The PowerMatcher
Smart Coordination for the Smart Electricity Grid

Koen Kok
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The PowerMatcher: Smart Coordination for the Smart Electricity Grid
promotor: prof.dr. J.M. Akkermans
To my mother and to Bianca.
ALMOST TWENTY YEARS ago, in the spring of 1994, while cycling through the Zuiderdiep, a street in the city of Groningen, I decided to aim my professional development at obtaining a PhD. At the time, I did not have a Master’s degree. So, I should fix that first. After that, I realised, I would be too old to live off a PhD-student’s loan. I should pursue the PhD as part of a regular job. So, I was aware the whole thing would be a long term plan. I gave myself 15 years.

What made me having these thoughts at that moment? Was it the influence of Mr. Kruisdijk, my teacher during my final years in primary school? He taught my class about the value and fragility of our natural environment and about the necessity of a switch to renewable energy. Or was it Mr. van der Bijl, a teacher at the polytechnic in Alkmaar, who strengthened my interest in the cutting edge of computer technology? Certainly, at that time, I wasn’t a scientist yet, having earned BSc degrees in two engineering disciplines in 1992 and 1993. However, I had gained my limited working experience as an engineer working in a scientific environment. I had done an internship in the instrumentation group of the Biology Department at the University of Amsterdam, helping to create measurement equipment for brain research. I had lived in Colchester, England for almost half a year doing one of my Bachelor’s projects at the University of Essex in the group of professor Simon Lavington. There, I engineered the driver software to couple experimental hardware for rapid information processing to a workstation host computer. As well, in that 1994 spring I was developing measurement software for a new instrumented car at the Traffic Research Centre (TRC) of the University of Groningen. In each of these cases, I was working as an engineer providing technical support to a university research group. These working experiences gave me an insight into the day-to-day business of doing research and, more importantly, I experienced for myself, and recognised in others, the strong drive and passion that come along with it.
My time at the TRC definitely planted the seed. Working with Karel Brookhuis, Dick de Waard and others on the DETER project was my first introduction to European research projects. I hadn’t worked so closely to the actual research before. Building-up the hard- and software in the back of the research car with Peter Albronda to get it ready before the driving experiments would start. Testing and tweaking software in the back seat while Dick drove the car over the highway to prepare for experiments with volunteer drivers. At the time, I attended the public PhD defence of several TRC colleagues, wondering if I would be able to do the same, albeit in a completely different discipline. In the coach-house attic of the ‘Huis De Wolf’, the grand villa where the centre was located, I also learned that doing research was good fun. Fokie Cnossen, Monique van der Hulst, both starting their PhD work in that period, and a number of interns had their share of the attic and of the fun.

In 1998, I received a Master’s Degree in Computer Science from the University of Groningen and started to work at the technical services department of ECN, the Energy research Center of the Netherlands. At the first interview, I mentioned my long-term goal to pursue a PhD. Once on the job, I tried to get a PhD project off the ground. The idea was to apply machine learning techniques in different corners of the energy research arena. However, the gap between this and the core mission of ECN was too wide to let it fly. After a period of trying, I more or less gave up and decided that doing interesting modelling projects was good enough for the time being. Interesting projects came along and the PhD plan went to the background. It had become, however, a self-fulfilling prophecy. Just when I stopped hunting, it stopped trying to flee from me. Just when I stopped looking for it, it came looking for me.

Luc Hamilton, who hired me at ECN and knew about my ambition, basically started the whole thing off by simply putting me in contact with Hans Akkermans, who later became my PhD supervisor. This is the point where I will start to thank people. Thanks, Luc! Around the same time, I switched departments within ECN and started working for DEGO, a research group focussing on energy in the built environment. Integration of renewable electricity generation in the energy infrastructure was an emerging topic and CRISP the project we worked on. Hans and I wrote a project proposal for a PhD project focussing on the use of electronic markets for this integration, also based on the work we did in CRISP, and submitted it to the STW, a local research funding organisation. The project was rejected, however, I used the text I wrote on the problem statement and the technological idea as a basis for a paper to the AAMAS, a major conference in agent technology. This paper was selected as one of the best industrial contributions to the conference and an extended abstract was published in the IEEE Intelligent Systems magazine. The
original paper and the magazine article are still among my highest-cited publications. At DEGO, Gerrit Jan Schaeffer became my manager. Without wanting to disqualify his predecessors, he was the first direct manager I had as a young scientist who completely understood the things I was working on and could be used as a sparring partner. I thank him for the role he played in starting off my PhD work. In these early days, having a manager who himself earned a PhD was important in getting the right preconditions in place.

One of these preconditions was the time I could spend at the VU as part-time visiting researcher. I would like to thank the people who worked for the VU Business Informatics group at that time. Especially, I want to mention Zsófi Kráussl-Derszi who has been a close co-worker. We managed to get the same study case, described from two totally different angles in two papers, accepted for a major conference. In that period of weekly visits to the VU, I have had many valuable discussions with Jaap Gordijn, Jos Schrijnemakers, who unfortunately is no longer with us, and Vincent Pijpers. I would like to thank them for the insights these discussion brought.

Almost anyone pursuing a PhD has to deal with circumstances delaying the process. My case has been no exception. Some of these circumstances were self-inflicted, others were just my life happening. The decision to work on a thesis as part of, and next to, an existing job brought me a struggle when it came to balancing short-term tasks and long-term developments. Naturally, this became worse the moment I took up management tasks when I became a research coordinator at ECN. On the other hand, this also brought me a lot in personal and professional development, but also in developing the research reported in this thesis. The coordinator role enlarged my span of control and strengthened my influence on a wide variety of validation activities —field experiments and simulation studies— performed with the PowerMatcher. A lot of these activities added highly-valuable results to the validation part of this thesis, providing a full insight in the merits of the PowerMatcher in all key application area’s. I refer to Section 11.2 in this thesis for an overview of these validation activities and the people and cooperation partners involved in each of these.

Clearly, I could never have produced all findings in this thesis on my own. The PowerMatcher, the central technology in my thesis, has been a result of teamwork from the very beginning. Therefore, I am greatly indebted to a large group of people who contributed to the development of the PowerMatcher and/or to the research performed around it. Firstly, there is a big group of colleagues from our time at ECN. Some of them are still a colleague at TNO, some not. Cor Warmer and René Kamphuis were there from the very beginning working on the system that became the PowerMatcher. I remember intense discussions on the concept and software design during these early days. Later on more and more people jumped in, went
along and provided important input: Maarten Hommelberg, Bart Roossien, Pamela MacDougall, Olaf van Pruissen, Gerben Venekamp and Joost Laarakkers. Then, there is a large group of people at ECN who helped with the technical realisation of the PowerMatcher itself, the simulation tool and the field deployment projects. Especially, I would like to mention Sjaak Kaandorp, Fred Kuijper, Ton Ruiter, Arie de Waard and Oscar Brouwer, who was externally hired in. Further, I would like to thank Gonno Leendertse who provided help with some of the mathematics in this thesis.

In the beginning, most colleagues in the growing PowerMatcher team at ECN worked as part the unit DEGO, later called EGON. I want to thank the complete set of extraordinary people that worked in this unit. The social coherence and camaraderie, as well as the drive to do something meaningful in the world through energy research, made this unit a wonderful place to work. Thank you for that! Also, thanks to Marije Lafleur, Ivo Opstelten and Gerrit Jan for providing the kind of leadership that made this possible. In a later stage, Martin Scheepers played an important role in many different ways after he became program manager of the smart grids research at ECN and, later on, also unit manager. I am thankful for his guidance in my role as research coordinator. Further, Martin stimulated a better outside-visibility of PowerMatcher and stepped up activities towards commercialisation. In this respect, I also want to thank Annelies van Herwijnen and Marco Pieterse who contributed greatly to this process.

Further, I am thankful to the cooperation partners in the different projects I worked on when the contents of this thesis has been formed. These include all partners in the European projects CRISP, FENIX and INTEGRAL, the NL-national project EIT, and the industry-funded Micro-CHP VPP project. Discussions and co-operations with individual people in these projects have been vital for the development of the ideas and results in this thesis. Further, I would like to thank the following people (in no particular order and with their affiliation at the time we worked together): Per Carlsson of EnerSearch, Rune Gustavsson, Per Mellstrand, and Björn Törnqvist at BTH, Nouredine Hadjsaid, Christophe Andrieu and Christophe Kieny at IDEA, Laurent Schmitt and Matthias Muscholl at Areva T&D, Peter Lang at EDF Energy Networks, Jan Willem Turkstra and Pierre Bartholomeus, Frits Blikk at Gasunie, now DNV KEMA, Jörgen van der Velde and Marten van der Laan at ICT Automatisering, Marcel Eijgelaar at Essent, Joep van Leersum, Martin Rapos, Pieter Nijsse, Alex Bouw and Aldo Eisma at IBM, Hugh Maaskant and Maarten Pennings at NXP, and Martijn Bongaerts and Peter van der Sluijs at Alliander. The complete group of people, who have been involved in projects, discussions and other activities related to the PowerMatcher is much larger than I can mention here on an individual basis. I sincerely thank you all for your contribution.
A special place is for the SmartHouse/SmartGrid project. I had the privilege
to be closely involved from the early idea to the end of the project. Thanks to all
consortium partners for creating an environment in which cooperation and shared
ideas could flourish. Especially, I would like to mention: Anke Weidlich and Stam-
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Britta Buchholz, Barbara Dörsam and Stefan Drenkard at MVV, and David Nestle
and Jan Ringelstein at Fraunhofer ISET.

Also, a special thank you to my new colleagues at TNO. After the transfer of
ECN’s smart grids activities to TNO, a number of original TNO-ers got involved in
PowerMatcher developments and related activities. Thank you for the new coop-
erations and ideas that emerged when our activities merged. I won’t provide a list
of names, as the recent developments, albeit significant, did not add to the contents
of this thesis. However, you know who you are. Be thanked! I do, however, want
to mention Jurjen Veldhuizen, my direct manager at TNO, and thank him for the
opportunity and the stimulation to finish this thesis.

