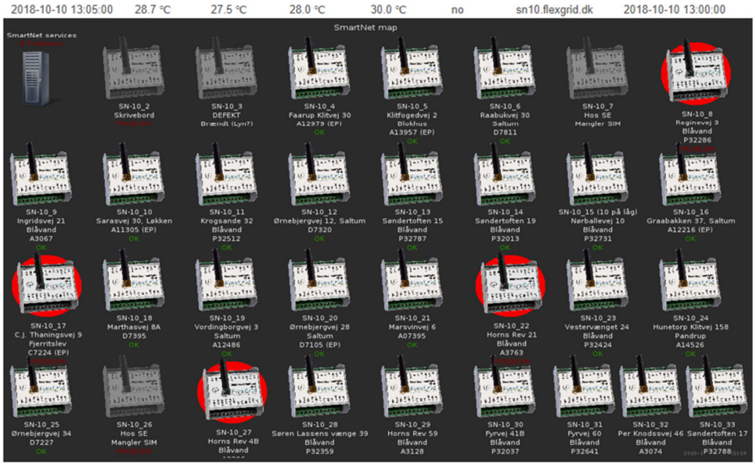

Figure 7.20 Monitoring data communication of all the 30 summer houses.

Some of the issues that has been a result from the 'lower-level' implementation and operation of the Danish Pilot, can be good Lessons Learned for other projects or companies, who will operate a similar system. Some examples are listed here:

- Using 3G tele communication for remote areas with a limited coverage of tele communication networks, can be a challenge. Especially because of the limited bandwidth in periods when there are many people in the summer houses using Wi-Fi and mobile phones.
- Some of the people renting the summer houses was shutting off the heating installation or the power to the control system, which gave some challenges when operating it automatically.
- A batch of SIM cards for the control unit (SN-10) had a problem with material it was made of, resulting in a small deformation and therefore unstable connection between the SIM-card and

the SIM-card connector. This resulted in periodic disconnect from the network and unstable data communication, until the SIM-cards was replaced.

These technical issues and operational challenges are all particularly good Lessons Learned and all-in-all part of the recommendations that can be concluded from the MO's side are:

- Automatic **Condition Monitoring** is essential when operating IoT units in the field.
- Make the IoT unit and management system an integrated part of the summer house rental service, so that the **user comfort preferences**, can be a feedback to the energy management system.
- Make sure the **data communication** is with high Quality-of-Service and with an off-line fallback solution in case of periods with no communication.
- **Low CAPEX can result in high OPEX** - meaning that if the investment in IoT in the field (summer house) is to low, which will course frequent service and maintenance visits in the field, then the operation cost can be too high for the limited income from flexible load control.
- **Value Added Services** for the users and owners of the summer houses, can make the business model more interesting. This could be IoT units and services for remote controlled access control, alarm and security, remote status of water, head and power, measurements for climate control and more.

Some key learning points from the Danish Pilot are as follows:

- **Adaptive estimation (ML) – learn the dynamics per house**
    - Pool cover – on/off affects model (Algorithm set up)
    - Exception handling vs. respect research results – research is done while house is occupied.
    - The model is learning from the pool in order to handle speed of heating and cooling.
- **Communication between service colleagues onsite in Blokhus & Blåvand and engineers**
    - Manual vs. auto
    - Call for heat or not
    - Owner setting
    - Sensor calibration – manual measured vs. system measure
    - Forecast window – 24h vs. 48h to guest arrival – faith in adequate pool temperature at guest arrival time
- **Equipment learnings**
    - Equipment from various suppliers on market
    - SN-10
    - Disadvantage with SIM card as this tends to be less environmental resistant. - prefer to use Wi-Fi signal
    - Not proprietary protocol

- Flex-Control
- Wired solution works fine also as full Smart house solution but for large scale roll-out an end-to-end system integration including guest's interaction is needed.
- Operational experiences
- If you do not integrate the IT you do not harvest efficiency (booking no., door key, meter reading)
- Scenario building; brain storm on exception handling. What to do when guest gets reallocated to another house etc.

Finally, the Technical Aggregator has gained experience with providing a DMS for a project with frequently changing requirements and many project participants. The project has also given experience with maintaining frequently changing static data for the system and distributing this overview to all project participants. The Technical Aggregator has gained experience with providing a platform for running externally developed Forecast/Control models within the forecast engine. The project has given useful experience with presentation of the forecast engine interface and educating external model developers. As a platform provider to a project with many stake holders, this project has also emphasized that detailed online monitoring of the entire system inputs and outputs are important to ensure a reliable control system.

