ECN
Energy research Centre of the Netherlands

Universal Power Manager:

Integrating ECN's PowerMatcher with Nedap's Atrium

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Summary

In the Universal Power Manager (UPM) project, the research was focused on the development of a novel energy management system. The UPM integrates novel, complex power electronics with high speed data communication. The UPM is a combination of two advanced technologies. The *Atrium*, designed by Nedap, contains the hardware with the power electronics and high speed data communication. The Atrium is remotely controlled by ECN's PowerMatcher technology, which optimizes the energy flows. This document discusses the integration tests between the Atrium and the PowerMatcher.

1. Introduction

In the Universal Power Manager (UPM) project [1], the research is focused on the development of a novel energy management system as shown in Figure 1.1. This energy management system, UPM, manages and controls the following for households and small offices (i.e. build environment):

- The input of energy from the electricity grid.
- The input of energy from decentralized generators, such as micro-CHPs, solar panels, fuel cells and urban wind turbines.
- The input of electricity from storage units such as batteries and super capacitors (DC).
- The output of electricity using demand side management of large energy consuming devices such as washing machines, dishwashers, refrigerators and freezers.
- The charging system for storage of electricity in batteries and super capacitors.

The system has a modular design and is future-proof, such that functionalities can be easily (i.e. plug-and-play) added or removed. The UPM integrates novel, complex power electronics with high speed data communication. Due to its advanced data communication, the system can be controlled remotely. Furthermore, it is able to operate off-grid, for example during black out periods. The UPM is a combination of two advanced technologies. The *Atrium*, designed by Nedap, contains the hardware with the power electronics and high speed data communication. The Atrium is remotely controlled by ECN's *PowerMatcher* technology, which optimizes the energy flows.

This document briefly discusses the PowerMatcher architecture as well as the integration testing between the Atrium and the PowerMatcher.

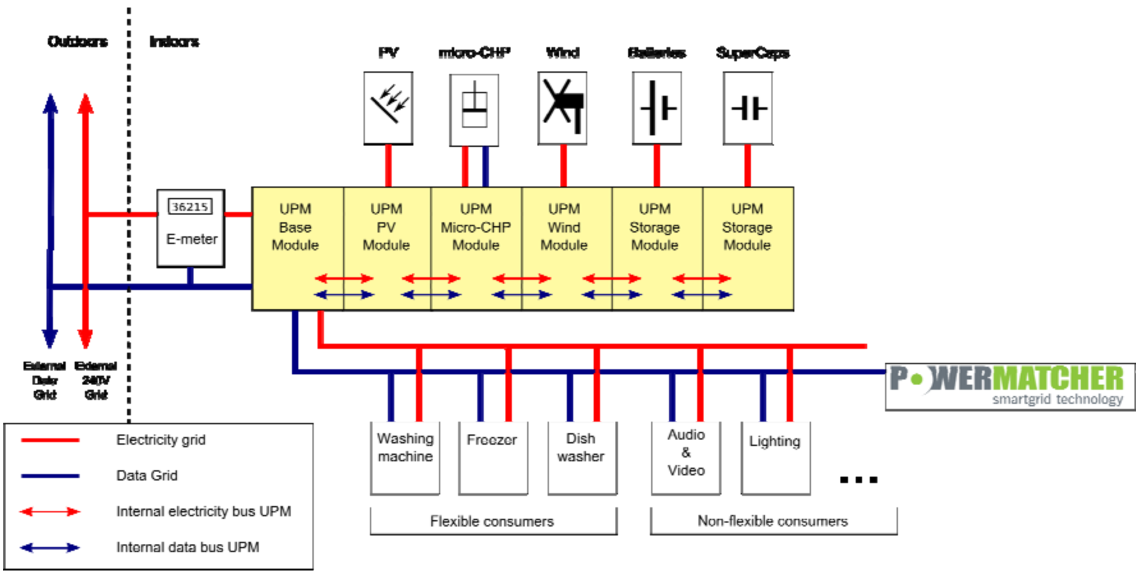


Figure 1.1 *Schematic overview of the Universal Power Manager*

2. PowerMatcher

This chapter describes the PowerMatcher technology, its structure and the business cases as used in the integration tests with the Atrium.

