# Dynamic Pricing by Scalable Energy Management Systems - Field Experiences and Simulation Results using PowerMatcher

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*(Invited Paper)*

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| SmartHouse/SmartGrid | *www.smarthouse-smartgrid.eu* | (Sections IV & VI) |
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**Technology:**

PowerMatcher smartgrid technology is a technology of TNO innovation for life

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***Abstract*—Response of demand, distributed generation and electricity storage (e.g. vehicle to grid) will be crucial for power systems management in the future smart electricity grid. In this paper, we describe a smart grid technology that integrates demand and supply flexibility in the operation of the electricity system through the use of dynamic pricing. Over the last few years, this technology has been researched and developed into a market-ready system, and has been deployed in a number of successful field trials. Recent field experiences and simulation studies show the potential of the technology for network operations (e.g. congestion management and black-start support), for market operations (e.g. virtual power plant operations), and integration of large-scale wind power generation. The scalability of the technology, i.e. the ability to perform well under mass-application circumstances, has been proved in a targeted field experiment. This paper gives an overview of the results of two field trials and three simulation studies. In these trials and simulations, demand and supply response from real and simulated electrical vehicles, household appliances and heating systems (heat pumps and micro co-generation) has been successfully coordinated to reach specific smart grid goals.**

***Index Terms*—Dynamic pricing, demand response, smart grids, market-based control.**

## I. INTRODUCTION

THIS PAPER describes recent experiences with dynamic pricing using the PowerMatcher Smart Grid Technology. Demand response, response of distributed generation and operations of electricity storage (e.g. using vehicle to grid) will be a crucial part of power systems management in the future. There are two main reasons why these *Distributed Energy Resources* (DER)[1] will play a major role in electricity systems operation in the future:

- The rising share of both **renewable energy sources** and **distributed generation** in the energy mix decreases the controllability of the supply side. The rise in needed balancing power can be fulfilled by utilising the flexibility potential in demand and distributed generation.
- The **electrification of everything** will drive our **ageing electricity networks** to their limits. As an alternative to grid reinforcements, the flexibility potential in local demand and generation can be used to cope with grid overload situations.

Dynamic pricing is key in the development of a uniformed and multi-purpose mechanism to utilise device flexibility at the premises of the end-customer. The PowerMatcher smart grid technology [1] is an example of such a mechanism. Since its incarnation in 2004, the PowerMatcher has been implemented in three major software versions. In a spiral approach, each software version was implemented from scratch with the first two versions being tested in simulations and field experiments [2], [3], [4], [5]. The results described in this paper are based on the third version of this system.

In section II, we give a high-level overview of the PowerMatcher. Section III reports the key aspects of a field experiment with a collection of 22 households in Groningen. In section IV, we report on experiments to asses scalability to the level of commercial-grade applications. The three subsequent sections report on simulation studies which investigate the impact of this technology in specific applications: congestion management in distribution grids using smart-charging electrical vehicles (Sec. V), efficient integration of wind power (Sec. VI), and peak-load avoidance in extreme circumstances (Sec. VII). The conclusions are given in Section VIII.

## II. POWERMATCHER, MARKET-BASED COORDINATION

This section describes *The PowerMatcher*, a multi-agent based distributed software system for market integration of small and medium sized DER units, ranging from household appliances via electric vehicles to industrial installations of 5 to 10 MW. It is a general purpose mechanism for near-real-time coordination (balancing) in smart electricity grids. Designed for scalability, it targets the huge numbers of distributed generators, demand response units, and electricity storage that need to participate in future electricity system operations.

Within a PowerMatcher cluster, agents are organised into a logical tree. The leaves of this tree are a number of *local device agents* and, optionally, a unique *objective agent*. The root of the tree is formed by the *auctioneer agent*; a unique

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[1]The term *Distributed Energy Resources* encompasses distributed generation, demand response, and electricity storage connected to the distribution grid in this text.