Then, I want to thank a few people who helped in getting my thesis in shape.
George Huitema for reading through the full draft and providing helpful comments
on the structure and overall argument of the thesis. Pamela MacDougall for being
my ‘English eye’. She proofread the complete thesis text—some parts more than
once—and gave subtle grammar lessons along the way. Further, she was always
available to help out with the nitty-gritty problems a dissertation writer encounters.
Thanks, Pam! You are worth your weight in gold, probably more. Then, I want
to thank Dr. Tom Jankowski for fostering PhinisheD.org, an online community for
academic writers. I could not have completed this without that website and the
wonderful group of anonymous scholars that populate it.

Naturally, I owe special thanks to Hans Akkermans, my PhD supervisor at the
VU. Thank you for all our discussions on smart grids, business informatics, agent
systems, and the like. Even more for all discussions we had on other academic issues
such as running large international projects, social structures within research com-

Certainly, I haven’t been constantly busy chasing that goal during these 20 years
after that particular cycle ride through Groningen. My life happened as well. I
sailed a lot, especially in the first 10 years. Got my skipper’s licence for large sailing
ships and worked as a professional skipper for two full summer seasons. I married
Bianca, my girlfriend and the love of my life. We had a lovely & creative daughter
together, Marije, now aged 12. I learned how to play the piano and lost the knack
of it again. We got a great son, Sil, aged 7 now. In him, I recognise much of myself at that age. We went on vacations, camping, sailing. We had the privilege to get another sweet daughter, Linde, now 4 years old, a dancer before she could walk. Plus, I improved my jazz playing on the bass guitar.

I want to thank my family and friends for the interest expressed in the process I was engaged in over these years. Thanks for your kind understanding in those occasions I stayed home working, while I could have been at a social event. Finally, I want to thank Bianca. Without your support, it would not have been possible to complete this journey. I am deeply thankful and grateful for the trust you have put in me and for the sacrifice you evidently brought.

Delft, 7th of May 2013.
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Chapter 1

Introduction

1.1 PowerMatcher: ‘A World’s Top Sustainable Solution’

This PhD thesis presents the PowerMatcher, an innovative ICT technology for making the electricity grid smart. At the United Nations Conference on Sustainable Development in Rio de Janeiro, June 2012, this technology was honoured as a world’s top sustainable solution. Sustainia100, the 100 most powerful sustainable solutions in the world, presented at the conference, lists no less than two sustainability projects involving the PowerMatcher technology. Gathered from 56 countries spread over six continents, Sustainia100 is a complete guide to innovative and scalable solutions instrumental in creating sustainable societies. Building on ready and available solutions only, Sustainia100 is as a tangible tool for sustainability professionals—from politicians to CEOs—dedicated to create desirable and sustainable societies. Connie Hedegaard, EU Commissioner for Climate Action: “By 2030, the world will need at least 50 per cent more food, 45 per cent more energy and 30 per cent more water. This is why we need a more sustainable growth model. Sustainia shows that many of the solutions are already there.” Among these solutions is the PowerMatcher, the central result of the research presented in this thesis.

PowerMatcher is a novel coordination mechanism designed to integrate numerous small electricity consuming and producing devices in the operation of the electricity infrastructure. In this way, PowerMatcher integrates large amounts of renewable energy in the electricity system and, at the same time, avoids overload situations locally in our ageing electricity distribution networks. Both Sustainia100 entries for the PowerMatcher smart grid technology are sustainable electricity demonstration projects: the EcoGrid prototype of the European smart electricity grid and PowerMatching City, the first living smart grid community in the world.

Sustainia100 widely covers 10 different sectors from renewable energy sources to sustainable modes of transportation and energy-efficient buildings to smart electricity. “I’m very excited and inspired by the Sustainia100, as it makes it absolutely clear that our mission is possible,” says Arnold Schwarzenegger, Honorary Chair of Sustainia. “It says we do have the ammunition we need to tackle this challenge.”
That we have what it takes to create fun and attractive societies without destroying our planet.”

1.1.1 EcoGrid

The EcoGrid solution enables the electricity grid to handle large amounts of renewable energy. It demonstrates the ability of the Danish island of Bornholm’s energy system to handle a large share of wind energy. More than 50% of the electricity supply on the island is coming from renewable energy sources. The central idea of EcoGrid is the introduction of market-based mechanisms to release balancing capacity, particularly from flexible consumption. Approximately 2,000 residential consumers (out of a total of 28,000 customers) participate in this Smart Grid demonstration project, with flexible demand response tied to real-time price signals. The EcoGrid demonstration project is among the largest EU-funded Smart Grid projects. The Sustainia100 jury report emphasises the significant challenge of integrating large amounts of renewable energy from wind and solar farms into the electricity grid as we know it. “Raising eyebrows all over Europe for its ability to handle large amounts of fluctuating renewable energy in its system, the EcoGrid project of Bornholm is a demonstration of the future of energy grids” says the jury. “The size of the project, and the amount of fluctuating renewables integrated, make the project particularly noteworthy”, according the report.

The PowerMatcher is one of the technologies demonstrated on the Danish island. The system will turn a planned 700 houses into smart homes that react to the electricity price and buy the needed electricity as cheap as possible. “As the price will go down during an unexpected peak in renewable energy production, consumption will go up at the same time. This will help the integration of renewables”, says TNO expert George Huitema. “We let the electricity consumption on the island follow the wind energy generation more closely.” The EcoGrid project means a significant step in the number of households handled by the PowerMatcher. “The technology has been designed for scalability”, says Huitema, “so we are confident we will make this project a success. The inclusion in this prestigious Sustainia100 list is the icing on the cake.”

1.1.2 PowerMatching City

The PowerMatching City project, the other entry in Sustainia100, focusses on the reversed relationship between supply and demand in the coming smart power grid as well. Where electricity production (supply) used to respond to demand from consumers, the smart power grid of the future will enable consumers to respond to
fluctuations in supply of electricity generated from renewable sources. The project is centered around a living-lab of 25 households in the Hoogkerk district of the City of Groningen in the Netherlands. The PowerMatching City project demonstrates the ability of consumers to be active players in the energy system by providing them with demand response capabilities. Heat, for example, is produced with heat pumps when very cheap electricity is available, and then stored for later use. At the same time, consumers generate their own electricity with photovoltaic solar panels and micro combined heat and power units. In addition, they are able to exchange energy with each other on a local energy market. Joost Laarakkers, the TNO-internal project leader: “This local market has been realised using TNO’s PowerMatcher technology. The system gives priority to the locally produced electricity and/or to green electricity from outside the district above less-sustainable energy sources.”

Again, the Sustainia100 jury stresses the importance of demand response in the grid as one of the primary ways to integrate higher amounts of renewable energy into the system. “When demand for energy becomes flexible, intermittent renewable energy becomes more competitive, as the need for storage, grid interconnection, or backup capacity is reduced”, according to the jury report.

1.1.3 The Best Sustainable IT Project and the Blue Tulip

EcoGrid EU was among the ten solutions from the Sustainia100 list to be nominated for the Sustainia Award. In October 2012, the project was awarded the title “Best Sustainable IT Solution” by the Sustainia jury. Only one month later, PowerMatcher won the Blue Tulip Energy Innovation Award 2012 during a major award event in Amsterdam. The award was handed over by mrs Huizinga-Heringa, a former Dutch cabinet minister and the chair of the jury. On behalf of the jury, she praised the PowerMatcher as a green technology essential to achieving the government’s sustainability goals for the year 2020.

1.2 The Future of Electricity

The PowerMatcher is an answer to three important trends in our electricity system. Firstly, the much needed rise in electricity from the wind and the sun poses a challenge in keeping the supply and demand of the grid in balance. For more than a century, supply followed demand in the electricity grid. Now the supply is becoming more fluctuating and more unpredictable. Secondly, the electrification of everything drives our ageing distribution networks to their capacity limits. Our electricity infrastructures have mainly been built during the 1960s and 70s. Now, electricity demand in 2030 is expected to grow to three times the level it was at the
beginning of the new millennium. Overloading our grid will shorten the life span of the lines, cables and transformers, which are already close to their life end. Contrarily, precautions will stretch the life time of these assets considerably. Then, thirdly, electricity production is becoming decentralised to a great extent. The number of small generation units is increasing steeply and is expected to do so for the years to come. Photovoltaic panels, small wind turbines and combined heat & power production units, all connected to the grid at distribution level, deliver their energy close to the location of consumption.

1.2.1 A New View on the Electricity Consumer

These trends will drastically change the end-customer’s view on the electricity grid and, conversely, the view of the sector on the end-customer, residential, commercial and industrial customers alike. To begin with, the electricity end-user will cease to exist, as he or she will be a producer of electricity as well. The consumer becomes a prosumer: sometimes producer, sometimes consumer. Therefore, we rather speak of an end-customer than an end-user. For more than a century, there have only been one-way flows in the electricity networks, now at times, the ‘consumer’ is delivering electricity to the grid. On top of that, the end-customer will become a deliverer of an additional service: the flexibility service. As described for EcoGrid and PowerMatching City, appliances in smart homes are going to react to the availability of cheap and green energy. Thus, operational flexibility of the end-customer’s electricity consuming and producing devices has a value in the future electricity grid.

This flexibility is valuable in maintaining the demand and supply balance in the electricity system as a whole. More wind and solar power means more fluctuations in electricity supply creating a need for flexible units to react to these variations. In today’s liberalised market, this type of balancing takes place in the wholesale markets for electricity. Which would make the energy supply company—being the intermediary between the end-customer and these markets—interested in buying the flexibility service the end-customer would be able to deliver. Then, there is the operator of the distribution network the end-customer is connected to. Investments in the distribution networks can be deferred when electricity demand moves away from the peak hours and local supply moves towards these time periods. Consequently, this network operator is a potential buyer of this flexibility service as well.