2.1 Background

ECN has developed the PowerMatcher [2] concept for decentralized coordination of supply and demand in electricity networks, with a large share of distributed energy sources, sinks and storage units [3]. It is based on a unification of control theory and microeconomics into a multi-agent system for market-based control [4]. Furthermore, the PowerMatcher has been developed to optimally alter the operation of electricity producing and consuming devices in order to increase the over-all match between electricity production and consumption. Figure 2.1 depicts the different entities in a PowerMatcher network and the relations between them.

A PowerMatcher network contains a single *auctioneer*, which is the electronic market place in the system where the electricity is traded. Devices that can and wish to trade on this market are represented by *device agents*. Such agents attempt to operate the associated processes in an economically optimal way, whereby no central optimization algorithm is necessary and communication with the auctioneer is limited. The only information that is exchanged between the agents and the auctioneer are bids. These bids express to what degree an agent is willing to pay or be paid for a certain amount of electricity. Bids can thus be seen as the priority of a device to turn on or off. As a response to these bids, the market clearing price is returned to the agent. The device agents react appropriately by either start producing (or consuming), or wait until the market price or priority of the device changes.

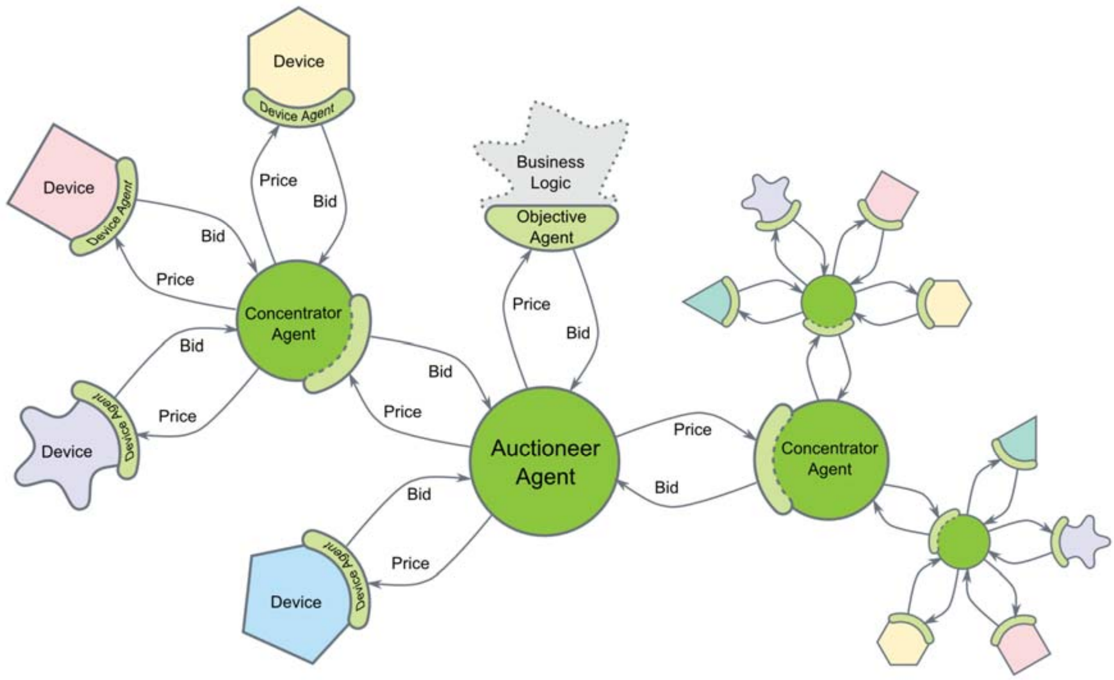


Figure 2.1 *Schematic overview of the entities in a PowerMatcher network*

At the intermediate levels between device agents and the auctioneer, one or more *concentrators* may be located. In their simplest functionality, concentrators aggregate the bids sent by their lower level agents. Additionally, they also can have local responsibilities, such as preserving network constraints, leading to different price-forming scenarios; for example locational marginal pricing. As the communication interfaces of both device agents and concentrators are equal, an auctioneer or higher level concentrator is unable to distinguish between bids received from device agents or lower level concentrators. This property ensures a standardised interface for all types of devices. The use of concentrators at multiple levels allows economical optimizations for multiple stakeholders. While an energy trader, for example, minimizes its portfolio imbalance at the auctioneer level, a grid operator can use a concentrator to handle high peak loads in its substation, to ensure only those that are directly involved with the high peaks are affected. Likewise, a concentrator at household level can optimize for the devices solely inside the house.