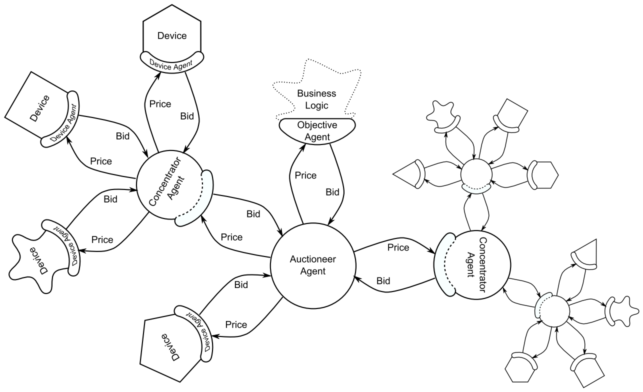


Fig. 1. Example PowerMatcher agent cluster. See the text for a detailed description.

agent that handles the price forming by searching for the equilibrium price. In order to obtain scalability, *concentrator agents* can be added to the structure as tree nodes. A local device agent acts as a representative of a DER device. This control agent tries to operate the process associated with the device in an economically optimal way. It coordinates its actions with all other agents in the cluster by trading the electricity consumed or produced by the device on an near-real-time electronic market. The auctioneer agent performs the price-forming process by concentrating the bids of all agents directly connected to it into one single bid and searching for the equilibrium price. This price is communicated back to the connected agents whenever there is a significant price change. A concentrator agent is the representative of a sub-cluster of local device agents. It concentrates the market bids of the agents it represents into one bid and communicates this towards the auctioneer. In the opposite direction, it passes price updates to the agents in its sub-cluster. An objective agent gives a cluster its purpose. Depending on the specific application, the goal of the cluster may vary. If the cluster has to operate as a *virtual power plant*, for example, it needs to follow a certain externally provided set point schedule. Such an externally imposed objective can be realised by implementing an objective agent which interfaces the agent cluster to the *business logic* behind the specific application. In absence of an objective agent, the goal of the cluster is to balance itself, i.e., it strives for equality supply and demand within the cluster.

The self-interested behaviour of local agents causes electricity consumption to shift towards moments of low electricity prices and production towards moments of high prices. As a result, the emergence of supply and demand matching can be seen on the global system level. The aggregated, or concentrated, bid of all local control agents in the cluster —as held by the auctioneer agent— can be regarded as a dynamic merit-order list of all DER participating in the cluster. Based on this list, the units that are able to respond to a certain event most efficiently are selected to do so. In this way, the cluster as a whole is able to operate the (near-)real-time coordination activity optimally.

In the design of the PowerMatcher a number of choices have been made to meet the important requirement of scalability. The auctioneer and the concentrator agents form a *pool market*. Through this pool market each device agent negotiates with all other device agents in the market while it communicates to one single concentrator agent only. This market is implemeted in a distributed fashion as it is formed by the auctioneer and all concentrators. Further, the use of *one-shot* communications eliminates the need for iterative communications in the market solution search. Communication is simplified by using only demand functions and prices, thereby reducing the communication overhead and enabling easy protocol standardisation. Finally, *distributed aggregation* of demand functions in a tree topology results in a low computational and communication complexity. We will address the scalability properties of the PowerMatcher further in section IV.

## III. Field trial: PowerMatching City

Over the years, a number of small pilots have been successfully conducted with the PowerMatcher technology [6] to demonstrate its feasibility and potential. The experiences and lessons learned from these pilots were used to create Europe's first fully developed Smart Grid: PowerMatching City. PowerMatching City is a living lab environment based on state-of-the-art off-the-shelf consumer products that have been altered to provide flexibility to and allow coordination by the smart grid. One of the unique aspects in PowerMatching City is that it takes the, sometimes conflicting, interests of three main stakeholders in a smart grid into account: the prosumer (a consumer who also produces energy), the distribution network operator (DNO) and the commercial aggregator (CA) (e.g. utility or energy service company).

The back-bone of PowerMatching City is 22 common Dutch households, located in the suburb of Hoogkerk near the city of Groningen, the Netherlands. Each are fitted with either a domestic combined heat and power unit (micro-CHP) or a heat pump with gas fired heater and 14 $m^2$ of photovoltaic panels. Some households also contain an intelligent washing machine and dishwasher and one of the households was given a 5 kWh battery. Additionally, two electric vehicles, each having a 37 kWh battery and a 5 kW controllable modular charger have been added to the cluster. Finally, outside the district, a 2.5 MW wind turbine is available. The output power of the wind turbine can be digitally scaled down to match the consumption of the households. All devices are interfaced with PowerMatcher software to operate PowerMatching City as a virtual power plant.

The twelve air-water heat pumps are used for base load heating throughout the season, while the gas fired heaters provide additional heat during peak loads and for domestic hot water. The ten micro-CHPs have an electric capacity of 1 kW and provide heat for both base and peak load heating. The CHPs and heat pumps are connected each to a 210 litre thermal storage tank, which allows the heating devices to be turned on or off independent of the heat demand of the household, thus providing flexibility to the smart grid [7].

