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# PowerMatching City, a living lab smart grid demonstration

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**Abstract**—PowerMatching City is a living lab Smart Grid demonstration in the Netherlands consisting of 25 interconnected households (phase-I). It focuses on the development of a market model for intelligent network operation under normal market conditions that allows simultaneous in-home optimization (prosumer), technical coordination (distribution system operator) and commercial coordination (balance responsible). The coordination mechanism, provided by the agent based PowerMatcher technology, is extended to allow these simultaneous optimizations. Mature smart grids require a transparent coordination mechanism which allows various energy sources and appliances to be interconnected on a non-segregated and plug-in basis. It should seamlessly combine distributed generation with demand response. A generic design has been developed that allows seamless coordination of hybrid heat pumps,  $\mu$ -CHPs, electric cars, smart appliances such as freezers, washing machines etc. in a single ICT solution. End-user acceptance is guaranteed by advanced comfort control mechanisms and monitored in a participating design program.

*Index Terms*—intelligent networks

## I. INTRODUCTION

**D**ISTRIBUTED energy sources are a promising solution to solve today's energy and climate challenges but large scale integration in our currently top-down oriented energy infrastructure provides new technical, economical and social challenges for grid operators and utilities. Intermittent energy sources like wind and solar energy require flexible energy sources like combined heat and power (CHP) technology and energy storage to balance out the fluctuations. At the same time our energy consumption changes: (light) electric vehicles become our means of transportation, traditional heating system are replaced by  $\mu$ -CHP systems and heat pumps and various appliances allow to be coordinated in a smart way. The energy

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supply chain will become completely bi-directional and market roles will change: consumers will become self-producing so called prosumers and new market parties, like commercial aggregators, will enter the supply chain. In order to fully exploit the potential of this new emerging energy landscape advanced ICT solutions will enable smart grid solutions and provide the essential coordination communication infrastructure to seamlessly match supply and demand of energy without user interaction and loss of comfort.

## II. OBJECTIVES

**I**N the European project INTEGRAL (EU FP6-038576), normal, critical and emergency operation of smart grids are studied in order to define a common information and communication infrastructure to serve these grid conditions. PowerMatching City is one of the three demonstrations of INTEGRAL focused on the development of a market model for smart grids under normal operating conditions.

Normal operation requires simultaneous optimization of different goals of the various stakeholders in a smart grid. In PowerMatching City a local real-time energy market facilitates these simultaneous optimizations. The optimization goals of these stakeholders can be defined as follows:

### A. In-Home Optimization

The prosumers who have invested in their own power production facilities are looking for the optimal economic benefits of their investments. Since the electricity grid in North West Europe has a very high availability > 99,995% there is hardly any need to improve the availability of the network. From a household perspective the network can be regarded as a very large battery. The economic benefits for a prosumer can be maximized by continuously seeking the highest profits for energy export towards the grid and minimizing the costs for import from the grid. This provides the flexible reactive power for a smart grid. The real time price is used as a balancing mechanism to express the scarcity or surplus of energy in the grid. With the introduction of a transport tariff or energy tax effectively the in-home market is partly decoupled from the local electricity market. This introduces a preference to consume the in-home produced energy and results in less flexibility to be provided to the grid. Self-supporting off grid optimizations will be covered in the common design of INTEGRAL (see also section IV, E).

### B. Technical Coordination

Distributions System Operators (DSOs) will be confronted with changing energy demands and load profiles. The electrification of the energy system will lead to increased network loads. Extensions of transport capacity of existing networks in especially cities are very expensive and labor intensive operations with a high impact on the built environment. Therefore the development of advanced distribution automation, as in [8], is highly relevant to manage future load profiles and manage congestion and peak loads in local grids and on distribution stations. Within PowerMatching City the DSO can influence the load profile on the transformer by locally transforming the price in real-time. It effectively partly decouples the local market in that network section from the central market. In this way it can actively limit the import or export of energy. It should be noted that the applied price signal is a soft control signal that stimulates certain behavior but does not enforce it. The local agents should take care that the appliances are effectively switched off at extreme market prices. (see also section IV, D)

### C. Commercial Coordination

The interconnection of  $\mu$ -CHPs into a Virtual Power Plant (VPP) is a commonly known concept nowadays that can be used for reduction of power imbalances and for optimization of trading portfolio's. Within Power-Matching City the whole cluster is treated as a VPP and is directly controlled from the trading room. By continuously altering the balance between energy production and demand the resulting power production or demand of the cluster can be influenced and for example be exploited to smoothen peak power demands and prevent dispatch of costly spinning reserves (see also section IV, C).

### D. True Integration and Valorization of Renewable Energy

Since the PowerMatcher model, as described in section IV in more detail, is based on a marginal cost price mechanism it inherently first dispatches power production of renewable energy sources like wind and solar power since the marginal costs of them is zero. Effectively it prioritizes renewable energy that is injected into the grid. The valorization of the renewable energy is achieved by always selling the energy for the equilibrium price of the whole cluster.