Additionally, an objective agent can be included in the PowerMatcher network to input its business oriented goals to the PowerMatcher entities in the form of a standardised bid function. Thus, a trader may trigger, for example, demand response actions in a PowerMatcher market based on its portfolio imbalance. For this task, the objective agent can obtain additional information from the auctioneer, such as the aggregated bid curve.
By clustering of a large number of intelligently coordinated small devices, this can create enough flexibility to provide or consume a significant amount of power, comparable to that of a power plant. Such a cluster, also commonly known as a virtual power plant (VPP), has the opportunity to trade on electricity markets or provide the means for congestion management, which has been demonstrated with the PowerMatcher in a number of field tests [5].

2.2 Business cases

The integration tests between the PowerMatcher and the Atrium have been performed utilizing two simple business cases. These business cases have primarily been used for the design of the PowerMatcher network architecture within the UPM project and not so much for the integration testing itself.

Business case 1 : Trading on variable price energy markets

Energy markets at national levels are known for their time-varying electricity prices. Due to the larger demand, electricity prices are usually higher during the day, especially in the early evening when the demand has reached its daily peak. In the Netherlands, three types of markets are known. The Amsterdam Power Exchange (APX), a day ahead market with hourly prices, an imbalance market with 15 minute timeslots and a recently introduced intra-day market. As opposed to large consumers (and producers) such as energy retailers and industrial facilities, small consumers are not directly affected by these varying prices. They commonly pay either a flat or dual (day/night) tariff. However, if these households consolidate in a virtual power plant, they have the opportunity to trade on these national energy markets.
The first business case for the UPM project is trading on an energy market with hourly-variable prices as this time interval is considered the most interesting for battery electricity storage (and e.g. plug-in hybrid electric vehicles). The prices used in this business case are based on the APX, which are a good indicator of the demand for electricity in the Dutch market. Although the APX is a day-ahead market, it can be safely assumed that the household (or the VPP the household participates in) is small enough that it does not (yet) affect the APX prices themselves and therefore, can be used real-time.

Business case 2 : In-home optimization

On ideal market places, the prices for selling commodities are exactly the same as prices for buying those commodities. In reality there is a gap between the net prices of sold and bought commodities as the market place provider and optional intermediate brokers require a share for their services. Additionally, taxes are raised over the sold or bought goods. A household participating on a national energy market will, thus, not receive the same price for selling electricity as it would have to pay if the electricity was bought directly from the grid. If an import/export tariff (or subsidy) is invoked at household level, the household may want to utilize its flexibility to minimize lost revenue due to this invoked tariff.

Consider a household that may buy electricity in one hour, but sells it again in the next. If the market price in the second hour is significantly higher than in the first hour, a profit can be made even if a tariff is required for the imported and exported electricity. However, if there is little variation in the market price between the first and second hour, the household can utilize its flexibility to match its own, in-house, supply and demand. In such a way, there is no net import or export in the first and second hour, thus saving the tariff costs. Therefore, the household must find a trade off between exchanging on an external market and in-home matching of supply and demand. An example of tariffs that are commonly found at household level are taxes, grid transport costs and subsidies for in-home consumption of self-produced energy.

2.3 Agents

The Atrium used in the integration testing contains three modules: one for batteries, photovoltaic panels (PV) and the connection with the electricity grid. Each of these modules is represented by a PowerMatcher device agent. Additionally, a household device agent representing the remaining non-flexible household demand was used for testing purposes. The PowerMatcher network architecture for the integration test was completed with two concentrators, one at the UPM level and another at the household level, an auctioneer and an APX objective agent. This architecture is depicted in Figure 2.2. A brief description of these PowerMatcher entities is given below.

Photovoltaics device agent

The photovoltaics device agent represents the electricity that is produced by the solar panels. In practise, the power output of a photovoltaic panel cannot be controlled (although technically this is possible) and thus, the bid-curve is a horizontal line below the x-axis as shown in Figure 2.3a. Although the solar panels don’t offer flexibility, their production is included as it affects the trade behaviour of the storage unit.