The goal of the first stage of PowerMatching city was to develop and demonstrate a combination of three types of coordination of RES/DER:

- Technical coordination (stake of the Distribution System Operator, DSO), such as grid congestions and peak shaving.
- Commercial coordination (stake of the Commercial Aggregator), using the virtual power plant to optimise energy trading strategies, provide regulatory power for system balancing and increase efficiency of large fossil fuel power plants.
- In-home coordination (stake of the household) to maximise consumption of self-produced electricity and minimise costs by shifting demand to off-peak hours.

Simultaneous optimisation of the system was achieved using a multi-layered PowerMatcher network. The PowerMatcher network consisted of a top-level auctioneer, three main concentrators at different locations in the country and a lower-level concentrator for each household. The concentrators not only aggregated bids, but were also able to apply bid and price transformation to provide incentives to a small part of the cluster for local optimisation goals.

A number of use cases were studied with one or more types of coordination. It was demonstrated that the households were able to accommodate up to 60% of the imbalance generated by the wind turbine [8]. Furthermore, the concept of bid/price transformations at concentrator level was proven and a peak load reduction of 15% in the common substation of the households was achieved. In a third use case, it was shown that the battery was able to store locally electricity of the household and supply it in times of net demand, minimising import and export of electricity.

One of the most interesting use cases studied was the operation of the cluster as a VPP within the portfolio of a commercial aggregator (CA), in this case an energy utility company. The CA used the price profile of the day-ahead spot market to optimise the energy profile of the cluster. Additionally, the CA offered regulatory power to the national system operator for balancing purposes. The PowerMatcher technology was used to ensure that the cluster followed the optimised energy profile and at the same time made real-time adjustments in the cluster allocation to provide regulatory power requested by the system operator. The optimised profile, including regulatory power requirements, and the cluster realisation are shown in figure 2. It was concluded that the VPP successfully followed its optimised energy profile and provided the required regulatory power at the same time.

Overall, PowerMatching City demonstrated that PowerMatcher is not only able to perform technical, commercial or in-home coordination, but also optimise VPP operation for a combination of these types of coordination, yielding maximum benefits for all stakeholders.

## IV. Scalability Testing

The PowerMatcher has been designed with scalability as the key quality attribute. However, as none of the field trials performed to date approaches a mass-application scale, there is no empirical backing of the theoretical scalability properties. To over come this, we take an empirical approach by implementing and testing a full top-to-bottom slice of the architecture needed to cluster one million households in a virtual

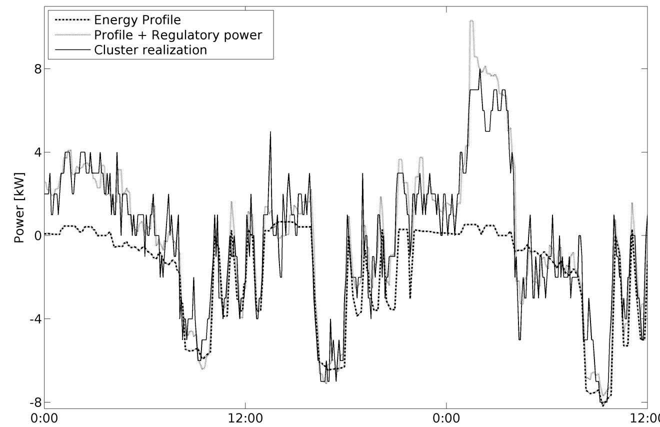


Fig. 2. VPP cluster in a real market environment, trading on the spot market (forecast) and regulatory market.

power plant. Side-branches cut away from the architecture are replaced by data mimicking agents generating the data traffic volume of the pruned branch. In this way, the data traffic from a real cluster of Smart Houses is combined with mimicked data sources placed at strategic points in the architecture. Accordingly, we are able to test the full architecture from the smart home to the enterprise systems running at a VPP-operator at mass-application data traffic levels. The cluster of real smart homes used is the one described in section III.

For this experiment, we have to define (1) what we consider as mass-scale, (2) a proper metric indicating the performance of the system, and (3) a proper threshold value to conclude if the test is successful.

A medium-sized utility company in Europe serves approx. 6 million customers. If more than 10 to 15% of such a client base participates in a VPP, we consider this a mass-scale. Accordingly, a customer base of 1 million households participating in a VPP can be regarded as mass-scale.