In summary, unleashing the flexibility potential present in electricity consuming and producing devices at end-customers will be vitally important to keep the electricity grid going in an affordable way. Also, there are—at least—two parties interested in using this flexibility to create value: the energy supply company and the electricity network operator.
1.2.2 The Need for a New Coordination Mechanism

So, the end-customer side of the electricity system, currently passive, needs to get actively involved in the system coordination. This means a change in the role of the end-customer, as we have seen, as well as a huge change in the way coordination is done in the electricity system. At the level of the distribution networks, this type of coordination is completely absent at this moment. The vast majority of the distribution networks are operated passively with only a small amount of sensoring in place. For the task of balancing demand and supply at the system level, coordination is currently done by centrally managing a relatively small number of large power plants.

Now, the challenge is twofold. Firstly, to involve electricity consuming and producing devices in the coordination task. In comparison with the average power plant, these devices are much smaller, present in huge numbers and highly distributed into the capillaries of the infrastructure. On top of that, these devices are owned by, and located at the premises of what is now-called the end-user. So, the coordination mechanism itself must be distributed in nature and in agreement with this new relationship with the end-customer. Using the current paradigm of centralised control will fail, as it will be impossible to communicate with such a huge number of devices from a single point. Even if that would work, there are problems regarding privacy and autonomy attached to the direct control of consumer-owned devices by some external authority.

Secondly, the challenge is to create a coordination mechanism that combines balancing at a system level with distribution network management at a local level. As explained above, both tasks will benefit from the use of end-customer provided flexibility and, in an unbundled electricity market, both tasks are performed by different parties simultaneously. In a few words:

The needed coordination mechanism must be fully decentralised and fit into the liberalised energy market.

1.3 Coordination Mechanism Requirements

Thus, the challenge at hand is to involve electricity consuming and producing devices in both balancing at a system level and network management at a local level in the distribution networks. On the fly, we formulated two meta-level requirements for this system: the mechanism must be fully decentralised and fit into the liberalised energy market. In this section, we divide these further into six main requirements: three non-functional and three functional requirements.
Let’s focus on the devices first. These encompass three classes of devices that we collectively refer to as Distributed Energy Resources:

- **Demand Response** (DR) is the ability of electricity consuming installations and appliances to alter their operations in response to (price) signals from the energy markets or electricity network operators in (near-)real time. Demand response can be achieved through avoidance of electricity use and/or by shifting load to another time period.

- **Distributed Generation** (DG) is the production of electricity by units connected directly to a (medium and low voltage) distribution network or to a customer’s site. A subclass of DG is in potential able to alter their operations in response to external (price) signals.

- **Distributed Storage**, i.e. devices connected to the distribution network capable of bi-directional exchange of energy with that network.

In this respect, responsive electricity consumption is regarded as a resource due to its flexibility in operation: the ability to shift electricity production or consumption in time. The needed coordination mechanism needs to be open enough to interface to all types of DER devices in these three classes. Above all, the design of the mechanism needs to reflect the fact that these devices are owned by end-customers and serve a purpose for this end-customer. In other words, it is important to realise that aiding the electricity system isn’t the primary reason of existence for DER devices. An industrial freezing house, for instance, has been built to keep food products frozen. While this installation can be of great value in the electricity system when its demand response potential would be unleashed, the primary objective of its control system is to keep the inner temperature below, say, -18°C. In general, a DER device is able to deliver operational flexibility only within some constraints set by the physical process behind the device and/or by the preferences of the user or owner of the device. Taking these considerations into account we formulate the following requirement:

**R1. Openness**: The coordination mechanism must be open for a wide variety of DER devices without hampering the device’s primary purpose.

Furthermore, the mechanism must not communicate privacy sensitive information from the end-customer to any outside body or system:

**R2. Privacy Protection**: The coordination mechanism must involve DER devices at the premises of electricity end-customers without infringing the privacy of the end-customer.

Then, as explained earlier, coordination in the future electricity system involves a huge number of relatively small units. Scalability is key:
1.4 Main Result: The PowerMatcher

**R3. Scalability:** The coordination mechanism must be scalable to mass-application levels.

Note that these three are non-functional requirements. Naturally, there are functional requirements as well, as the mechanism must provide a solution to the two main problems as sketched above: system balancing and active distribution management. Inherently, the mechanism must be part of, or an extension of, the liberalised electricity market. As stated before, in the liberalised market, balancing is to a great extent delegated to the parties active on the wholesale markets for electricity, notably the market for balancing. Hence, the following requirement:

**R4. Trade & Supply Functionality:** The coordination mechanism must be able to improve the wholesale market position of an energy trade & supply business.

Similarly, we define a requirement regarding the involvement of DER in network operations:

**R5. Active Distribution Functionality:** The coordination mechanism must be able to contribute to active management of electricity distribution networks.

These two requirements are formulated from the points of view of a trade & supply business and the operation of the distribution network. Having a clear business benefit is an important prerequisite for a broad uptake of the technology by these parties. At the same time, one of the main drivers behind smart grid developments is the integration of renewables. In a given electricity system, the amount of renewable energy resources that technically can be integrated is limited to a certain maximum, the so-called accommodation ceiling. In the current system, this ceiling lays around 15% renewable generation as experience in, for instance, Northern Germany and Denmark shows. The desired mechanism must be able to aid in the integration of renewables. Hence, we formulate:

**R6. RES Integration:** The coordination mechanism must be able to raise the electricity system’s accommodation ceiling for renewable energy sources.

### 1.4 Main Result: The PowerMatcher

The main result in this thesis is the PowerMatcher, a novel coordination mechanism that integrates DER devices in the operations of a smart electricity grid. PowerMatcher puts the end-customer in a central position in the smart grid. It is the end-customer who owns the domestic appliance, electrical car and/or industrial installation that is potentially able to offer the operational flexibility needed for a smart and sustainable electricity grid. PowerMatcher empowers the end-customer
to sell this flexibility to the parties interested. This selling is completely automatic using a piece of intelligent software installed at the premises of, and running under the authority of, this end-customer. This so-called intelligent agent trades on behalf of the end-customer. In this way, the integrity of the costumer’s private environment is maintained, in contrast with other smart grid response techniques that involve direct and remote switching of end-customer appliances. For this trading activity on behalf of the device owner, the uniformed data messages exchanged are stripped of specific local information. Only aggregated information regarding power levels and prices is exchanged, protecting the privacy of the customer.

The PowerMatcher has been extensively validated both in field deployments and in simulation studies with good results (see Table 1.1). The field experiments performed integrate a wide variety of DER devices into the operations of the smart electricity grid. Home appliances, electrical vehicles and industrial installations have been made responsive and participated in highly relevant smart grid applications.

<table>
<thead>
<tr>
<th>Validation Item</th>
<th>Result</th>
<th>From</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trade &amp; Supply</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portfolio Balancing</td>
<td>Wind imbal. reduction: 40 to 60%</td>
<td>Field</td>
</tr>
<tr>
<td>Balancing Market Reaction</td>
<td>Realisation of desired reaction</td>
<td>Field</td>
</tr>
<tr>
<td><strong>Active Distribution Mgmt</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congestion Management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordination of $\mu$-CHPs</td>
<td>Peak reduction: 30–50%</td>
<td>Field</td>
</tr>
<tr>
<td>Smart charging of EVs</td>
<td>Peak reduction: up to 30%</td>
<td>Simulation</td>
</tr>
<tr>
<td>Smart charging of EVs</td>
<td>Peak reduction: 35%</td>
<td>Field</td>
</tr>
<tr>
<td>VPP &amp; Congestion Mgmt</td>
<td>Proof of Principle of FastLMP</td>
<td>Field</td>
</tr>
<tr>
<td>Black-Start Support</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordination of HPs</td>
<td>Grid capacity can be $3 \times$ lower</td>
<td>Simulation</td>
</tr>
<tr>
<td><strong>RES Integration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased RES utilisation</td>
<td>Uncommitted RE used: 65–90%</td>
<td>Simulation</td>
</tr>
<tr>
<td>Avoided gray energy usage</td>
<td>Reduced use of gray: 14–21%</td>
<td>Simulation</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large-scale VPP reaction</td>
<td>1M households in $&lt; 1$ min.</td>
<td>Field</td>
</tr>
</tbody>
</table>

The PowerMatcher has shown to improve the match between electricity consumption and the availability of green electricity. In the current liberalised market setting, this is directly beneficial for a trade & supply company having large capacities of wind power in its trade portfolio. PowerMatcher reduced the imbalance.
1.4. Main Result: The PowerMatcher

caused by unpredictable behaviour of wind electricity generation with 40 and 60% in two separate field experiments. This was gained by letting electricity consuming and producing home appliances and industrial installations react to the unpredictable wind power fluctuations. Such imbalance reductions substantially reduce the wind-energy-induced imbalance cost. Similarly, a PowerMatcher-based virtual power plant is able to react to the momentary situation on the imbalance market, as one of the field experiments showed. In these ways, the system aids the integration of renewables in the current energy system. Moreover, when the share of renewable generation becomes substantially large, PowerMatcher raises the accommodation ceiling for wind and solar produced electricity. In the future electricity grid, and already today in regions such as Denmark and Northern Germany, the total regional renewable electricity production surpasses electricity demand at times. The uncommitted renewable power has to be either exported or curtailed. If adjacent regions are facing a similar situation, exporting isn’t possible. Thus, the local usage of renewable electricity has to increase to avoid spillage of green energy. In a large simulation, focussing on a real-world future scenario, PowerMatcher has been shown to increase the local utilisation of sustainably produced energy such that 65 to 90% of the otherwise uncommitted renewable energy was actually used within the region. By doing so, a gray energy saving of 14 to 21% was obtained.