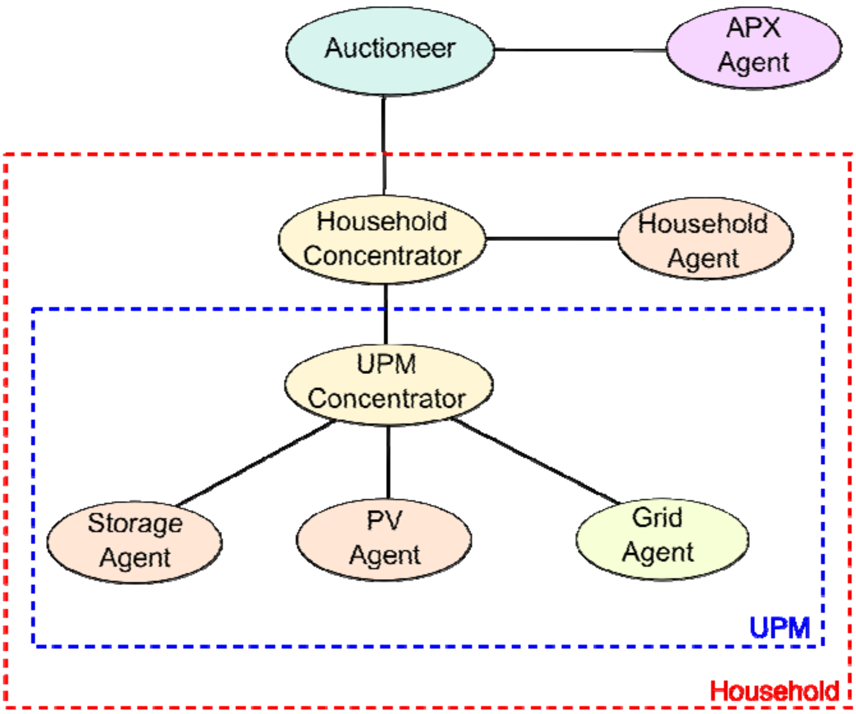
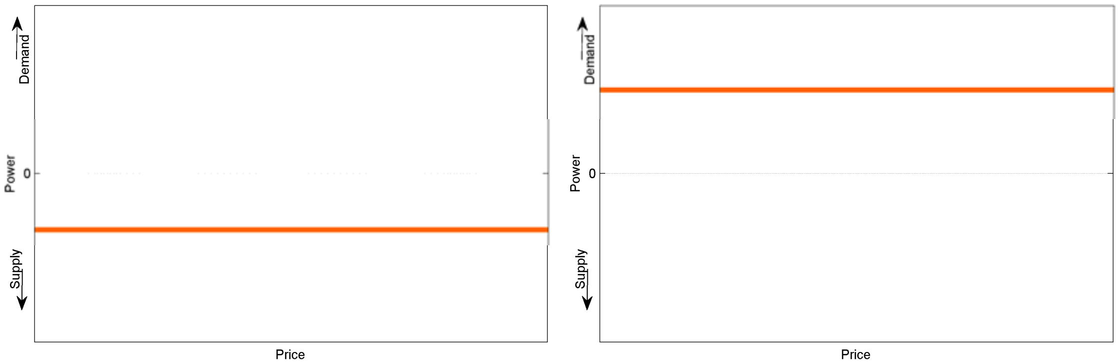


Figure 2.2 *PowerMatcher architecture in the UPM integration test*

Household device agent

The household device agent represents the remaining non-flexible electricity consumption in a home. This demand is simulated using data provided by ECN's energy pattern generator for an average Dutch household with a 10 minute time resolution. As the demand is non-flexible, the bid-curve for this agent is also a straight line. This bid curve is shown in Figure 2.3b.
If the household consumption flowed through the UPM (such as shown in Figure 1.1, the household device agent would be connected to the UPM concentrator as opposed to the household concentrator. It would then also possible to join the UPM concentrator with the household concentrator.



(a) *(b)*

Figure 2.3 *Bid curves of non-flexible devices where (a) is the bid curve for a PV panel and (b) the bid curve for household demand*

Storage device agent

The device agent that represents the batteries has a complex optimization task. As opposed to, for example, a washing machine or a heat pump, it does not have any constraints regarding its flexibility. Thus, the agent solely acts on price signals from the market. Therefore, a good understanding of the expected market price profile is required within the agent. Periodic profiles, such as the APX, can be accurately forecasted with advanced techniques such as mixed-seasonal ARIMA modelling. Optimization methods can be used to determine the charge/discharge profile of the storage to maximize its revenues based on this forecasted price profile. For the UPM integration test, however, a simplified version of a storage agent is used to avoid the complexity of advanced forecasting techniques, although some research has been done on ARIMA modelling of time-series.