"fig. 1," provides an impression of the multi-goal optimization model of an intelligent network in a liberalized energy market like in PowerMatching City. In the overlapping area between the Commercial Aggregator (CA) and the Distribution System Operator (DSO) conflicting objectives can occur: for example when a local congestion of the grid occurs and the distribution station is overloaded the DSO wants to reduce the export of energy. At the same time the CA could have a short position on the national grid and is requesting more power from the VPP and thus also from this overlapping section of the local grid as well. In such cases the DSO is allowed to alter the local price signal and reduce the power production of this section of the grid. As a result the CA has effectively less reactive power available from the VPP as a whole.

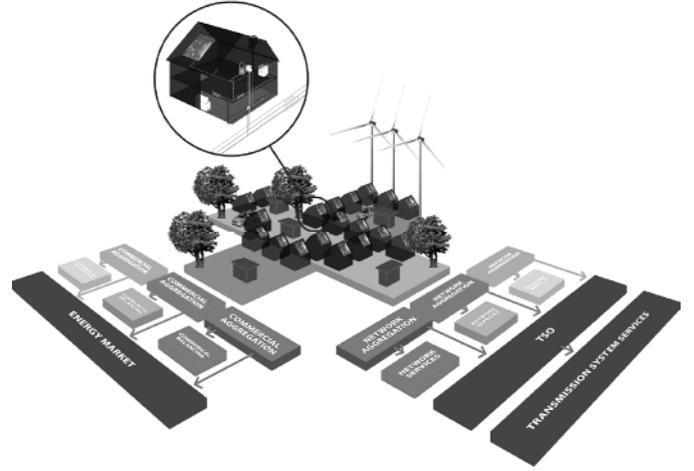


Fig. 1 The multi goal optimization topology of the intelligent network of PowerMatching City.

The beauty this coordination mechanism is that it provides the essential multi goal optimization required by a smart grid.

## III. LIVING LAB CONFIGURATION

**M**ATURE smart grid solutions require a transparent coordination mechanism that allows various energy sources and appliances to be integrated on a non-segregated and plug-in basis and combines demand response with distributed generation. Within PowerMatching City such a solution is demonstrated in a Living Lab environment based on the state-of-the-art of the shelf consumer products. Various technologies have been applied to demonstrate the full concept of a smart grid, but these customer of-the-shelf products have been altered to provide flexibility to the grid and allow coordination and control by the smart grid. In the section below the various applied technologies are described.

### A. Distributed Energy Resources (DER)

In PowerMatching City *DER* are applied in the form of *Combined Heat and Power (CHP)* and *Renewable Energy Sources (RES)*.

$\mu$ CHP provides high efficient local power generation in half of the households of PowerMatching City. The units have an output power of 1 kW<sub>e</sub> and 6 kW<sub>th</sub>. A 210 liter hot water buffer has been applied to decouple the production of heat and electricity.

Next to these  $\mu$ -CHP units a mini Gas Turbine with an output power of 30kW<sub>e</sub> and 60 kW<sub>th</sub> can be connected as well to provide additional flexibility. The output power of this unit can be altered between 7 and 30 kW. In a future fully sustainable energy scenario these CHPs should be fired with bio- or syngas.

*RES* provide sustainable energy form solar and wind power. In PowerMatching City each household is connected to at least 14 m<sup>2</sup> of PV-solar panels providing 1590 W<sub>p</sub> and 880 kWh. Local weather forecast data is used to predict the output power and an adaptive algorithm is used to adjust to the actual effi-

ciency of the solar panels used, as in [1].

Additional power is provided by a wind turbine with a nominal power output of 2.5 MW. The output is scaled down to match the cluster size of 25 households. The AVDE wind prediction model is used to accurately predict the wind power production, as in [2].

### B. Demand Response (DR)

DR is exploited by *Smart Hybrid Heat Pumps (SHHPs)* and various *Smart Appliances (SA)*

SHHPs combine high efficient air-to-water heat pumps with a condensing boiler. The heat pumps are used for base-load heating throughout the season, but during peak loads, for example for tap-water or during cold winters when the efficiency of the heat pump drops, a condensing boiler is used as an additional or under some circumstances as a more efficient source of heat. These systems are applied as a heating system in the other half of the households of PowerMatching City. The heat pump units have an output power of 4.5 kW<sub>th</sub> and the condensing boiler a power of 20 kW<sub>th</sub>. A 210 liter hot water buffer has been applied to decouple the consumption of heat and electricity. This provides a cost effective heating solution and allows switching between electricity and natural gas depending on the price ratio between them.

SA The households of PowerMatching City will be equipped with a *smart washing machine* and a *smart dishwasher* that can be programmed by the participants. On the control panel the latest end-time can be programmed into the machine to enter the time that the laundry or the dishes need to be clean. An agent automatically determines the optimal period to complete the washing program against the lowest expected costs without any further user interaction.