7.7 Dissemination Activities: National Workshop

The national workshop was arranged at the TSO premises. In total, around 60 people attended the national work, and this includes a number of people from Danish TSO, DSOs, BRPs, Energy-IT companies, and energy supply and smart grid companies in general. The workshop also created some attention from people outside Denmark, for example, people from NREL (USA), Argonne National Lab (USA), Korea (Grid planning people), Indonesia and Austria (AIT). It was mentioned several times that SmartNet project has really focused on some of the main challenges of the future smart grids, such as challenges the DSOs (and TSOs) will face given more EVs, PV, Heat Pumps, etc.

Denmark hosts almost 50% fluctuating renewables (wind + solar) in its power system, and the challenges will increase. However, it was also discussed that the fluctuations could potentially be balanced by Danish robust DH system. The knowledge on how to use the huge flexibility of the DH systems to provide grid services could benefit from what was learned in Danish Pilot of the SmartNet project. The conclusion from the national workshop is also that it will be tried to apply for further funding in order to be able to continue with the principles and methodologies developed in the Danish Pilot and SmartNet in general.

8 Conclusions

The Danish Pilot paves the way for new developments and creation of new technologies that help in providing extra flexibility to the energy sector. In addition, in the consumer level, they can gain extra benefits from such methodologies and set-up from some of the challenges this pilot has faced during the execution phase. For instance, summer houses (both owners and renters), the followings are of utmost importance and also challenges throughout the course of Danish Pilot:

This deliverable introduced the Danish Pilot of SmartNet project in detail and presented its key functionalities and valuable results as well as lessons learned. The architecture of the Danish Pilot was based on the current situation in Denmark (in terms of DERs' penetration and uniform taxation scheme). The Pilot assessed to what extent flexible summer houses could provide ancillary services as balancing services and voltage regulation. To materialize that, a field testing of 30 summer houses with indoor swimming pools was performed, which was clearly a sufficient proof-of-concept for the estimation of the potential of summer houses in the provision of ancillary services in Denmark. The control models and algorithms of the Pilot were drawn from the models devised in various contributions in the SmartNet project. Danish Pilot benefited from utilizing SE-OS concept, which is a framework for implementing energy flexible solutions consisting of top-down, one-way communication from aggregators to DERs using price-based control method. A similar idea for the Danish pilot has been implemented in the cloud with a dedicated DMS. It promotes a common flexibility market for system operators. Danish Pilot was split into upper and lower levels. The former, included market clearing at the MO and the interactions among MO, Economical Aggregator, DSO, and TSO while the main focus of the lower level was to compute optimal heating schedules actuate the computed heating schedule for the swimming pools. To validate the technologies developed and incorporated, Danish Pilot did a laboratory test, HIL simulation, and real field test. Throughout these validation phases, Danish Pilot faced several challenges, most of which were handled successfully and will be considered to improve in future projects. Results obtained, and advanced technologies developed in the Danish Pilot attracted the attention from all around the world.

The Danish Pilot paves the way for new developments and the creation of new technologies that help in providing extra flexibility to the energy sector. In addition, in the consumer level, they can gain additional benefits from such methodologies and set-up from some of the challenges this pilot has faced during the execution phase. For instance, summer houses (both owners and renters), the followings are of utmost importance and also challenges throughout the execution of Danish Pilot that can be addressed and rectified in future:

- kWh and money savings now due to optimized heating and in 2020 when market turns to variable rates per hour.
- Will it be possible to obtain a sustaining competitive advantage and attract new owners because of this?

- How will the rental company use this as branding – most competitors are not able to imitate this because of the complex value chain integration
- Business case needed to find out if it is possible to roll this out to all pool houses in Denmark
- What about other countries? - can this SmartNet solution be scaled up to all 50.000 houses in 29 different countries depending on house type.
- Sales concepts – energy saving (35.000 kWh/year/house)
- Coastal near houses in areas with high variation in energy demand – hence the flexibility is needed
- Electrification of summer houses, cars, heat pumps etc.
- What if the DSO/TSO are notified about booking patterns in 10.000 houses? (Energy sector value chain integration)
- Adaptive estimation (ML) – learn the dynamics per house
- The model is learning from the pool in order to handle speed of heating and cooling – hence lower usage
- Remote pool management to align pool temp. with guest arrival in order to optimize usage
- Smart House implementation – kWh, access control, Ph & chlorine value measurements

In general, the Danish pilot has achieved its objectives, in how to apply new control algorithms, defining new technologies for such systems and for larger scale scenarios it will help reduce the CO_2 emissions and provides cost savings to the energy consumers.

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