The bid strategy of the storage device agent is based on the relation between the state of charge and the expected price range. As opposed to a price profile, a price range (i.e. an expected minimum and maximum price) can be easily derived from historic price data. The state of charge is bounded by a minimum and maximum level L_{min} and L_{max}. Such a bounding can, for example, reduce the battery degradation or ensure enough energy is available to keep devices running in the household in case of a black out. The state of charge as function of the price, used in the UPM, is linear, but more complex functions can be exploited. Some of these functions may be risk-averting, while others may be risk-taking. As a result of numerous electricity buying and selling transactions, energy is lost because the batteries are, of course, non-ideal and have a cycle-efficiency of less than 100%. To compensate for these losses, the sell price, e, must always be higher than the buy price, c.

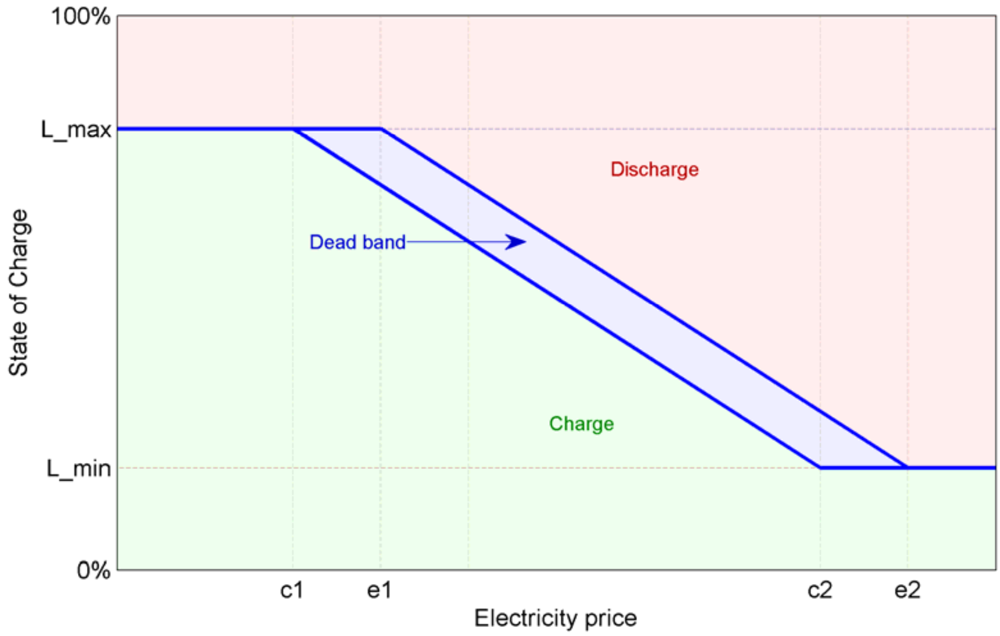


Figure 2.4 *The bid strategy is based on the relation between the state of charge of the battery and the excepted price range for electricity*

Figure 2.4 shows the bid strategy for the storage device agent. To determine the bid, first the corresponding buy and sell price values are calculated using the inverse of the following:

$$f_x(x) \begin{cases} L_{max} & x \leq x_1 \\ \frac{L_{min}-L_{max}}{x_2-x_1}(x-x_1)+L_{max} & x_1 < x < x_2 \\ L_{min} & x \geq x_2 \end{cases} \quad \text{for } x \in \{c, e\}$$

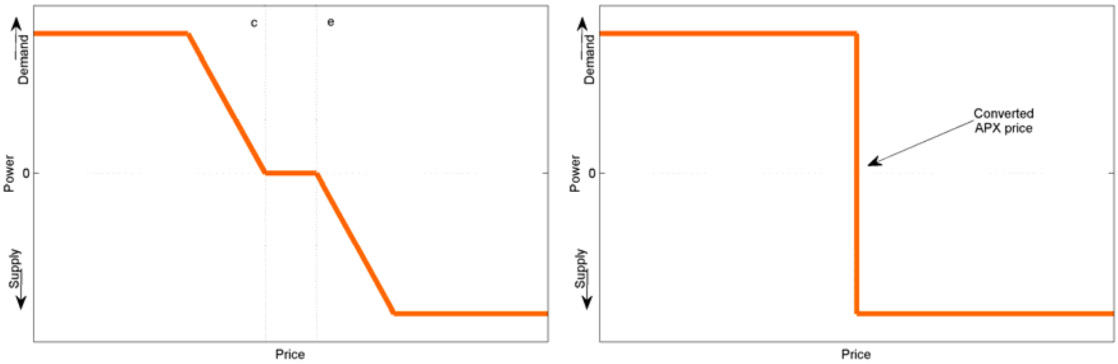
With *f* being the current measured state of charge and where

$$c_i = \eta_{cycle} e_i$$

From these buy and sell price values, the bid curve can be constructed as is shown in Figure 2.5a.