As a proof of principle a *smart freezer* has been constructed that can store the coldness by allowing it to freeze between -18°C and -25°C. An agent optimizes the power consumption of the freezer and minimizes the electricity costs. Although the system meets the (food) safety requirements it is only operated as a demonstration object in our laboratories.

### C. Electricity Storage (ES)

ES is provided in by *Electric Vehicles (EV)* and *In-Home Electricity Storage (IHES)*.

Two full EV and one plug-in hybrid car are connected to the grid of PowerMatching City. The capacity of the batteries is 37 kWh and 6 kWh respectively. Data communication is provided by a VPN router over UMTS and the charging process is controlled by an agent that runs on an on-board car pc. In the first phase of PowerMatching City smart charging strategies will be tested and therefore can be regarded as a form of demand response.

IHES is provided as another proof of principle by a 5 kWh electricity storage system. It provides storage of in-home produced energy as well as energy that has been purchased cheaply on the market. The local agent maximizes the benefits by providing energy when the electricity price increases.

### D. Automatic Meter Reading (AMR)

AMR is applied on both the *Household Level (HL-AMR)* and on *Device Level (DL-AMR)*.

HL-AMR is applied to measure the total electricity and gas consumption/production of each household. The local port (P1) of the meter is used as the communication port with the *Energy Service Gateway (ESG)* and the meter data is collected and locally logged at a high frequency. The meters match the Dutch smart meter standard. The communication protocol of the local port however has been altered to allow high frequency readout on a second level to meet our agent requirements.

DL-AMR Each individual device is equipped with smart meters to measure the relevant electricity/gas consumption and production at a high frequency in the seconds time domain. At a number of households also the heat production is measured to provide a reference measurement for the efficiency of the heating systems. All these meters use the M-Bus protocol.

### E. Energy Service Gateway (ESG)

A low power PC in the meter cupboard of each household functions as an ESG. All agents that control the various devices in home are running on the ESG in our configuration. However in the future this code could be a part of the onboard logic of the appliances once they become commercially available. In the electric vehicles an identical solution has been chosen and in a more mature solution the agent logic could be integrated in the onboard logic of the car as well. Most importantly we propose to keep the agent logic in the car since there is a strong interaction with the end-user behavior and preferences, which is naturally stored in the car logic. To stay more in-line with the current developments in the car charging infrastructures that are developed our agent logic could also be integrated in the charging pole. In such a solution more data needs to be exchanged between the car and the charging pole.

### F. Data Communication Network (DCN)

The communication between the households and the central servers for coordination and control of the cluster as well as data collection by the central servers is provided by a VPN network. In order to keep the cluster of households manageable and prevent failure introduced by actions of the home owners a dedicated communication channel is used. These local connections are created by a separate ADSL connection. In the future these connections can of course be provided by an existing broadband internet connection in the household. The electric vehicles are connected in a similar way but with the communication channel provided by a UMTS modem.

### G. Detailed Data Access (DDA)

DDA is facilitated by the AMR and is opened up by three portals a *User Portal*, an *Operator Portal* and a *Data Analysis Portal*.

The *User Portal* provides detailed insight into the energy consumption and production profiles of the end-user via a smart phone, a PC or an in home wall display. Aggregated data as well as individual near real time signals of individual de-

VICES can be monitored and compared with the average of the whole group to entice the end user to reduce their own energy consumption.

The *Operator Portal* is used for remote monitoring and maintenance purposes. This portal provides configuration & monitoring functionality and allows operators to detect faults even before end-users experience them and take corrective measures in time.

The *Data Analysis Portal* can generate automated reports as well as individually configurable reports for data mining in all the data collected in the experiment. This allows detailed analysis by the scientists involved in the project.

#### H. Advanced Distribution Automation (ADA)

Since the phase-I households are distributed over a larger area and not physically connected to an individual distribution station, the load on the "virtual distribution station" has been reconstructed based on the sum of the loads of the individual households. This allows us to test the technical coordination objectives. The drawback of this construction is that it is not possible to investigate power quality issues. In the next phase of the project we will extend the living lab environment with an intelligent distribution station and a relevant set of households behind one or more feeders.

## IV. COORDINATION MECHANISM

THE coordination of the cluster is provided by the Power-Matcher technology. It is a distributed energy system architecture and communication protocol, which facilitates implementation of standardized, scalable smart grids that can include both conventional and renewable energy sources. Through intelligent clustering, numerous small electricity producing or consuming devices operate as a single, highly flexible smart grid, creating a significant degree of added value in electricity markets. The concept is based on a distributed multi-agent based system and that uses a local energy exchange market to coordinate a cluster of devices with the objective of matching electricity supply and demand as described in [3,5]. The concept has been demonstrated previously in a number of smaller field-tests and simulations, as described in [4,7]. Each device is controlled by a software agent that trades on the real time market (auctioneer) with the objective to optimize the benefits on behalf of the device.