The main purpose of a VPP is to deliver flexibility. If the flexibility potential can be accessed fast enough, it can be used for operations in the balancing market which is the most volatile wholesale market for electricity. In a PowerMatcher-based virtual plant, a change in the desired power output (or input) of the plant translates in a changed price on the internal electronic market being communicated down to the device agents. Accordingly, a metric for the reaction speed of the VPP is the time it takes to communicate such a price update to all agents. Therefore, we define the *update time* $t_u$, as the time it takes to communicate a price update to all agents.

The settlement period used in balancing markets is typically 15 or 30 minutes. In order to react to the actual imbalance situation, either in the own portfolio or in the control zone, the reaction time must be smaller than the settlement period. VPP reaction times must allow the operator to react to an imbalance situation occurring in the first part of the settlement period by VPP actions that take effect during the same period. Therefore, a reaction time below 5 minutes is desirable.

At the top of the architecture (see Figure 3) is the so-called Enterprise System, the conglomerate of all relevant sub-systems running at the level of the utility company op-

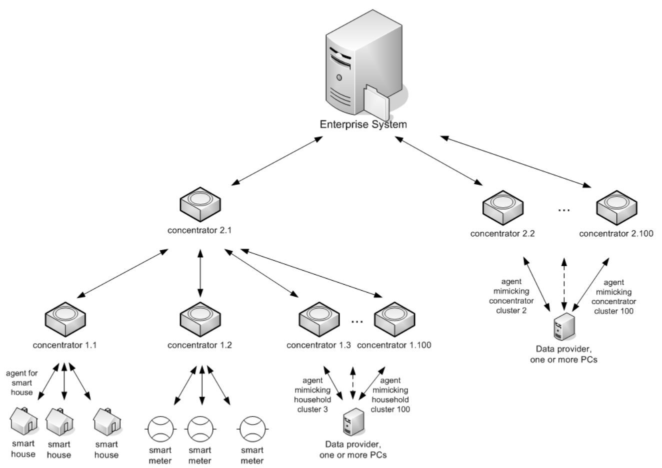


Fig. 3. Test Configuration

erating the VPP. Functionalities include dispatch of (virtual) power plants, metering data collection, rating and billing. The architecture below the Enterprise system hosts two different processes: (1) VPP operations, a small-bandwidth high-frequency process of small data messages communicated up and down, and (2) metering data collection, low-priority bulk data communicated upwards to the enterprise.

The infrastructure of the VPP and the metering data collection system is organised in a tree structure having concentrators at the nodes and end-customers at the leaves. To serve one million end-customers, two levels of concentrators are needed, each serving a sub-tree of 100 nodes. Then, 1 million households are connected to the first-level layer of 10,000 concentrators, which are connected to 100 second-level concentrators.

Latencies have been measured at four different levels in the architectural slice and at each level 29 measurements have been taken. The latencies averaged over all 29 measurements are listed in the second column of Table I, labelled '$t_u$ (measured)'. The average time to reach the device agents is 240 seconds which corresponds to 4 minutes. This is well under the success value of 5 minutes. The standard deviation in the latency measurements at the device level is 14 seconds, so there is little spread among the measurements. The highest observed latency was 279 seconds, which is still under the success value of 5 minutes. Thus, we may conclude that a multi-agent-based virtual power plant connecting one million households is fast enough to participate on the wholesale market for balancing power. However, the architecture implemented contains a number of places where extra latency is introduced due to specific design choices. This extra, artificial, latency would not occur when the full top-to-bottom architecture would be designed and implemented in one go. If we correct for the artificially introduced latencies, the total latency reduces to 30 seconds, as listed in the last column of Table I. This is well under the success value of 5 minutes.

To summarise, in this scalability test, performed within the SmartHouse/SmartGrid project, we tested the ability of a multi-agent-based smart grid coordination technology to deliver balancing services under mass-application circumstances.

TABLE I
LATENCY TIMING RESULTS.

| Node | $t_u$ (Measured) | Overhead | $t_u$ (Corrected) |
|---|---|---|---|
| Enterprise | 0 sec | - | - |
| Concentrator level 2 | 70 sec | 30 + 30 sec | 10 sec |
| Concentrator level 1 | 142 sec | 30 + 30 sec | 22 sec |
| Home gateway | 205 sec | 60 sec | 25 sec |
| Device | 240 sec | 30 sec | 30 sec |

Both the uncorrected and the corrected update times $t_u$ are well below the desired value of 5 minutes. Thus, we have shown that under mass-application circumstances the flexibility potential of the PowerMatcher cluster can be accessed fast enough for operations in the balancing market. Thus, this proves PowerMatcher's scalability to mass- application levels.