In addition, PowerMatcher has shown to be able to relieve overloaded distribution networks by performing congestion management and delivering support in black-start situations. Under normal operational circumstances, PowerMatcher reduces the peak-loading of distribution networks with values between 30 and 35% as the majority of field experiments and simulation studies shows. These experiments and simulations involved a variety of responsive demand and flexible distributed generation such as micro combined heat and power units (micro-CHPs), heat pump systems and electrical vehicles. A simulation study into restoration of a distribution grid under extreme circumstances, showed the black-start potential of the technology. By introducing smart coordination, the design capacity of the grid could be three times lower. These results form a potential cost reduction for distribution network operators in three different ways. Firstly, overload situations shorten the life time of grid components such as cables and transformers. Consequently, congestion management lowers the failure probability of ageing grid assets. Secondly, congestion management defers grid reinforcements and, thirdly, reduces the investment cost of new grids. Additional to the grid management results above, it has been field-proven that congestion management in a grid area can be performed simultaneously with virtual power plant operations by energy supply companies using the same flexible DER. This is an important result as these two processes will be performed simultaneously in the future smart grid.
1. Introduction

Scalability has been a key design objective for the PowerMatcher. There have been a number of specific design choices made in order to meet this important requirement. A specific field experiment performed under mass-application circumstances provides empirical evidence for the theoretical scalability properties. The experiment shows that the reaction of a PowerMatcher architecture serving 1 million households is below 1 minute. This shows that under mass-application circumstances the flexibility potential of a PowerMatcher cluster can be accessed fast enough for operations in the balancing market, the most volatile electricity market.

Currently, the PowerMatcher is being productised by a number of industry partners along the electricity value chain.

1.5 Research Design

Figure 1.1 gives the design of the research performed. Central to the research in this thesis is the design of the smart grid coordination mechanism. Hence, the main research question is formulated as:

Q0. How to design a coordination mechanism that integrates distributed energy resources in the operation of the electricity system and meets the requirements for Openness, Privacy Protection, Scalability, Trade & Supply Functionality, Active Distribution Functionality and, last but not least, Renewables Integration?

Naturally, the desired coordination system needs to be built on a firm theoretical basis. The theoretical work presented in this thesis aims at strengthening this basis by providing answers to four theoretical research subquestions (Q1 to Q4), further detailed in the next section. The corresponding results reinforce the theoretical foundation both under the design of the system and under its application in practical use cases. Answering the first three subquestions lead directly to design choices for the mechanism. The forth question focusses on the strategies of individual DER devices participating in the system. The answer to this question led to a set of design directions for DER device control agents.

The PowerMatcher smart grid technology is the coordination system designed in answer to the main question. Thus, the PowerMatcher is a software system that implements a coordination mechanism that is claimed to meet the six requirements defined in Section 1.3. By design PowerMatcher meets the requirements for Openness, Privacy and Scalability. After answering all subquestions and designing the coordination mechanism, the main question is answered only if the mechanism has been thoroughly validated, especially regarding the requirements not met by design. Here, an empirical approach has been chosen as the desired coordination system is required to aid in the operation of the electricity system, a highly practical
1.5. Research Design

Figure 1.1: Research design. The arrows denote the direction of progress and traceability of research.
and operational goal. Hence, five of the six system requirements were validated in a series of field experiments and simulation studies. Later on in this thesis, in Chapter 11, we detail these five requirements into a series of validation goals for the field and simulation studies. We refer to that chapter for an in-depth treatment.

Both the theoretical and the applied research in this thesis is multi-disciplinary in nature. The applied part of the research, dealing with the design of the PowerMatcher and it’s application, methods have been developed for electricity market trading and electricity network management. These have been based on distributed computing, micro-economics and ICT-architecture modelling. Having had a focus on value drivers in the smart electricity application field on one hand and a firm theoretical basis under energy management technology developments on the other, gave a good utilisation potential for the developed technology. Field deployment has been an important driver for a successful technology development. Here, an spiral approach has been followed. A number of times, PowerMatcher has been redesigned into a new software version on the basis of field experiences.

1.6 PowerMatcher’s Theoretical Basis

In designing the PowerMatcher and validating it against the requirements defined, a number of existing theories have been used. At the same time, a number of theoretical challenges needed to be tackled, leading to four concrete theoretical contributions.

1.6.1 Existing Theory and Open Questions

As explained above, the scalability requirement forces a break with the standard paradigm of centralised control currently used in the electricity system. When centralised mechanisms fail, an obvious thing to do is to turn to distributed, decentralised mechanisms. In Computer Science, the field of Multi-agent Systems (MAS) studies distributed computing techniques that can be used to solve problems that are difficult or impossible for a monolithic system to solve. A software agent, or for short just agent, is a self-contained software program that acts as a representative of something or someone. In a multi-agent system, a large number of such agents are interacting with each other. When designed well, Multi-agent systems are open, flexible, scalable, and extensible ICT systems able to operate in highly-complex environments.

A sub-field of MAS studies resource allocation. Resource allocation is the process of assigning resources in an economic way to applicants taking into account the availability of the resources and the preferences of the applicants. In a MAS, such
a system can be realised using *electronic markets*, fully automated market systems, where software agents are participants. When these software agents perform a local control task (i.e. control of a physical process), *Market-based Control* (MBC) emerges. In MBC, agents in a MAS are competing for (one or more) resources on an equilibrium market whilst performing a local control task that needs those resources as an input. In MBC, communications are uniformly based on market information. This results in an open system based on a communication protocol that is easily standardisable and doesn’t include specific local data. Note that these are two important aspects with respect to our requirements regarding Openness (R1) and Privacy Protection (R2). Adding the favourable scalability properties mentioned above, MBC provides a tool to meet our three non-functional requirements. When making the move from the current centralised control paradigm to distributed control, it is important to have insight in the optimality of MBC. Hence we formulate the following research question:

**Q1. Optimality of Market-based Control:** Consider an interactive society of a large number of agents, each of which has an individual control task. Is it possible to provide mathematical proof of the optimality of the control strategy that interactively emerges from this agent society with respect to both local and global control performance criteria?

Electricity is a *flow commodity*. A flow commodity is a physical stream that is infinitely divisible. Apart from electricity, examples of flow commodities are physical flows of gas or liquid. The MAS literature describes a number of algorithms for *resource allocation of flow commodities*. However, these algorithms do not take characteristics of the underlying flow network into account. For instance, capacity constraints in a flow network often have impact on the feasibility of a particular allocation outcome. By not considering these constraints in the market algorithm used, it is implicitly assumed that the network has virtually infinite capacity. In Electrical Engineering terms: the network is assumed to be a “copper plate”. It would be desirable if algorithms for allocation of flow resources would yield *network feasible solutions*, i.e. allocation solutions that obey the characteristics of the underlying passive flow network. Surprisingly, this white spot in Computer Science can be filled in using knowledge from the Power Engineering field. Power systems economics provides a framework called *Locational Marginal Pricing* (LMP) which runs an electricity wholesale market while considering line capacity constraints and energy losses in the electricity transmission network. Hence the following research subquestion:

**Q2. Network Feasible Solutions in Resource Allocation:** How can algorithms for allocation of flow resources be extended to yield network feasible allocation solutions obeying characteristics of passive flow networks? How can the mechanism of locational marginal pricing from the field of power systems economics be formulated in computer science terms?
As mentioned before, the “electrification of everything” will put a major strain on the (low to medium voltage) networks for electricity distribution. In the future, congestion management is expected to be standardly used in these networks, so, there will be a need to use locational marginal pricing in distribution networks. Originally, however, LMP has been designed for high-voltage transmission networks. Electricity distribution networks are having a much higher number of network nodes as well as connected actors. The LMP algorithm does not scale well with regards to the number of nodes in the network, which gives a problem when applied to the distribution level in the electricity system. However, another difference between distribution and transmission networks is their topology. Where transmission networks are generally operated in a meshed topology, the distribution networks are predominantly operated in a radial, non-cyclic, topology. This observation leads to the following research subquestion:

Q3. Locational Pricing in Radial Networks: How can algorithms for Locational Marginal Pricing in non-cyclic passive flow networks take advantage of this topological property to find solutions against a lower computational burden?

At this point, our toolbox consists of Market-based Control, Resource Allocation algorithms, and Locational Marginal Pricing. In computer science terms, using these, one is able to build optimal and scalable coordination systems in which local control agents situated in a networked environment compete for a flow commodity needed for their control tasks. The design task set by our main research question is to apply these tools in a meaningful way to craft the coordination mechanism for the future electricity grid.

Once one has decided on a system design, one needs to know how DER devices can best be involved in the coordination task. Is there a dominant strategy, i.e. the best strategy an agent can follow regardless of the strategies of the other agents in the market? If so, how is this strategy influenced by the devices primary process? To participate in an electronic market, the device agent must formulate a market bid that reflects the momentary available flexibility within the constraints set by this primary process. Hence, the final research subquestion:

Q4. Bidding Strategies of DER Device Agents: Consider DER devices participating in an electronic market to coordinate their electricity production and/or consumption in (near-)real-time. How can the bidding strategies of these devices be formulated in micro-economic terms, e.g. marginal costs and market price dynamics? How does the nature of the physical process behind the DER device influence its dominant strategy?
1.6. PowerMatcher’s Theoretical Basis

1.6.2 Multi-Disciplinary Approach

The knowledge basis on which the future electricity grid is going to be built does not originate in Electrical Engineering alone. Yet, it needs to incorporate aspects of a very diverse set of disciplines including market-economics, business science, computer science, and control theory. The research described in this thesis focuses on a number of discipline combinations around smart electricity. Answering each of the research questions involved multi-disciplinary research.

Figure 1.2: Disciplines used to address the four research subquestions.
Figure 1.2 (A) depicts the disciplines involved in answering Q1. MBC itself is a technology that is positioned in the conjunction of Systems Control, Microeconomics and MAS, as the left-hand side of subfigure (A) shows. To assess the optimality property of MBC, theories from all these three disciplines were used together with existing MBC knowledge. The answer to Q1 provides knowledge regarding MBC itself and contributes to the theory of Systems Control and Multi-agent Systems, as indicated by the double-sided arrows. Addressing Q2 and Q3 involves theories from MAS, Power Systems Engineering and Power Systems Economics (see Figure 1.2, B). The results of this research are contributions to the Multi-agent Systems field. Further, the developed method for fast calculation of locational pricing in radial networks adds knowledge to the field of Power Systems Economics.