APX agent

The APX agent is an objective agent that ensures the PowerMatcher market price equals that of the APX. The agent converts the APX prices (euros/MWh) into units compatible with the PowerMatcher market price (commonly eurocents/kWh). To force this price within the auctioneer, the APX agent sends a bid curve as shown in Figure 2.5b, where the demand and supply values are chosen in such a way to ensure the auctioneer price matches the current APX price.



(a) *(b)*

Figure 2.5 *Bid curves of (a) storage device agent and (b) APX objective agent*

Grid agent

The purpose of the grid agent is single-fold: it controls the Atrium grid module, but it does not bid on the PowerMatcher market. Such an implementation is slightly different than usually described with the PowerMatcher. The reason is that in the design, the storage agent is unable to control the storage units directly. This ensures that in case the PowerMatcher is not present, erroneous or there is a black-out, the Atrium continues to operate as one would expect. The grid agent is a derivation of the objective agent, because it obtains the aggregated bid curve. However, instead of retrieving the latest aggregated bid curve from the auctioneer the grid agent obtains it from the UPM concentrator. From this bid curve and the market price, the grid agent can determine how much power the Atrium grid module should import from or export to the electricity grid.

Concentrators

In the integration test, both the UPM and household concentrators are aggregators. For researching the second business case, bid and price transformations should be applied in the household concentrator to implement a tariff. For detailed information on bid curve transformations see the Integral project [6].

3. Test Set-up

The integration test set-up contains an Atrium with a storage and grid module, but not a photovoltaic module. The storage module was connected to 5 kWh of lead-acid batteries with a maximum charge and discharge power of ± 5 kW, while the grid module was connected to the public electricity grid. A measurement system was set up to measure current, voltage and temperature at different locations in the system. Part of the measurement system contained a software interface between the CAN messages of the Atrium and the PowerMatcher data. The interface contained a database to log all the signals for research purposes. Measurements were performed at intervals of 10 seconds, including the retrieval of the Atrium CAN messages.

(a) *(b)* *(c)* *(d)*

Figure 3.1 *Photos of the test set-up. (a) the Atrium, (b) the lead-acid batteries, (c) close-up of the Atrium display and (d) the data acquisition equipment*

4. Results

Over a period of four months, several tests were been performed with the PowerMatcher coordinated Atrium system. Beforehand, the Atrium itself had been tested, which is described in a separate document [7]. In this chapter the results of the integration test are described.

4.1 Atrium coordination

As explained in an earlier chapter, the grid agent controls the power consumption and production by the Atrium. For proper coordination of the Atrium by the PowerMatcher, it is important that the allocated power from the grid agent in the PowerMatcher system is realized by the Atrium. In other words, the market contract should match the physical power flows in the grid. Figure 4.1 shows the allocated power (i.e. the “contract”) from the grid agent, the realized power (i.e. physical flow) by the Atrium and their difference over a period of five days.