The only information that is exchanged between the agents and the auctioneer are bids or more precise bid-price-curves, see "fig. 2". These bid-price-curves express to what degree an agent is willing to pay or to be paid for a certain amount of electricity based on the marginal costs and hence express 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 and thereby its set-point is allocated. The device agents react appropriately by either starting to produce (or consume), or wait until the market price or priority of the device changes. In this project the PowerMatcher Architecture logic is extended with bid-price-curve transformations that allow simultaneous in-

home optimization, technical and commercial coordination (see section IV, C-E).

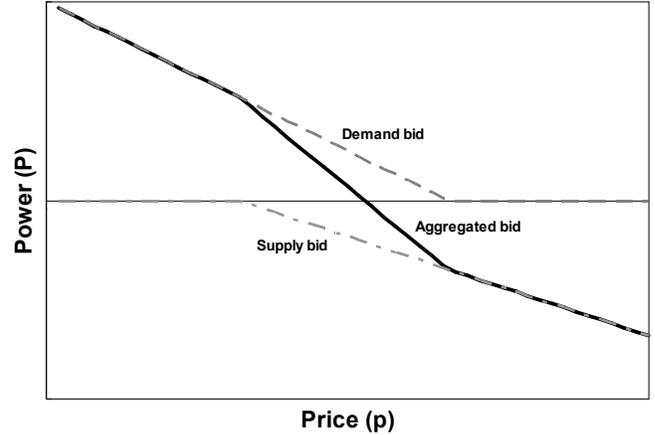


Fig. 2. The bid-price-curve for an energy consuming device (dashed line) and a energy producing device (dashed dotted line) and the resulting aggregated bid-price-curve (solid line). The point where the line crosses the axis, where  $P=0$ , is the equilibrium point where the demand matches the supply.

#### A. Solution Architecture

For this field trial the solution architecture as depicted in "fig. 3" has been applied.

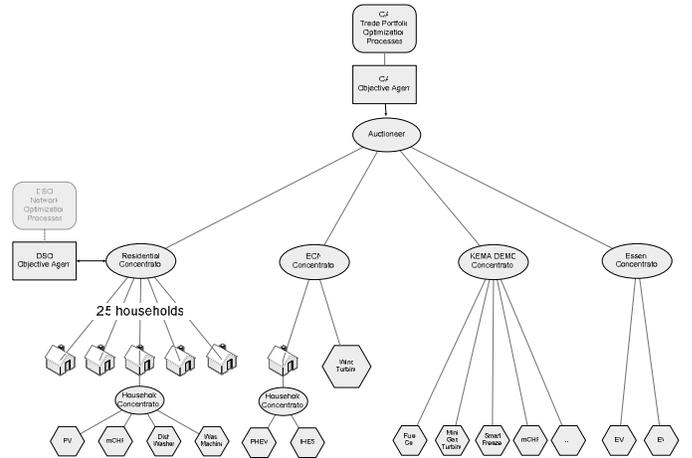


Fig. 3. Solution Architecture of PowerMatching City.

At the top an auctioneer determines the aggregated bid-price-curve of the whole cluster and the connected commercial aggregator objective agent controls the market price in the cluster (see section IV, C). Four concentrators are applied in this case, but scalability can be provided by adding more concentrators in the path towards the auctioneer at the top of the cluster. Each of the concentrators will limit the amount of communication since only a single aggregated bid price curve will be sent to the above laying node. A DSO objective agent is connected to the concentrator that collects all the bids of the households involved. This agent optimizes the network load in the cluster (see section IV, D). At household level a household concentrator collects all the bids of the various device agents in each household and provides the functionality to do the in-home optimization (see section IV, E).

### B. Exploiting Flexibility

In order to match supply and demand the flexibility on both the production and the demand side needs to be exploited. Flexible loads should shift to moments when there is a surplus of (renewable) energy available in the cluster and the market price will be relatively low. Flexible production should shift to moments that the market price is relatively high and/or when renewable energy becomes scarce. In most cases this mechanism it will only lead to a shift in the supply or demand of energy without a net effect on the energy production or consumption. For example the flexibility of a  $\mu$ -CHP is provided by decoupling the heat consumption from the electricity production. This is achieved by buffering the heat in a thermal heat buffer. It enables the Stirling engine to follow the electricity demand in the grid. The total electricity production is limited by the heat demand of the household. In a similar way the load of a hybrid heat pump system on the electricity grid can be shifted by buffering the produced heat in a heat buffer. In this case the maximum shift in electricity demand is limited by ratio of the heat buffered in the vessel and the heat demand of the household. It is clear that the flexibility in both cases is influenced by the seasonal effects of the heat demand in an household and therefore the whole cluster will react differently based on the outside temperature.

In a similar way cold is stored in the freezer and electricity is stored in the batteries of the electric vehicles and the in-home electricity storage system.