Finally, the work regarding bidding strategies of DER device agents, (C) in the figure, combines knowledge from MBC, Microeconomics and Power Systems Engineering. The results are fed back into the latter discipline. Already in this thesis, the outcomes of this theoretical work led to a set of practical design guidelines for DER agents.

1.6.3 Contributions to Theory

This thesis provides four concrete theoretical contributions in answer to the four research subquestions:

1. In answer to research question R1 regarding the Optimality of Market-based Control this thesis provides a formal mathematical proof that Market-based distributed control and centralised ‘omniscient’ optimisation are identical.

2. In answer to research question R2 regarding Network Feasible Solutions in Resource Allocation, this thesis introduces the concept of locational marginal pricing in passive flow-commodity networks to the discipline of Computer Science. This is done by formulating a general-applicable Multi-agent Systems framework for finding network-feasible solutions in commodity flow networks.

3. In answer to research question R3 regarding Locational Pricing in Radial Networks, this thesis presents a novel fast algorithm for locational pricing in non-cyclic passive flow networks that scales with the height of the tree spanning the network under consideration.

4. In answer to research question R4 regarding Bidding Strategies of DER Device Agents, this thesis shows the existence of a bid strategy spectrum for DER
units participating in a market-based control cluster. On one end of the spectrum, bidding strategies are based straightforwardly on true marginal cost or benefit. On the other spectrum end, optimal bidding strategies are dependent on the price dynamics in the electronic market context and the desired risk level.

These findings are elaborated in chapters 5, 6, 7, and 9, respectively. In each of these chapters, the relevance of these findings is discussed from different viewpoints.

1.7 Structure of this Thesis

Chapter 2 discusses the need for a smart electricity grid and usage of the internet as a metaphor for the smart electricity grid: the ‘Internet of Energy’. Chapter 3 explains why the world isn’t that simple. This is followed by the theoretical part (Part II) which opens with an overview of Market-based Control theory in Chapter 4. This is followed by a series of three chapters presenting theoretic results on optimality of Market-based Control (Chapter 5), network feasible solutions in resource allocation (Chapter 6) and locational pricing in radial networks (Chapter 7). The opening chapter of Part III, Innovation Concept, describes the design of the PowerMatcher, followed by a chapter on bidding strategies of individual DER device agents (Chapter 9). Chapter 10 makes a side step into smart grid applications in the business of trade & supply to provide the background basis for the related validation work later on. Part IV describes all activities performed to validate PowerMatcher’s design against the requirements defined above. Chapter 11 opens this part detailing the validation criteria and providing an overview of the field experiments and simulation studies used for the validation. This chapter also describes the validation against the Openness requirement. The subsequent four chapters cover trade & supply functionality (Chapter 12), active distribution functionality (Chapter 13), integration of large-scale wind generation (Chapter 14) and scalability (Chapter 15). These chapters present results of five different field experiments and four simulation studies. Chapter 16 concludes the thesis.

1.8 Publications

This thesis is based on and has led to the following list of international refereed publications:

- Koen Kok, Bart Roossien, Pamela MacDougall, Olaf van Pruissen, Gerben

Invited paper to the Systems Economics panel session.


Invited paper to the Dynamic Pricing panel session.


Part of overview article: “Agents in Industry: The Best from the AAMAS 2005 Industry Track”.


Awarded one of the best industry contributions to AAMAS 2005.


Hans Akkermans, Jos Schreinemakers, and Koen Kok. Emergence of control in a large-scale society of economic physical agents. In *AAMAS ’04: Proceedings*
1.8. Publications


1. Introduction


- Pamela MacDougall, Cor Warmer, and Koen Kok. Raising the Accommodation Ceiling for Wind Power by Intelligent Response of Demand and Distributed Generation, International Workshop on Large-Scale Integration of Wind Power into Power Systems, 2011.


1.9 Glossary of Important Terms and Abbreviations

**Accommodation Ceiling for Renewable Energy Sources (RES):** a technical maximum to the share of renewable energy resources in a given electricity system.

**Agent:** ▶ Software Agent
1. Introduction

**BRP:** ▷ Balance Responsible Party

**Balance Responsible Party (BRP):** party that is responsible for a balanced energy volume position on the wholesale market for electricity. A BRP plans and achieves a balance between energy volumes as traded on the wholesale market and as exchanged with the electricity network by the BRP itself or its contracted customers.

**Centralised Optimisation:** Optimisation procedure with a central computing system performing the optimisation, where all relevant local information needs to be communicated to the central system.

**CHP:** ▷ Combined Heat and Power.

**Co-generation:** ▷ Combined Heat and Power.

**Combined Heat and Power (CHP):** energy conversion unit to simultaneously produce useful heat and electric power.

**Competitive Market:** a market in which all market participants have limited market power and, thus, have no individual influence on the market price. In such a market, all participants are ▷ Price Takers.

**Consumer:** Party purchasing electricity for their own use. In a liberalised market, a consumer is free to purchase electricity from the supplier of their choice.

**Demand Response (DR):** the ability of electricity consuming installations and appliances to alter their operations in response to (price) signals from the energy markets or electricity network operators in (near-)real time. Demand response can be achieved through avoidance of electricity use and/or by shifting load to another time period.

**DER:** ▷ Distributed Energy Resources.

**DG:** ▷ Distributed Generation.

**Distributed Generation (DG):** the production of electricity by units connected directly to a (medium and low voltage) distribution network or to a customer site.

**Distributed Energy Resources (DER):** all devices and installations that are either ▷ Distributed Generators, ▷ Demand Response or ▷ Distributed Storage.

**Distributed Market-based Control:** a term used interchangeably with ▷ Market-based Control emphasising the distributed nature of MBC.
Distributed Storage: energy storage devices directly connected to the distribution network or to a customer site and that are able of bi-directional exchange of energy with that network.

Distribution Network: \(\triangleright\) Distribution System.

Distribution System: electricity network for delivery of electricity to customers via low voltage, medium voltage and (sometimes) high-voltage distribution systems.

Distribution System Operator (DSO): party responsible for operating the electricity distribution system in a given area and the connections to the transmission grid. It ensures the system’s long-term ability to meet reasonable demands for the distribution of electricity. To carry out these responsibilities, the DSO ensures the maintenance and, where necessary, the development of the distribution grid.

Dominant Strategy: the best strategy an agent can follow regardless of the strategies of the other (competing) agents, e.g. in a market system.

DR: \(\triangleright\) Demand Response.

DSO: \(\triangleright\) Distribution System Operator.

Electric Vehicle (EV): vehicle that uses one or more electric motors for propulsion. In the context of this document an EV is always a \(\triangleright\) Plug-in Electric Vehicle.

Electricity Supplier: party responsible for the sale of electricity to customers.

Electricity System: the collection of all systems and actors involved in electricity production, transport, trading and delivery.

Electronic Market: a fully automated market system, where \(\triangleright\) Software Agents are participants. Electronic Markets are a way to perform \(\triangleright\) Resource Allocation in a \(\triangleright\) Multi-agent System.

Emergence: the way complex systems, patterns and behaviours arise out of a multiplicity of relatively simple interactions.

End-customer: party that is either a traditional \(\triangleright\) Consumer or a \(\triangleright\) Prosumer.

Energy Supplier: in the context of this document equal to an \(\triangleright\) Electricity Supplier.

EV: \(\triangleright\) Electric Vehicle.
**Flow Commodity**: a physical stream that is infinitely divisible, such as electricity, gases and liquids.

**LMP**: ▷ Locational Marginal Pricing.

**Locational Marginal Pricing (LMP)**: a resource allocation method applied in electricity wholesale trading that is ▷ network-feasible with regard to the electricity transmission network.

**Market-based Control (MBC)**: a variant a ▷ Multi-agent System, where agents in a MAS are competing for (one or more) resources on an equilibrium market whilst performing a local control task (e.g., classical feedback control of a physical process) that needs those resources as an input.

**MAS**: ▷ Multi-agent System.

**MBC**: ▷ Market-based Control.

**Multi-agent System (MAS)**: a multi-agent system (MAS) is a computational system where software agents cooperate or compete with others to achieve individual or collective tasks.

**Network-feasibility**: a ▷ Resource Allocation outcome is network-feasible if it obeys the characteristics and constraints of flow network underlying the allocation problem.

**‘Omniscient’ Centralised Optimisation**: ▷ Centralised Optimisation.

**Passive flow network**: a networks for the transportation of a ▷ Flow Commodity in which the commodity flows via the path of least resistance, possibly via a number of parallel trajectories, from the point of injection to the point of subtraction without any external means to direct the flow through a particular path.

**PEV**: ▷ Plug-in Electric Vehicle.

**PHEV**: ▷ Plug-in Hybrid Electric Vehicle.

**PID Control**: proportional-integral-derivative (PID) controller, type of automatic feedback control used to control a specific parameter in a physical process. A PID controller calculates an “error” value as the difference between a measured process variable and a desired setpoint and calculates the control action by taking a weighted sum of the proportional, integral and derivative value of this error value. PID control is widely used in industry and in building comfort systems.
Plug-in Electric Vehicle (PEV): Electric Vehicle powered by electricity stored in an on-board battery and originally taken from the Distribution Network.

Plug-in Hybrid Electric Vehicle (PHEV): Plug-in Electric Vehicle that has an additional internal combustion engine used for direct propulsion or to generate electricity.

Price Taker: market participant that takes prices as externally given.

Producer: party generating electricity, including large power producers and Distributed Generation (DG) operators who produce electricity with small-scale distributed generation.

Prosumer: Consumer operating Distributed Generation at its premises and, therefore, delivers electricity back at the Distribution Network at certain times.

Renewable Energy Resources (RES): energy resources that are constantly and rapidly renewed by natural processes.

RES: Renewable Energy Resources.

Resource Allocation: the process of assigning resources in an economic way to applicants taking into account the availability of the resources and the preferences of the applicants.

Setpoint: the desired value for a controlled variable, set externally e.g. by the user, that an automatic control system will aim to reach.