## V. Coordination of electric vehicle charging

With the increasing popularity of plug-in hybrid and full electric vehicles, their impact on the electricity infrastructure can no longer be ignored. Electric vehicles can double the amount of energy consumed by households, especially where homes are heated using energy sources other than electricity. For example, an average Dutch household uses 3600 kWh/year, while an electric vehicle will need about 3000-4000 kWh/year. With a large number of cars being used for commuting between home and work or school, there is a high similarity in how the cars are used. As a result, many cars will be charged at the same time. This high simultaneity factor increases the negative impacts on the grid even more. A simple solution to solve this grid congestion is to reinforce the grid. However, the expected financial investments needed to do so create a significant barrier for the introduction of electric mobility. It is expected that coordinating the charging behaviour of electric vehicles can postpone, reduce or even eliminate these grid investments.

Within the Grid4Vehicles project, a simulation study has been done to look at the impact of electric vehicles on the peak load of substations in residential districts and how much PowerMatcher could contribute to reducing this peak load. A stochastic driving behaviour model was developed, based on a German mobility survey [9], which was used to calculate when cars arrived at the residential charging point, when they would leave it again and how much the battery needed to be charged within that time frame. The configuration of the simulation was based on information from real districts in Europe, including nominal power of the substations, the number of homes, and measured 15-minute based load profile data of these homes. The total number of cars in the district was estimated based on the number of homes.

Simulations were performed with and without PowerMatcher coordination for different districts in Europe and for different penetration values of electric vehicles [10]. Each district included 50 to 200 electric vehicles. An objective agent was used to represent the substation, with the aim to reduce the peak load below its nominal power. As PowerMatcher is based on real-time coordination, no planning or scheduling tools were used to decide when a car could charge.

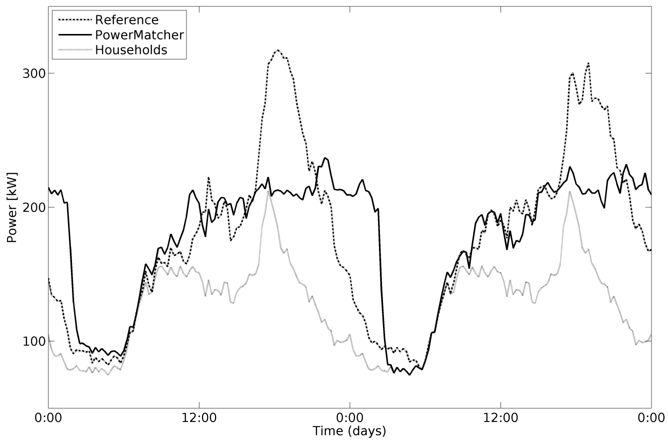


Fig. 4. Substation load for two arbitrary days, showing the inflexible demand of the households and the demand profile with and without PowerMatcher coordination of the electric vehicles.

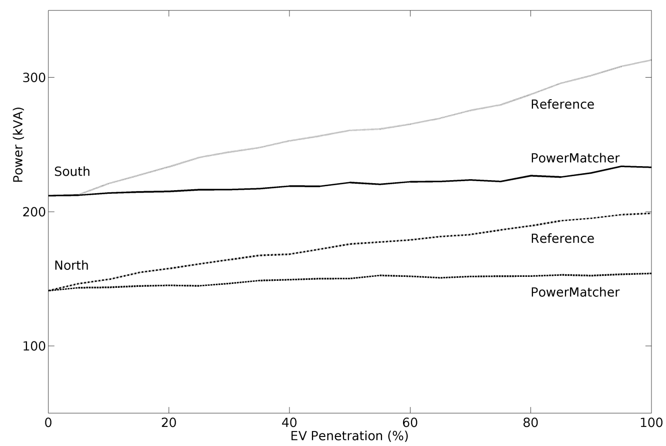


Fig. 5. Substation peak load for an urban district in North-Europe and South-Europe with and without PowerMatcher coordination.

Figure 4 depicts substation load patterns for an urban district in the south of Europe with an electric vehicle penetration of 100%. The household pattern shows the total demand of the households. The reference situation represents the total load at substation level (i.e. household demand + electric vehicles) when the cars are not coordinated. This means that charging starts immediately when the car connects to the charging point and stops when the battery is full. This figure demonstrates that when the vehicles are not coordinated, there is a high electricity demand in the evening, with a peak load at least 60% higher than that of the households alone. However, when PowerMatcher is used to coordinate charging of the cars, this peak is shifted into the night resulting in a maximum peak load that is almost as low as that of the household demand.