The essence of each of these systems can be described as the relative filling level ( $F_{level}$ ) of the energy buffered:

$$F_{level} = \frac{L - L_{min}}{L_{max} - L_{min}} \quad (1)$$

Where  $L$  is the relevant parameter measured inside the buffer, for example the temperature in the buffer.  $L_{min}$  and  $L_{max}$  form the control boundaries of this parameter  $L$ . Now  $F_{level}$  ranges between 0 – 100% depending on the actual fill level of the buffer. This enables the agents to optimize the filling level of the buffer and the agents to optimize the devices can be described in a similar way. The agent should ensure that with each bid the benefits stay above the marginal costs of each device, for example one would not start a  $\mu$ -CHP if the profit drops below the fuel costs.

The bidding strategy of the agents depends essentially on two parameters: the price expectation and the expected buffer usage; how fast will the underlying process deplete the buffer in the upcoming period. The agent should keep the buffer filled above the minimum filling level but additional logic, on a lower level, is always implemented that controls the whole system and ensures that the comfort levels are guaranteed under all circumstances. If the bidding strategy of the agent fails the control system takes over to ensure the desired comfort levels. One would not want his freezer to defrost and have all the stored food to decay just because the electricity price did not move into the expected price range in time.

The bidding strategy that an agent follows can vary depending on the risk one is willing to take and the additional costs that arise once the agent fails to keep the buffer level between the control boundaries.

The objectives of the various stakeholders can be achieved in different ways in the PowerMatcher cluster and are described in more detail in the following sections:

### C. Commercial Coordination

For commercial coordination a commercial objective agent is connected to the auctioneer at the top of the cluster as depicted in "fig. 3". Although various optimization strategies can be carried out by commercial aggregators, in essence the optimization target is to increase the demand or supply of the cluster as a whole. The objective agent will shift the price in the cluster away from the equilibrium point to  $p_{commercial}$  the energy demand or production matches the request of the commercial aggregator, see "fig. 4". In this way a transparent relation between the price and the delivered power by the VPP is provided and allows cost based dispatching.

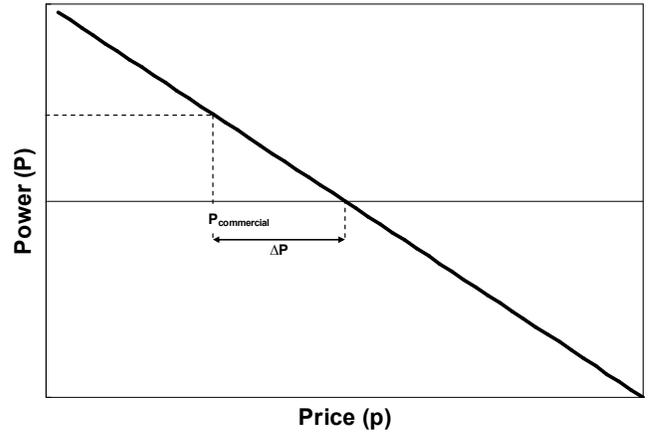


Fig. 4. An example of an aggregated bid-price curve where the price is shifted towards  $p_{commercial}$  for commercial optimization.

### D. Technical Coordination

For technical coordination a DSO objective agent is connected to a local concentrator as depicted in "fig. 3". The objective of the agent is to manage local congestion and limit the import or export of electricity of a network section. To do so a bid-price-curve transformation can be carried out where the import is shifted to the limiting level  $P_{max}$  as depicted in "fig. 5". The resulting shifted aggregated bid-price-curve is sent towards the above laying concentrator or in this demonstration set-up directly to the above laying auctioneer where a new equilibrium in the cluster is achieved. The new market price is transformed back to a new price,  $p_{new}$ , that is sent to the agents below the DSO concentrator. As soon as the import or export of a subnet approaches the maximum load of the distribution station more aggressive bids are provided by the objective agent to prevent fast aging of the assets. However the agent should keep in mind that the flexibility is in most cases only a timely shift in energy demand. Therefore (self learning) optimization strate-

gies are essential to characterize the underlying cluster of applications and households. The beauty of this solution is the transparent mechanism that it provides with a unambiguous relation for the costs of active capacity management. This allows DSOs to objectively balance the costs of network capacity extension and active capacity management. This will become more and more important in the future driven by the ongoing electrification of our energy system.