Software Agent: a self-contained software program that acts as a representative of something or someone.

Supplier: Electricity Supplier.

Transmission System: the high-voltage interconnected electricity network for bulk and longer-distance transport of electricity, the transmission grid.

Transmission System Operator (TSO): party responsible for operating the Transmission System in a given area and, where applicable, its interconnections with other systems. It ensures the system’s long-term ability to meet reasonable demands for the transmission of electricity. To carry out these responsibilities, the TSO ensures the maintenance and, when necessary, the development of the transmission system.

Part I

Digital and Electrical (R)evolutions
Chapter 2

Why “Smart” Electricity Networks?

SYNOPSIS: Over the course of the 20th century, the electrical power systems of industrialised economies have become one of the most complex systems created by mankind. On the other hand, the technology of electricity transmission and distribution did not change significantly in the first century of its existence. For instance, the way the demand/supply balance is maintained in the grid did not change in this first century. Now, three major trends are forcing technological changes: (i) the Transition to Sustainability, (ii) the Electrification of Everything, and (iii) the Decentralisation of Generation. These trends call for a drastic change in the way electricity grids are operated. The end-customer side of the electricity system, currently mainly passive, needs to be actively involved in the system coordination. Coordination changes from centrally managing a few power plants to coordination among a huge number of smaller generators and responsive loads. Centralised control of such a complex system will rapidly reach the limits of scalability. An intelligent electricity grid, generally referred to as ‘the smart grid’, is needed. In visions on the future electricity infrastructure, the internet is used as a metaphor for a smart electricity grid: the internet of energy. The internet has a number of desirable properties one would like to achieve in the smart grid, such as self-organisation and self-healing in a network-of-networks topology. Plus the user-centric design that allows active participation from and collaboration with the end-user and the smart systems that surround her.

In the year 1888, Nikola Tesla presented his “New System of Alternate Current Motors and Transformers” [71], laying the foundation for today’s electricity infrastructure. Tesla’s ‘new system’ made it possible to transmit electrical power over long distances using a single infrastructure for all power delivery. Previously, generators needed to be located near their loads due to highly-inefficient transmission. Furthermore, multiple electric lines were needed for each application class (lighting, mechanical loads, etc) requiring different voltage levels. Over the course
2. Why “Smart” Electricity Networks?

Figure 2.1: Electricity turned from a novelty, into a convenience, into an advantage, and into an absolute necessity. Top: Nikola Tesla sitting in his laboratory in Colorado Springs circa 1900 (photo: Carl Willis and Marc Seifer), electric street light in Paris (source unknown). Bottom: Electricity as telecommunications enabler (photo: Ericsson), Premature baby in an incubator (photo: Thomas Hartwell).

of the 20th century, the electrical power systems of industrialised economies have become one of the most complex systems created by mankind. In the same period, “electricity has made a transition from a novelty, to a convenience, to an advantage, and finally to an absolute necessity” [4].

On the other hand, the technology of electricity transmission and distribution did not change significantly in the century after Tesla’s inventions. For instance, the way the demand/supply balance is maintained in the grid did not change in the first century of electrical power systems. Now, three major trends are forcing technological changes: (i) the Transition to Sustainability, (ii) the Electrification of Everything, and (iii) Decentralisation of Generation.
2.1 Transition to Sustainability

There are a number of reasons why we should reduce our fossil fuel dependency and substitute fossil fuels for sustainable energy sources. Three of these reasons are:

- **Climate Change and Other Environmental Concerns:** Fossil fuel usage is one of the biggest contributors to global warming due to greenhouse gas emissions. On top of that there are other environmental concerns including different kinds of pollution. Most fossil fuels are used as input for a combustion process which emit pollutants such as aerosols (e.g. soot), sulfur oxides and nitrogen oxides. At the same time, there are environmental and public health concerns associated with nuclear energy: the nuclear waste problem and contamination risks.

- **Depletion of Oil Reserves:** The world’s oil and gas reserves are finite. Although the known reserves increased over the last few decades, we no longer find large easy-exploitable reserves. Oil and gas production is moving to more remote and challenging areas. The recent disaster with BP’s Deepwater Horizon drilling rig, one of the few rigs designed for drilling in waters up to 2.4 km deep, is symptomatic for this trend. Another indicator is the Energy Return on Energy Investment (EROI) figure, which has been declining since the early days of large-scale oil production. The EROI is the number of barrels produced for each barrel (equivalent) used in extraction, transportation and refining. When large-scale oil production began around 1930, the EROI was approximately 100 [32]. The EROI of the world oil production in 2006 was estimated to be 18 [29]. As this decline indicates, it is becoming harder to extract oil from the remaining oil reservoirs. When the EROI drops below 1, oil production is no longer a net energy source. Some expect the world oil production to peak in the near future, entering a stage of unstoppable exponential decline afterwards. On the level of single fields and regions this has been observed already [11].

- **Diversification of energy sources:** The energy need of most western economies is largely imported from outside those economies. As energy demand continues to grow, this external dependence could grow steeply in the next decades. Moreover, a substantial portion of fossil fuels are imported from politically unstable regions. A higher portion of sustainable energy in the energy mix reduces this dependency.
2. Why “Smart” Electricity Networks?

2.1.1 Sustainable Electricity Sources

Worldwide, two thirds of the electricity is still produced from fossil fuels (natural gas, oil and coal) while approximately 15% originates from nuclear sources [21]. Of the sustainable options for electricity generation, hydro energy is currently most significant in the world wide power production (17%). Other sustainable energy sources (wind, solar, biomass, and geothermal) contribute for only about 2% to the world wide electricity generation.

Hydro Energy

As said, hydro energy is the only sustainable energy source with a substantial share in today’s electricity supply. Worldwide, approximately 17% of electricity is generated by hydro power generators. However, the growth potential for hydro power is limited. In many countries, the capacity increase is due to new small hydro power facilities, instead of large hydro power plants. These generators are connected to the medium voltage distribution grid.

Wind Energy

With an annual growth of 25 to 30%, wind energy is becoming the second largest sustainable energy source for power generation. In 2008, the worldwide installed capacity was 121 GW [55] (3.2% of total power generation capacity world wide). With an annual growth of 25%, the wind generation capacity in 2020 will be 1750 GW, i.e., a share of at least 25% of the world wide power generation capacity. In 2008, Germany had 24 GW wind generation capacity installed with a production share of 7.5%, while in Denmark the production share reached 20% in that year. Among the countries with the largest wind generation capacity in 2008 are the USA (25 GW), Spain (17 GW) and China (17 GW). Initially, wind turbines with a capacity up to 1000 kW (solitaire or in a wind park) were connected to the distribution grid. Today, however, very large wind turbines with a capacities up to 5 MW each are installed offshore in large wind parks. Since the total generation capacity of these wind parks is often more than 100 MW, they are connected to the transmission grid. At the same time there is a trend towards smaller wind turbines, i.e., turbines with a capacity of less than 50 kW. These turbines are situated near dwellings and connected to the low voltage distribution grid.

\(^1\)Sustainable Electricity Sources are also referred to as Renewable Energy Sources (RES). In the remainder of this text we will use these terms interchangeably.
2.1 Transition to Sustainability

Solar Energy

The most abundant sustainable energy source worldwide is solar energy. Solar energy can be converted to electricity through a thermal route using a steam cycle, as in conventional power plants, and through photovoltaic (PV) cells. The thermal technique is used in large plants (some hundreds of MW), so called concentrated solar power. Panels with PV cells can be used in urban areas, for instance, mounted to the roofs of buildings and dwellings, and connected to the low voltage distribution grid. The total installed capacity of PV world wide in 2007 was 9100 MWpeak of which 40% in Germany [80]. If the average annual growth factor of about 30% continues, the installed total world wide generation capacity in 2020 may become 275 GWpeak. Although this will be only a few percent of the total installed generation capacity world wide, locally the share of electricity production from PV may be much larger.

Biomass

Biomass (wood, organic waste, etc.) has been used for power generation on a limited scale for decades. There is a large growth potential for this sustainable energy source. Different kinds of biomass can be co-fired in coal fired power plants (10 to 30%). Biomass can also be converted into electricity in dedicated biomass plants. The size of these plants is smaller than conventional power plants, i.e., up to a few hundred MW. Another form of bioenergy is biogas. Biogas, from waste water treatment or anaerobic digestion of manure, can be used as a fuel for gas engines producing electrical power. These units have a capacity of some MWs and are connected to the medium voltage distribution grid.

Geothermal, Wave and Tidal Energy

Other sustainable energy sources are geothermal, wave and tidal energy. These energy sources are only available in specific regions, where they may be of significant importance. Geothermal electricity generation in Iceland is an example of this.

2.1.2 The Supply Intermittency Problem

The rising share of renewable energy sources in the energy mix is changing the characteristic of power generation. The primary energy sources of conventional electrical power generation are continuously available and can be adjusted according to the electricity demand. Electricity from the intermittent sustainable energy sources, such as wind and solar energy, can only be produced if the primary energy source
is available. With the growing share of these intermittent energy sources it becomes more difficult to follow the fluctuating electricity demand.

The total demand and supply in an electrical power network needs to be balanced on the timescale of seconds at all times. Without this balance, the system collapses resulting in a black-out. From the early days of electricity networks on, this balance is maintained by the supply side. From the point of view of system operations, the demand just occurs and the supply side is controlled to follow it.

Generally, electrical power is generated by a relatively small number of large power plants. Of these plants a substantial part is controllable, while the demand side remains largely outside the reach of systems control. Demand patterns are generally predictable with high accuracy, however an unpredictable fraction remains. With the introduction of renewable energy resources, both the uncontrollability and the unpredictability of the supply side increases. As a result, it will become harder to maintain the demand/supply balance in the electricity system.