Figure 5 shows the substation peak load for a district in the north and south of Europe, as function of the penetration of electric vehicles. Without coordination, only low penetrations of electric vehicles can be realised without causing significant increase in the peak load. However, with PowerMatcher coordination enabled, the peak load is kept almost constant at all penetration levels without violating full-charge deadlines as set by the drivers. This makes investments in the electricity grid due to the introduction of electrical vehicles superfluous.

A plug-in hybrid converted Toyota Prius was used to test whether similar results could be achieved in the field, with a strong focus on the interaction between driver and PowerMatcher. A small computer, running the PowerMatcher software was installed in and interfaced with the car. A 10" touchscreen was mounted in the car, showing a graphical user interface. This display allowed the driver to configure and provide information to the PowerMatcher software, such as the expected departure time. The Prius was operated within a cluster of simulated cars under a virtual substation and similar results as in figure 4 were obtained. Most importantly, the (estimated) information of the driver was sufficient for the PowerMatcher to optimise the charging process.

It has been demonstrated, both in simulations and a pilot, that PowerMatcher is able to coordinate charging of electric vehicles to avoid grid congestion, by only using easily available information from the battery and driver, and without any form of scheduling.

## VI. Integration Of Wind Power

The scale of the individual trials performed with the PowerMatcher technology is growing over time. However, there is still no field experience at a mass-application scale. Hence, we must turn to simulation studies to get answers about the behaviour of larger clusters of responsive loads and distributed generators. We present the results of such a study, carried out in the SmartHouse/SmartGrid project, simulating 3000 individual households equipped with heating systems reacting to the fluctuating output of solar and wind energy systems in a future scenario of high wind energy penetration. Here, we address the research question whether end-user response can support the integration of windpower, and to what extent.

The simulations are based on the WLO-SE scenario on energy supply and demand in The Netherlands for the year 2040 [11]. As our study focusses on smart homes, the industry demand and supply have been removed from this scenario. Further, all figures have been scaled down to correspond to the 3000 households included in the simulation. This resulted in a base scenario having 156 kW installed capacity onshore wind, 750 kW offshore wind, 231 kW photovoltaics and 5.25 MW fossil fuelled power plants serving the demand in the 3000 households. The wind energy sector foresees a faster growth of off-shore wind as compared to the WLO-SE scenario. Accordingly, we performed a series of simulation runs, starting at the base case of 750 kW off-shore wind capacity per 3000 households and increasing in steps to 800, 850, 900, and 1000 kW total offshore wind per 3000 households.

The demand and supply flexibility in the households was realised solely by heating systems. Half of the households were equipped with a micro-CHP and the other half with a heat pump. Both devices are used for space heating as well as tap water heating and have heat buffers of 120 lites (space heating) and 90 lites (tap water) allowing for flexibility in their operations. The devices were modelled and validated according to those used in the field trial described in Section III.

The simulations ran under real-life circumstances. Household electricity demand profiles used in the simulations are randomly generated by a validated demand pattern generator and individualised per household. The same was done for the heat demand of each household (space heating and hot tap water). The wind power model uses measured wind velocity data from the Dutch meteorological office KNMI to accurately model wind power. Similarly, the solar power model was fed with measured irradiation data. A simulation tool specifically developed to run simulations with the PowerMatcher technology is used for this study. All device and household agents as well as models were developed to run with two types of controller, a traditional, business as usual, controller and a PowerMatcher controller. In this way PowerMatcher control could be compared to the business as usual case. The simulations covered a period of 2 weeks in the month of November. As detailed in the simulation setup paragraph above, five different scenarios have been calculated with total installed offshore wind capacity of 750, 800, 850, 900, and 1000 kW. All other energy factors have been left unchanged over the scenarios.

The main findings can be found in table II. A reduction in imported or exported energy indicates a better utilisation of the generated wind power. As can be seen, both export and import were reduced for all simulated cases.

TABLE II
PERCENTAGE OF TOTAL IMPORT AND EXPORT FOR EACH CASE.

| Offshore Wind | Export Reduction | Import Reduction |
|---|---|---|
| 750 kW | 90% | 14% |
| 800 kW | 85% | 16% |
| 850 kW | 79% | 17% |
| 900 kW | 74% | 18% |
| 1000 kW | 65% | 21% |

The second column in the table depicts the total reduction in export of energy from the cluster as a result of smart control. For all cases there was a reduction of well over 50%, even so high as 90% in the 750 kW wind case. In the Dutch scenario, this would mean less power exported to the interconnected zones Germany, Belgium and Norway. The reduction can also be translated in less investment for transmission capacity.