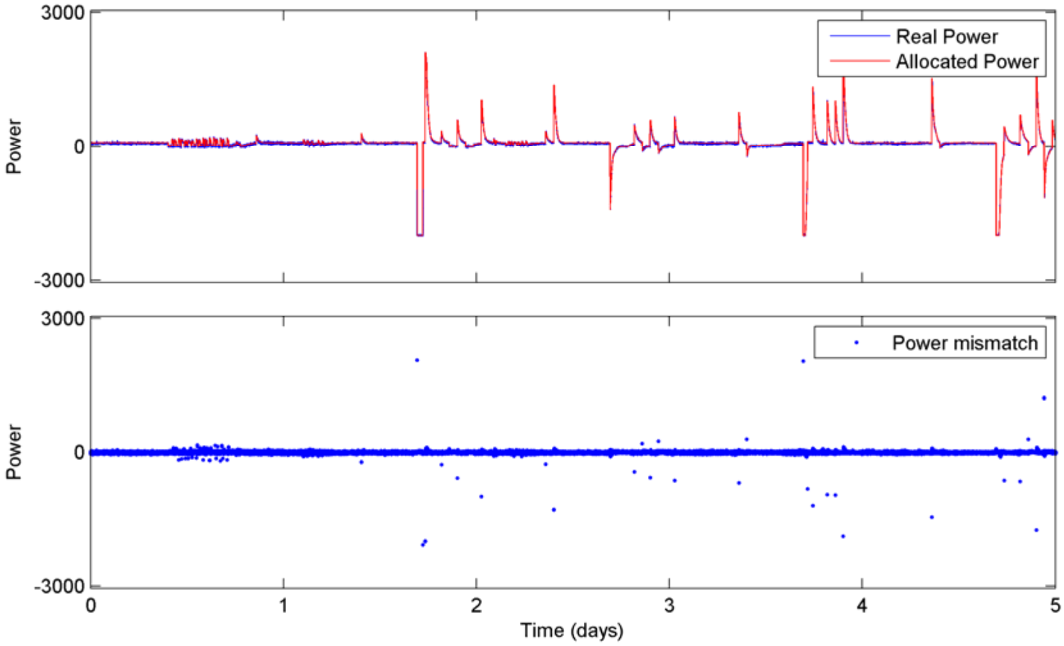


Figure 4.1 *Top graph shows the real power drawn from (positive) or supplied to (negative) the grid by the Atrium and the allocated power by the PowerMatcher. Bottom graph shows the difference between real and allocated power*

The power mismatch between allocated and realized power mainly fluctuates around 0 Watt, with the exception of a few individual points. Many of the relatively large deviations are caused by a delay in the communication system. It has been observed that the time between power allocation in the PowerMatcher software and realization of the physical flows in the Atrium vary between 2 and 15 seconds. With a measurements sampling time of 10 seconds, this can sometimes cause a mismatch between the allocated power and measured realized power. Compared to a much slower market time scale, the communication delay can be considered insignificant. However, improvements in the PowerMatcher-Atrium communication interface are possible, such as discarding the database, and should be able to reduce the delay to no more than one or two seconds.

The average deviation and average absolute deviation between the allocated and realized power in this 5 day period was found to be -7.7 watts and 13 watts respectively. Furthermore, the 98% confidence bounds were calculated to be 37 watts. The relative large deviations caused by the communication delays have been included in these confidence bounds. Seeing that the power of the Atrium ranged between -3 kW and 3kW, a 1% maximum deviation during 98% of the entire experiment is considered very accurate. Thus, it can be concluded that the Atrium strictly followed the coordination signals send by the PowerMatcher.

4.2 Business case

In the integration test, only the first business case (trading on APX market) was studied, i.e. the household did not pay any tariffs for importing or exporting electricity. Figure 4.2 shows the APX data for two weeks during the testing period. It can be observed that the APX price had a daily pattern with an average price during the day and night of about 5 and 3 eurocents per kWh respectively. However, there were also short price peaks that were much higher. Two of these peaks (which have been cut of at the top of the graph) reach prices of up to 40 cents per kWh. Note, that electricity prices in the Netherlands for small consumers, such as households, were about 10 cents/kWh in 2009 (and 22 cents/kWh if taxes and other tariffs are included).