### 2.1.3 The Traditional Reaction: Increase Regulation Capacity

The traditional reaction to unpredictability in the energy balance is adding controllability at the supply side. Following this, the introduction of renewables creates a need for more regulation capacity reserved from traditional power plants. At the same time, the share of power generated by these plants is inevitably going down. Figure 2.2 visualises profiles for demand and wind power in Denmark for 2008 and gives a projection for 2025. In 2025, 50% of the total demand is expected to be covered by wind power and wind power is expected to exceed total demand over 1,000 hours per year. At these moments, wind power needs to be exported or, when the same situation occurs in adjacent regions, it must be curtailed.

However, in periods of low demand and high wind, problems arise already before wind power exceeds demand. In off-peak periods, the demand is largely covered by base-load generators. Generally, these are non-regulating power plants running on low-cost fuels such as coal and uranium, or CHP plants providing heat to a residential area. The former are must-run generators for technical reasons, the latter because of the heat demand served. As it is impossible to stop these plants for a few hours, the electricity market price will fall until other demand or supply units respond. In these situations, the base-load generation is operated below its marginal price, and the same holds for the wind plants when the price becomes negative. In the wholesale market of Denmark and Northern Germany negative electricity prices have been permitted since 2009. When there are no other units responding before the price become negative, wind power production needs to be curtailed. However, at present there is only a small part of the installed capacity that is technically
2.1. Transition to Sustainability

Figure 2.2: Schematic of the current and future electricity demand and wind power generation in Denmark. Top: the situation in western Denmark in 2008: 20% of total demand covered by wind power; Wind power surpasses demand in 200 hours per annum. Bottom: the expected situation of the whole of Denmark in 2025: wind power production covers 50% of total demand; Wind power exceeds demand in more than 1,000 hours each year. (Drawing courtesy of Energinet.dk)
equipped to do so. A similar phenomenon happens in the opposite situation of high electricity demand and low winds. Enough generation capacity must be available to serve the demand peak in low-wind periods. The rise in wind power capacity lowers the number of occasions in which this peak capacity will be running. As the operational and capital expenditure does not change for these peak plants, peak prices will increase.

2.1.4 The Smart Reaction: Demand Response

The smart reaction is to involve the demand side in the control mechanisms of the electricity system. A response from the demand side to the momentary electricity price would bring relief in the problematic situations as described above. A demand side response to market prices increases the instantaneous demand when the electricity price falls, and vice versa.

Demand response is the ability of electricity consuming installations and appliances to alter their operations in response to (price) signals from the energy markets or electricity network operators in (near-)real time. Demand response can be achieved through avoidance of electricity use and/or by shifting load to another time period. At present, price elasticity of electricity demand is very low in the electricity markets. This means that the quantity in demand stays constant with a changing price. Higher elasticity in electricity demand would lead to:

1. A lower electricity price. During the California energy crisis, a demand reduction of 5% during the periods of the highest price peaks would have reduced these prices by 50% [38]. Similar, but less strong, effects would occur in normal market situations as Figure 2.3 shows.

2. Direct reduction of energy usage in the case demand response is achieved by avoidance of electricity use.

3. Lower usage of conventional peak power plants, which are generally inefficient and environmental unfriendly. For instance, for a number of European countries, a concentrated demand response effort of 20 to 75 hours per year leads to a 5% peak load reduction [27]. Not using the inefficient and highly polluting peak power plants means less CO₂ production and cleaner air.

4. Lower market power of producers. The number of market parties competing during peak load periods is generally low. This gives peak power producers high market power leading to price inflation. Price elasticity at the demand side will counteract this by increasing competitiveness, resulting in lower electricity prices as well.
Figure 2.3: Impacts of Demand Elasticity on Wholesale Price [38].

Typical large flexible loads include different types of industrial processes, e.g., groundwood plants and mechanical pulping plants, electrolysis, arc furnaces, rolling mills, grinding plants, extruders, gas compressors, etc. In the commercial and residential sectors, the largest electrical loads can be made responsive: space heating, space cooling, tap water heating, refrigeration, freezing, washing or drying. Figure 2.4 gives average appliance load profiles for a generic European home. For all listed appliances, operation can be shifted in time except for the water heater (when it is a water kettle rather than a hot tap water vessel) and the oven/stove.

Household appliances can be involved in demand response in two ways: smart timing of appliance cycles and/or interruptions of appliance cycles. In smart cycle timing, the start of an appliance cycle is chosen such that the complete cycle lies in a preferable time period. For appliances such as washing machines and tumble dryers, this may involve a user action to indicate the preferred maximal ending time of the cycle. For a refrigerator or a freezer this means that the cycle starts before the maximum allowable temperature is reached. In cycle interruption, the appliance cycle is interrupted for a certain period in time. For a washing machine or a tumble dryer, this means that during a running batch the heating process is interrupted for a certain time. For a refrigerator or a freezer this means that the cycle ends before the lower control temperature is reached.
2. Why “Smart” Electricity Networks?

- Figure 2.4: Appliance load profile of a generic European household averaged over a large number of households and over the period of one year [72].

- Table 2.1: Demand response by household appliances: flexibility boundaries (adapted from [72])

<table>
<thead>
<tr>
<th>Smart Timing of Appliance cycles</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing machine / dryer</td>
<td>Typical &lt; 3 hrs; Maximum 9 hrs</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>Typical &lt; 6 hrs; Maximum &gt; 12 hrs</td>
</tr>
<tr>
<td>Refrigerator / Freezer</td>
<td>Typical &lt; 30 mins</td>
</tr>
<tr>
<td>Other appliances</td>
<td>Typical &lt; 15 mins, ... 1 hr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interruptions of the Appliance cycle</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing machine</td>
<td>Typical &lt; 10 mins</td>
</tr>
<tr>
<td>Dryer</td>
<td>Typical &lt; 30 mins</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>Typical &lt; 10 mins</td>
</tr>
<tr>
<td>Refrigerator / Freezer</td>
<td>Typical &lt; 15 mins</td>
</tr>
<tr>
<td>Other appliances</td>
<td>Typical &lt; 15 mins</td>
</tr>
</tbody>
</table>

2.2 Electrification of Everything.

The world-wide electricity use has been ever-growing. Specifically, three major trends are accelerating its growth [4]:

- The rapid expansion of world population – the growth in the number of people needing electricity.
The “electrification of everything” – the growth in the number of devices that require electricity.

“Expectation inflation” – ‘the growth in the sense of entitlement that turns electrical conveniences into essentials demanded by all’.

The impact of these factors can be seen in Table 2.2 showing some related growth trends. The worldwide electric power generation is expected to grow 2.4% a year at least until 2030. In spite of this relatively small annual increase, world electricity generation would nearly double over the 2004 to 2030 period – from 16,424 billion kilowatt hours (kWh) in 2004 to 30,364 billion kWh by 2030 [20]. Only a small part of the world-wide growth in electricity usage takes place in newly electrified areas such as the county-side of upcoming economies such as India and Brazil. So, most of the growth takes place in the existing infrastructure.

Further, the transition to a more sustainable energy system is an additional accelerator of electrification. The route to governmental sustainability goals, such as the 2020 targets of the European Union, heavily depend on a switch to electricity for a number of energy intensive activities. An example is the transport sector. Creating a more efficient transport sector, largely fuelled by green energy, involves electrification of the contingent of smaller vehicles: passenger cars, delivery vans, etc. Electrification of these types of vehicles results in a better well-to-wheel energy efficiency even when the needed electricity is generated from fossil fuels. Further, it opens the possibility of CO\textsubscript{2}-free transportation if the vehicles are charged with 100% green electricity. As may be clear, a major increase in energy efficiency and sustainable energy use depends on higher electricity usage in this case.

Another example is the introduction of heat pumps for space heating. Where a heat pump replaces a resistive heater or a gas boiler, primary energy is saved. In regions where homes and utility buildings are predominantly heated by gas boilers, this efficiency gain involves a switch in energy carrier from gas to electricity.

### 2.2.1 Ageing Networks Operated to Their Limits

The electricity infrastructures of the western economies have largely been built during the 1960ies and the 1970ies. So, a huge number of grid components such as cables, lines and transformers have reached the end of their economic and technical lifetime. However, to a great extent, the technical lifespan of grid components is dependent on their usage history. As the ageing process is mainly driven by thermal stress caused by higher power flows, grid components are ageing faster when frequently operated close to, or exceeding, their nominal power load. If never loaded more than 70 to 80% of the maximum allowable load, grid components have virtu-
2. Why “Smart” Electricity Networks?

Table 2.2: Examples of Electricity Growth Trends, adapted from [4]

<table>
<thead>
<tr>
<th>Category</th>
<th>1950</th>
<th>2000</th>
<th>2050 (est.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Population</td>
<td>2.6B</td>
<td>6.2B</td>
<td>8.3B</td>
</tr>
<tr>
<td>Electricity as % of total energy</td>
<td>10.4%</td>
<td>25.3%</td>
<td>33%</td>
</tr>
<tr>
<td>Televisions</td>
<td>0.6B</td>
<td>1.4B</td>
<td>2B</td>
</tr>
<tr>
<td>Personal Computers</td>
<td>0</td>
<td>500M to 1B</td>
<td>6B to 8B</td>
</tr>
<tr>
<td>Cell Phone Connections* (USA)</td>
<td>0</td>
<td>0.8B</td>
<td>5B</td>
</tr>
<tr>
<td>Electric hybrid vehicles</td>
<td>0</td>
<td>55,800</td>
<td>3M</td>
</tr>
</tbody>
</table>

B = billion; M = million.
*Including machine to machine connections, e.g.: telemetering and telecontrol.

ally an infinite lifespan. So, the growing use of electricity is a threat to our ageing electricity infrastructure. Without action, overloading of old cables and transformers will occur more and more frequently resulting in a rising system downtime.

2.2.2 The Traditional Reaction: Grid Reinforcements

The traditional reaction to capacity problems in the electricity grid is to reinforce it, i.e. making investments in a higher network capacity. For about a century, the only answer to a grid load increase has been adding more copper, iron and aluminium to carry the increased load.