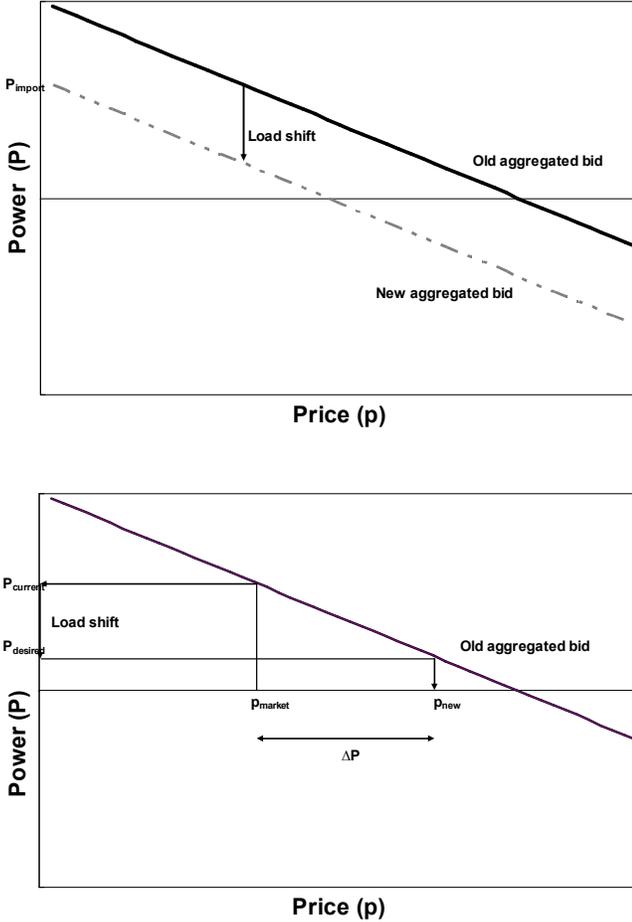


Fig. 5. An example of an aggregated bid-price curve transformation where the import is limited to  $P_{import}$  (top figure). The resulting market price ( $p_{market}$ ) is transformed back to a new price  $p_{new}$  which is send to the aggregated agents (lower figure).

### E. In-Home Optimization

To enable in home optimization import and export tariffs should be applied otherwise the home concentrator would act as a regular concentrator in the PowerMatcher network and thus treat every device agent identically. Once import and export tariffs are applied the internal bid price curve should be transformed as depicted in "fig. 6".

To compensate for export tariffs the part of the aggregated bid-price-curve, where  $P < 0$ , is shifted to the right and  $p' = p + p_{export}$ . To compensate for the import tariffs the part of the aggregated bid-price-curve, where  $P > 0$  is shifted to the left and  $p' = p - p_{import}$ . This example shows that the import and export tariffs can be different, but this surely depends on the applied policy. Furthermore it should be noted that in non-ideal cases,

no balance point might be found in a household and modified transformations need to be applied. However a detailed description of these phenomena is outside the scope of this paper.

Although a mind step is required to initially see through the applied transformations a transparent straight forward multi-goal optimization mechanism is provided based on a (local) real-time price market that reflects the actual market conditions in the smart grid.

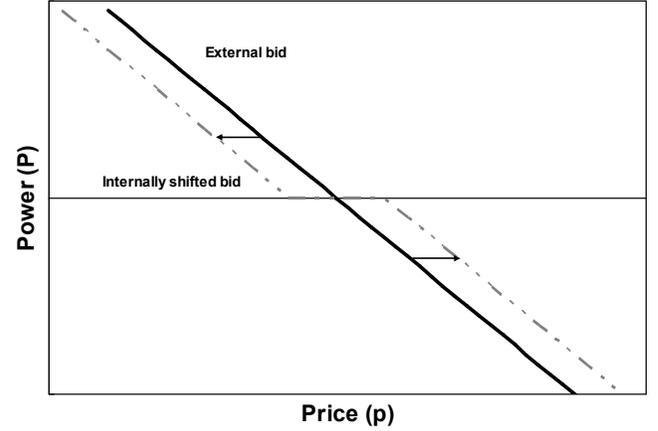


Fig. 6. An example of an aggregated bid-price curve where the solid line represents the external aggregated bid price curve and the dashed dotted line the internally shifted bid-price-curve.

## V. END-USER ACCEPTANCE

ONE of the essential success factors of the implementation of smart grid technology is the acceptance by the end-users. Privacy, security and 'big brother' emotions play a role in the hearts and minds of people. Therefore the end-user acceptance and satisfaction is monitored in a separate track within this project. Although the null measurement clearly indicates that the group of participants consist of a group of early adaptors with a green mindset they are still a rich and essential source of information.

### A. Comfort

One of the key elements of end user acceptance is the perceived comfort levels by the end-users. As described the whole system is designed in such a way that comfort levels are ensured under all circumstances and no user interaction is required to provide flexibility to the smart grid. The results of PowerMatching City show that once the comfort levels exceed the participants expectations the new technology is accepted and leads to a high level of satisfaction under the participants.

### B. Incentive Scheme

In upcoming measurement campaigns an incentive scheme will be introduced which will stimulate the participants to exchange comfort levels for financial rewards. This enables one to measure the price-sensitivity of the comfort levels of end-users.

### C. Participating Design

In a participating design track end-users contribute to the design process of the portal and provide insight into their

needs and requirements in data, functionality and perception of the experiment. It also results in unexpected feed-back; for example end users that indicate that their willingness to postpone doing their laundry to the next day if the electricity price hasn't dropped below a user defined maximum price. But most of all, the participating design track greatly contributes to the end-users involvement in the project.