The third column focuses on the effects of smart control on required import energy to the cluster. This import can be delivered from other zones, but it is more likely that these imports are delivered by fossil-fuelled power plants delivering reserve capacity. The last column in the table therefore denotes both reduction in required reserve capacity and reduction in fossil fuel based primary energy or in CO2 emissions, ranging from 14% for 750 kW of installed wind power to 21% for 1000 kW.

Figure 6 depicts the difference in (on- and off-shore) wind energy absorbed by the households for each simulated case. It is clear that for each simulated case more wind was utilized within the cluster using the PowerMatcher technology as compared to business as usual.

Therefore, this simulation study shows that the smart grid offers a huge potential in utilising flexibility of demand and supply in homes to accommodate high levels of wind power

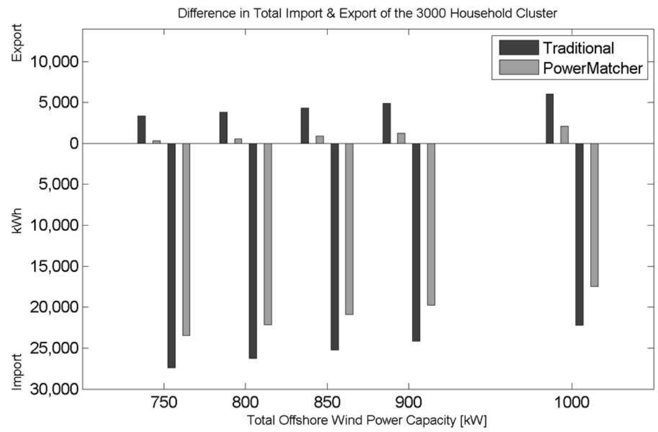


Fig. 6. Sum of Wind Potential Utilized for Each use case in Business as Usual and PowerMatcher Modes.

generation. More specifically, demand and supply coordination by the PowerMatcher raises the accommodation ceiling for renewables and reduces the amount of energy from fossil fuelled power plants.

Note that the amount of flexibility in the cluster was limited to household heating devices. If other household appliances, such as fridges, freezers, dishwashers, or electric vehicles are utilised in the same way, the flexibility in the cluster can be improved, leading to an even better outcome.

## VII. CONGESTION MANAGEMENT BY HEAT PUMPS

In buildings, the energy efficiency of space heating and hot tap water preparation can be increased significantly by installing heat pump systems instead of gas boilers or resistive electrical heating. In a typical set-up for household dwellings in Northern Europe, each dwelling has its own heat pump system for heating (tap water & rooms in the winter) and cooling (rooms in the summer). Groups of dwellings use a common aquifer for storing heat and cold in the underground. The electrical power of such a heat pump system is typically in the range of 2 to 2.5 kW. In extreme conditions, e.g. on extreme cold winter days, the heating power output of such a system is insufficient. To cope with such extremes, the heat pump systems are equipped with an additional electrical heater, a simple resistive element typically having a power in the order of 6 kWe.

The introduction of the heat pump poses a challenge for distribution grid operators, especially in areas where homes are heated predominantly using natural gas. Here, a switch from a gas-fired heater to a heat pump decreases the overall energy use while it increases electricity usage. On the level of a mid to low voltage transformer, typically connecting 150 households, the available design capacity per household is as low as 1 - 1.5 kVA. The electrical power of both the heat pump and its auxiliary heater exceeds this design capacity. In extreme circumstances, as we will see, the operational simultaneity of the heating systems is high. Hence, the local distribution grid needs to be dimensioned to 8 - 10 kVA per household. An network investment that will only be used a few short periods in the life time of the network assets. The simulation study described in this section assesses whether the PowerMatcher is able to ride through these extreme situations with a lower network capacity [12]. The study was performed within the SmartProofs project.

In cooperation with employees from the three main distribution network operators in The Netherlands, two critical scenarios have been formulated:

- **Black start recovery scenario:** Due to a contingency, the supply of electricity to the residential area has been interrupted for a longer time. As a result, the inner temperatures in the houses have gone down to temperatures varying between 7 and 13°C. After the electricity supply has been restored, all heating systems switch on and demand is at full power.
- **Cold winter morning scenario:** An early cold Monday morning ($-10^o$C) in early January, all people rise and demand a higher in-door temperature, and some of them take a shower. In all houses, the tap water boilers are being heated. Due to the extreme cold, all auxiliary electric heaters would switch on simultaneously to reach the desired user comfort level as soon as possible.