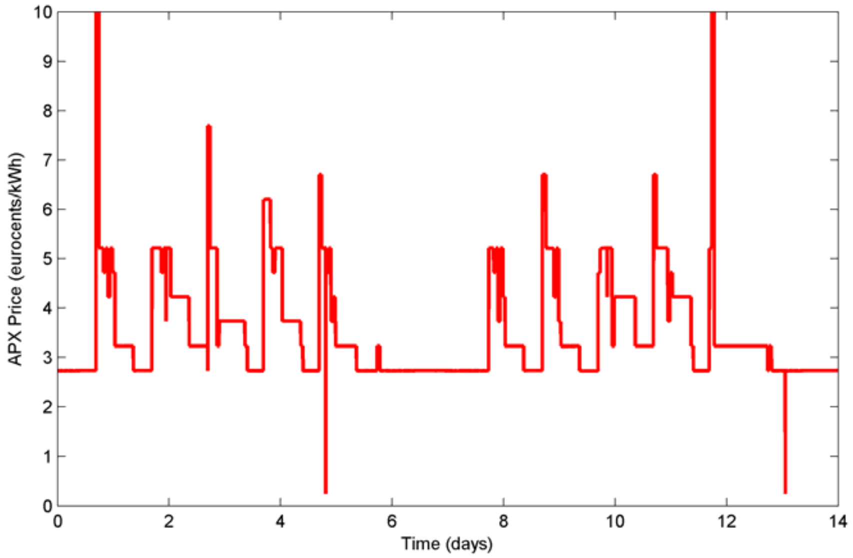


Figure 4.2 *The price on the APX market*

A specific span of 24 hours has been selected to show how the storage deals with those prices, which is shown in Figure 4.3. In this time span, the APX prices are characterized by a single peak of almost 40 cents/kWh, and comparably low prices (3-5 cents/kWh) during the rest of the period. At the start of the period, the batteries were fully charged. The charging (consumption) and discharging (production) of the batteries is represented by positive or negative power respectively. It is clear from this figure that when the PowerMatcher noted a relatively high price, it started to discharge the batteries. After this price peak, the batteries were charged in phases, as the PowerMatcher tries to find out if prices will drop even further. At the end of the day, the battery was fully charged again.

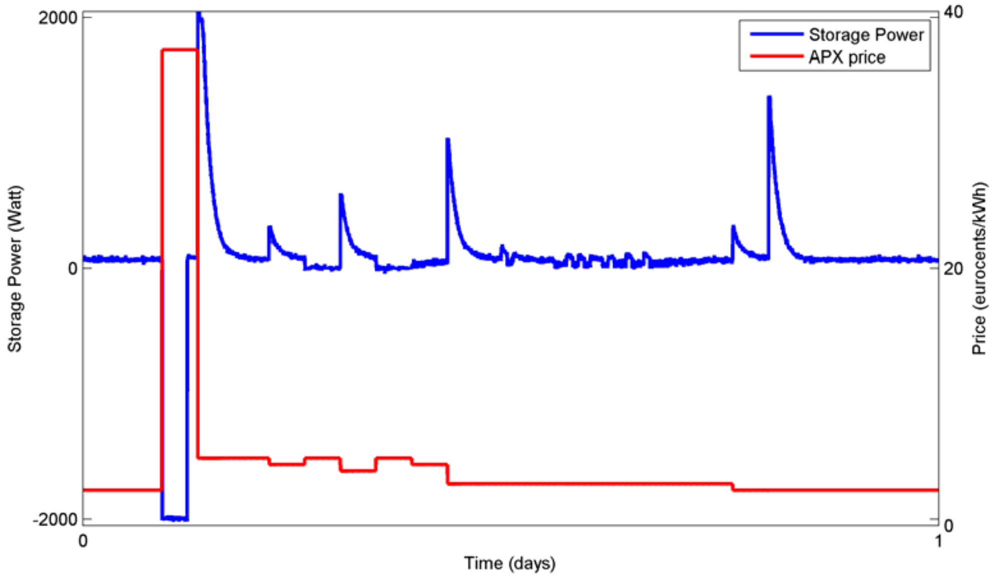


Figure 4.3 *The power output of the storage (blue) and the APX prices (red) during a 24 hour period. A negative power means that the batteries are discharged, i.e. export to the grid*

To calculate the earning, it is assumed that the prices on the APX market are also the prices that have to be paid or earned for bought or sold electricity. The earnings are compared to a reference household which has the same non-flexible demand profile, but no storage of electricity. Such a reference household would have to pay 39 cents for its electricity during this period. The PowerMatcher coordinated Atrium has earned 40 cents in this period. So remarkably, the UPM equipped household earns so much on the electricity market that it actually receives 1 cent instead of having to pay 39 cents.

The total revenue that the UPM can make on a yearly basis strongly depends on the available capacity in the storage system and the fluctuations of the prices on the electricity market. Such a calculation was not part of the integration test and have thus been left out.

5. Conclusions and Next Steps

In this report, the PowerMatcher architecture for UPM has been described. Furthermore, an integration test of the UPM between PowerMatcher and Atrium has been performed with a successful result. The PowerMatcher receives the necessary information from the Atrium for its optimization in the electricity market, while the Atrium acts swiftly and accurately on coordination signals sent by the PowerMatcher. A business case has shown that the UPM is able to generate revenues on electricity markets.

With the successful demonstration, the UPM will be demonstrated in its full functionality. The Atrium has been installed in one of ECN's test dwellings and has also been connected to a number of photovoltaic panels. It is expected that the PowerMatcher will run in early December 2009 as described by the architecture in Figure 2.2, including the bid transformations by the household concentrator. The demonstration of the UPM will be continued after the project ending (December 1st, 2009).

Figure 5.1 *Photo of the solar panels connected to one of the test dwellings, in which the UPM resides*

6. References

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