## VI. FIRST RESULTS

RECENTLY the commissioning phase of the project has been completed successfully. In a systematic process the functionality of the system is tested against the design documents. The behavior of all systems and subsystems are checked including data communication, logging and analysis tools. The performance data have been checked and tests have been conducted to check whether or not the comfort levels of the end-users can be maintained under all circumstances. In a second step of the commissioning phase the characterization of the agents and comfort controllers are validated and tested if they sufficiently represent the underlying physical hardware properly.

The first results are depicted in "fig. 7" are collected from one of the first measurement campaigns. This campaign is a scenario where the VPP is optimized from the trade room based on the APX price development. In the graphs the resulting requested fill levels are plotted as well as the resulting average actual fill levels of both the households with a  $\mu$ -CHP and SHHP in the summer season.

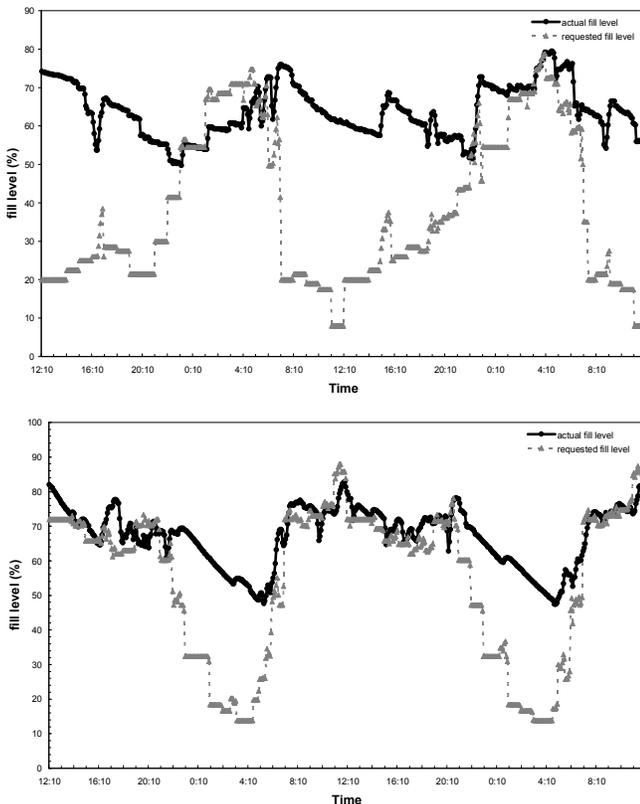


Fig. 7. shows an example of the first results of PowerMatching City. The Upper graph shows the average actual fill level and the requested fill level of all the households equipped with a  $\mu$ -CHP system. The lower graph shows the

average actual fill level and requested fill level of all the households equipped with a Smart Hybrid Heat Pump System.

As soon as the price rises the fill level request of the  $\mu$ -CHP increases and the fill level request of the SHHP drops and vice versa. One can clearly observe that as soon as the fill level request increases that the PowerMatcher cluster follows the request and that the cluster behaves as expected. One should keep in mind that the depletion of the heat buffers is based on the heat consumption of the households and hence is an uncontrolled process by the smart grid. Therefore the depletion of the buffers lags behind.

## VII. CONCLUSIONS

AN integrated solution is provided that supports the main goal of the project: the demonstration of a market model and corresponding coordination mechanism that allows the essential multi-goal optimization within a smart grid. It provides transparent cost relations for commercial optimization and simultaneous active capacity management based on a real-time (local) electricity market.

The flexibility provided by the various technologies applied can be exploited without impacting the comfort of the end-user or compromising the safety requirements, which form the essential building blocks that allow the optimization of a smart grid.

The flexibility provided by the various applied technologies can be generalized. This allows standardization of interfaces but more importantly an interoperable solution is provided for a heterogeneous smart grid solution that can grow organically.

The applied solution provides the essential scalability that is needed for large scale smart grid implementations and enables integration of numerous energy sources and devices.

The first results look very promising and the cluster of these smart homes demonstrates the true potential of a smart grid and will provide the essential data to validate the underlying business cases. Moreover it will reveal the potential of smart grids to seamlessly integrate (distributed) renewable energy into our energy infrastructure.