The latter scenario may occur once or twice a year during a period spanning a few weeks in the midwinter. The occurrence probability of the first scenario is much lower. However, the distribution system must be able to cope with such a situation otherwise it will be impossible to recover from an electricity outage.

The simulation model consists of 100 households represented by a building model and a combined model of the heat pump and auxiliary heater. Other electricity loads in the households have not been modelled. The load on the common low voltage to mid voltage transformer is represented by the sum of all heating loads. The capacity of the transformer, and the cable connecting the houses, is dimensioned at 275 kW, which equals the maximum power of 30 heating systems.

In the reference case, the heating system is controlled by a standard thermostat. In the PowerMatcher controlled case, the smart thermostat is expanded with a device agent. The device agent gives priority to the heat pump above the auxiliary heater and is able to modulate the auxiliary heater between 0 and 6 kWe. All heat pump agents communicate directly with a PowerMatcher auctioneer agent. Further, the transformer is equipped with an objective agent which monitors the transformer load. When the load surpasses a given cut-off level, this agent sends a bid to the auctioneer directing the cluster to ramp down. In both the reference and the PM-controlled case, the heat pump has a minimal run time of 30 minutes to avoid frequent switching.

The two critical situations described above were combined in one single simulation run having the following sequence:

1) **Start situation:** black-out. The houses have been cooled off to the situation described in the first scenario.
2) **Midnight:** the electricity supply comes back on. Houses are heated to their nightly set points varying between 16 and 17.5°C.
3) **Morning:** the heating systems turn on as described in the second scenario.

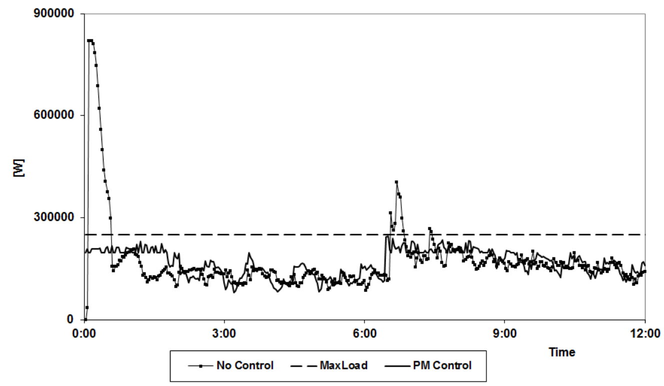


Fig. 7. Simulation results for a group of 100 households heated by heat pumps with auxiliary heaters. *Dashed*: Transformer capacity. *Line with dots*: transformer load in the reference case. *Solid Line*: transformer load in the PowerMatcher-controlled case.

Figure 7 gives the main result of this simulation. In the business-as-usual case, the transformer load surpasses the rated capacity both during the black-start recovery and during the cold winter morning. In the black-start scenario, the transformer is roughly 3 times underdimensioned. In the PowerMatcher case, the transformer load is kept within limits. The total electricity used in both scenarios is the same. The price paid is a slower heating curve for the homes. After the black-out, the heating time is just over twice as long. A slower heating in the morning scenario can be compensated by a smart thermostat which uses the heating curve of the last few days to determine the right starting time in order to reach its set point at the user's desired time.

This simulation study clearly shows the ability of the PowerMatcher technology to keep transformer load within rated capacity limits under extreme load conditions occurring during black-start recovery and on cold winter mornings.

## VIII. Conclusions

The PowerMatcher is a field-proven technology for integration of distributed generation, demand response and electricity storage into the electricity markets and into distribution network management. Through this technology, a large flexibility potential at medium-sized and small customers can be unleashed and utilized for integration of large-scale renewables and active management of overloaded distribution networks.

The results of the field experiments and simulation studies presented show that the PowerMatcher: (i) improves the wholesale market position of energy trade and supply businesses, (ii) contributes to active management of electricity distribution networks, (iii) raises the electricity system's accommodation ceiling for renewable power generation, and (iv) is scalable to mass-application levels. At the same time, the technology defends the interests of electricity end-customers by maximising their consumption of self-produced electricity and minimising costs by shifting demand to off-peak hours. Following a market-based approach, the PowerMatcher integrates the operation of retail and wholesale power markets.

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