## VIII. ACKNOWLEDGEMENT

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## IX. REFERENCES

*Technical Reports:*

- [1] Borg, N.J.C.M. van der, Korte termijn voorspelling van de opbrengst van PV-systemen, ECN, report no. C-01-128, 2001: <http://www.ecn.nl/docs/library/report/2002/c01128.pdf>
- [2] Brand, A.J., Wind Power Forecasting Method AVDE, ECN, report no. ECN-M--09-048: <http://www.ecn.nl/docs/library/report/2009/m09048.pdf>

*Papers from Conference Proceedings (Published):*

- [3] Kok, JK, Warmer, CJ, Kamphuis, IG. 2005. Powermatcher: Multiagent control in the electricity infrastructure. In Agents in the Industry The best from the AAMAS 2005 industry track, IEEE Intelligent Systems, March/April 2006.
- [4] Warmer, CJ., Hommelberg, MPF, Roossien, B, Kok, JK, Turkstra, JW. 2007. A field test using agents for coordination of residential  $\mu$ -CHP. ISAP conference, November 4-8.
- [5] Hommelberg, MPF, Warmer, CJ, Kamphuis, IG, Kok, JK, Schaeffer, GJ. 2007. Distributed control concepts using multi-agent technology and automatic markets. IEEE PES annual conference, June 24-28.
- [6] Kok, JK. 2009. Short-term economics of virtual power plants. CIRED, June 8-11.
- [7] Roossien, B. 2009. Field test up-scaling of multi-agent coordination in the electricity grid. CIRED, June 8-11.
- [8] Kester, J.C.P., Heskes, P.J.M., Kaandorp, J. J., Cobben, J.F.G., Schoonenberg, G., Malyna, D.V., de Jong, E.C.W., Wargers, B.J., Dalmeier, A.J.F., A smart MV/LV-station that improves power quality, reliability and substation load profile, CIRED, 8-11 June 2009.

## X. BIOGRAPHIES



coordination of Smart Grids activities and is specialized in the coupling between gas and electricity grids.

**Frits Blik** was born in 1968 and works as a senior energy market expert at KEMA. He studied Energy Physics at the University of Utrecht, the Netherlands and investigated charge exchange processes in thermonuclear fusion reactors for his PhD thesis. He graduated in 1997 at the University of Groningen, the Netherlands. His career started as a business consultant at Energy & Utilities department of Logica. In 2003 he moved to KEMA and today he is responsible for the business development & Grids activities and is specialized in the coupling between gas and electricity grids.



Nowadays is working at Essent Innovation as Innovation Manager and focused on flexibility and Smart Grids.

**Marcel Eijgelaar** was born in 1970. He studied Chemical Reactor Engineering at the Technical University of Twente, The Netherlands and graduated in 1996. Afterwards he completed an MBA, technical science management at the TSM Business School in 1999. He started his career at KEMA and moved to Essent Netwerk Noord (currently Enexis) and worked as business analyst at Strategy and Business Development department. In 2003 he moved to Essent Infra Products as a product



developer. Nowadays is working at Essent Innovation as Innovation Manager and focused on flexibility and Smart Grids.

**René Kamphuis** holds a PhD in chemical physics. He is currently employed at the department Efficiency & Infrastructure of the Energy research Centre of the Netherlands (ECN) where he works in the Intelligent Energy Grids program. He headed several projects integrating ICT and Energy via autonomous agent software technology and initiated and participated in the EU CRISP-project. He is the Dutch country expert in IEA-DSM programme projects (e.g. on Demand Response Resources) and chairman of the NL Smart Power System ICT-working group, studying the role of massive introduction of small distributed generators, e.g.  $\mu$ -CHP, on the grid from several perspectives is studied.



**Albert van den Noort** was born in 1978. After his study Chemical Engineering in 2002, he did a PhD on the flow behaviour of complex fluids at the University of Twente, The Netherlands and graduated in 2007. He continued his career as a scientific software engineer at Deltares, where he developed models for the flow of water. In 2009 he moved to Groningen to start as a researcher at the research lab of Gasunie, which was taken over by KEMA. He currently works at KEMA as a projectmanager for the PowerMatching City project and is involved in the research on Smart Grids.



**Bart Roossien** obtained a master's in applied physics in 2006 from the University of Groningen, after which he joined the department Efficiency & Infrastructure of the Energy research Centre of the Netherlands (ECN) where he works in the Intelligent Energy Grids program. His work is focused on the development of new technologies that help the energy infrastructure in the transition towards a sustainable and reliable energy supply in the future. This included the development of technologies to facilitate 'smart grids', research on electricity storage and electric mobility and the interaction between end-user and infrastructure.



**Jörgen van der Velde** was born in 1967. He studied Engineering Physics at the University of Groningen, the Netherlands, and graduated in 1993. Currently, he is employed at HUMIQ B.V. as technical consultant and senior software architect. Starting in the home entertainment and multimedia branche, Jörgen is now occupied in smart grid technology development. Before HUMIQ, he was employed at CTI, a company involved in research and development of hardware and software.



**Johan de Wit** was born in 1968. He studied Electrical Engineering at the NHL University of Leeuwarden, the Netherlands, and graduated in 1991 (electronics) and 1992 (technical computer science). Johan started his career with Philips Domestic Appliances, developing hard and software for consumer products. Currently he is employed at HUMIQ B.V. as software project manager. Within HUMIQ Johan started in the telecommunications branche, but the last years he is occupied in smart grid technology development.