Figure 2.5 gives an example for an increasing number of plug-in electrical vehicles (PEVs) in a residential area. A PEV charging its battery is a high load for the electricity network, even when it is using a 1 kW slow charger to charge its battery in around 5 hours. The synchronicity in power uptake from PEVs is much higher than that of other appliances. In a commuter’s area most of the cars will be connected to the electricity grid just after the traffic rush hour, contributing to the rush hour in the electricity network. When, in a certain residential area, owning a PEV becomes fashionable, the operator of the distribution network has barely enough time to dig in the required extra cables and install additional transformers.

2.2.3 The Smart Reaction: Active Distribution Management

The smart alternative is using the potential flexibility in local demand and generation to cope with these grid overload situations. In doing so, a step is made from the current passive management of the distribution networks to an active management. Then, not only the network itself is considered, but rather the system as a
2.2. Electrification of Everything.

Figure 2.5: The introduction of Plug-in Electrical Vehicles (PEVs) in an existing grid. Top: a typical mid-voltage load profile for a residential area having a demand peak at the beginning of the evening. There is room for a 5% penetration of PEVs. In the worst case, these cars are used for commuting and connect just before the evening peak. Bottom: Same situation with 25% PEV penetration. Grid reinforcement is needed. (Courtesy of the ITM project.)

whole, including connected systems at end-customer’s premises. For the plug-in electrical vehicles example, this solution is depicted in Figure 2.6. Plug-in Electrical Vehicles do have a huge flexibility potential, as most car owners need to use their car not earlier than the next morning. A collective intelligent system can assure the user’s mobility preferences are met while the electricity grid’s loading remains
2. Why “Smart” Electricity Networks?

Figure 2.6: Controlled charging of Plug-in Electrical Vehicles avoiding network overload as an alternative for network reinforcements as depicted in Figure 2.6.

within limits. The user’s preferences may include a fully charged car battery by the next morning, while the car must be ready within a short time frame for a short unexpected drive, e.g. to the local hospital. Note that such a system should not be limited to one class of loads. A proper response of other loads and generators in the local network brings relief to the overloaded network.

2.3 Decentralisation of Generation

Another ongoing change in the electricity sector is a decentralisation of generation. A growing share of the generation capacity is located in the distribution part of the physical infrastructure. This trend breaks with the traditional central plant model for electricity generation and delivery. For this type of generation the term *distributed generation* (DG) is used: the production of electricity by units connected to the distribution network or to a customer site.

Thus, DG units supply their generated power to the distribution network either directly or indirectly via a customer’s private network (i.e., the network on the end-customer’s premises, behind the electricity meter). Consequently, the generation capacities of individual DG units are small as compared to central generation units which are directly connected to the transmission network. On the other hand, their numbers are much higher than central generation and their growth is expected to continue [37].
2.3. Decentralisation of Generation

2.3.1 Distributed Generation: Types and Drivers

Sustainable or renewable energy sources (RES) connected to the distribution grid fall under the definition of DG. However not all RES are DG, as large-scale renewables, e.g., off-shore wind electricity generation, are connected to the transmission network. The same holds for Combined Heat and Power production (CHP). A CHP unit is an installation for generating both electricity and useable heat simultaneously. Dependent of their size, CHP units are either connected to the distribution grid (and, thus, fall under the definition of DG) or to the transmission grid. Table 2.3 categorises different forms of CHP and RES into either large-scale generation or distributed generation.

<table>
<thead>
<tr>
<th>Combined Heat and Power</th>
<th>Renewable Energy Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-scale Generation</td>
<td>- Large district heating*</td>
</tr>
<tr>
<td></td>
<td>- Large industrial CHP</td>
</tr>
<tr>
<td></td>
<td>- Large hydro**</td>
</tr>
<tr>
<td></td>
<td>- Off-shore wind</td>
</tr>
<tr>
<td></td>
<td>- Co-firing biomass in coal power plants</td>
</tr>
<tr>
<td></td>
<td>- Geothermal energy</td>
</tr>
<tr>
<td></td>
<td>- Concentrated solar power</td>
</tr>
<tr>
<td>Distributed Generation</td>
<td>- Medium district heating</td>
</tr>
<tr>
<td></td>
<td>- Medium industrial CHP</td>
</tr>
<tr>
<td></td>
<td>- Utility building CHP</td>
</tr>
<tr>
<td></td>
<td>- Micro CHP</td>
</tr>
<tr>
<td></td>
<td>- Medium and small hydro</td>
</tr>
<tr>
<td></td>
<td>- On-shore wind</td>
</tr>
<tr>
<td></td>
<td>- Tidal energy</td>
</tr>
<tr>
<td></td>
<td>- Biomass and waste incineration</td>
</tr>
<tr>
<td></td>
<td>- Biomass and waste gasification</td>
</tr>
<tr>
<td></td>
<td>- PV solar energy</td>
</tr>
</tbody>
</table>

* Typically > 50MW_e; ** Typically > 10MW_e

There are a number of drivers behind the growing penetration of DG (adapted and augmented from [22]):

- **Environmental concerns; Depletion of Oil Reserves; Diversification of energy sources.** All three as described in Section 2.1.1.

- **Deregulation of the electricity market.** As a result of the deregulation, the long-term prospects for large-scale investments in power generation have become less apparent. Therefore, a shift of interest of investors from large-scale power generation plants to medium and small-sized generation can be seen. Investments in DG are lower and typically have shorter payback periods than those of the more traditional central power plants. Capital exposure and risk is reduced and unnecessary capital expenditure can be avoided by matching the capacity increase with local demand growth.
2. Why “Smart” Electricity Networks?

- **Energy autonomy.** A sufficient amount of producing capacity situated in a local electricity network opens the possibility of intentional islanding. Intentional islanding is the transition of a sub-network to stand-alone operation during abnormal conditions on the externally connected network, such as outages or instabilities, e.g., during a technical emergency. In this manner, autonomy can be achieved on different scales, from single buildings to wide-area subsystems.

- **Energy Efficiency (i).** In general, distributed generation reduces energy transmission losses. Estimates of power lost in long-range transmission and distribution systems of western economies are of the order of 7%. By producing electricity in the vicinity of a consumption area, transport losses are avoided. There is, however, a concern that in cases where the local production outgrows the local consumption the transmission losses start rising again. But in the greater part of the world’s distribution network we are far from reaching that point.

- **Energy Efficiency (ii).** Heat production out of natural gas can reach higher efficiency rates by using combined heat-power generation (CHP) instead of traditional furnace burners. CHP is a growing category of distributed generation, especially in regions where natural gas is used for heating. In Northern Europe, for instance, CHP is already commonly used in heating of large buildings, green houses and residential areas. The use of micro-CHP for domestic heating in single dwellings is also expected to breakthrough in the coming few years.

2.3.2 Control Paradigm Mismatch

Decentralisation of electricity generation is changing the characteristics of power generation in three aspects:

- **Intermittency:** The power production of most types of DG is intermittent in nature. In section 2.1.2, we already discussed the intermittent nature of renewables. Additionally, CHP units operated to follow heat demand are intermittent in nature as well. As stated before, with the growing share of these intermittent energy sources it becomes more difficult to follow the fluctuating electricity demand.

- **Cardinality:** As a result of generation decentralisation, the number of electricity production units is growing rapidly while individual capacities are decreasing.
2.3. Decentralisation of Generation

**Location:** The location of power generation relative to the load centers is changing. Due to decentralisation, the distance between generation units in the grid relative to the location of electricity consumption is becoming smaller. On the other hand, central renewable generation is moving further away from the load centers as large-scale wind farms are being built off-shore and large-scale solar power plants in desert areas.

Distributed generation does not fit into the standard paradigm of centralised control of a relatively small number big central power plants. As distributed generation gradually levels with central generation, the centralised control paradigm will no longer suffice. The number of system components actively involved in the coordination task will be huge. Centralised control of such a complex system will reach the limits of scalability, computational complexity and communication overhead. The need to involve demand response in the coordination task, as discussed in 2.1.4, only adds to this problem.

2.3.3 The Traditional Reaction: “Fit and Forget”

The traditional reaction to DG is accommodation in the existing electricity system, i.e., network and markets. This is the “fit and forget” approach. Distributed units are running free, beyond the control of the grid operator or the market-party to which the generated energy is delivered. The individual capacity of each separate DG unit is too small to be active on the wholesale market for electricity. Therefore, electricity supply companies treat DG as being negative demand: it is non-controllable and to a certain extend forecastable. As with renewable energy sources, a growth in DG decreases controllability and predictability in the electricity system. Again, the traditional reaction is to increase the capacity of regulating plants, while the total generation share of central generators goes down.

2.3.4 The Smart Reaction: Distributed Coordination

In the smart reaction, distributed generation, demand response, and future options for electricity storage, are integrated in the coordination mechanisms of the electricity system. As argued above, this cannot be done by following the traditional paradigm of centralised control. Thus, a new paradigm for coordination tasks in electrical power systems is needed. The new coordination mechanism is likely based on the state of the art in information and communication technology (ICT).

Before we look into the requirements of the needed ICT system, we take a closer look into the systems that need to play a role in the coordination task at hand. From the viewpoint of controllability, DG and DR are equivalent: increasing production
has the same effect on the supply and demand balance as decreasing consumption, and vice versa. Due to this, demand response can be treated as a resource. The same holds for distribution network connected electricity storage. Due to this common nature, the overarching term Distributed Energy Resources (DER) is used to refer to this threesome: DG, DR and storage. Responsive electricity consumption is regarded as an energy resource as the main resource is flexibility in operation: the ability to shift electricity production or consumption in time.

The high-level requirements of the coordination system that integrates DER in power systems operations and markets include:

- **Scalability**: A huge number of systems spread-out over a vast area will have to be involved in the coordination task. Especially on the level of the distribution grids, huge growth in the number of components actively involved in the coordination is expected. The coordination mechanism must be able to accommodate this growth.

- **Openness**: The information system architecture must be open: individual DER units can connect and disconnect at will and future types of DER—with their specific operational characteristics—need to be able to connect without changing the implementation of the system as a whole. Therefore, communication between system parts must be uniform and stripped from all information specific to the local situation.

- **Multi-level Stakes**: The information system must facilitate a multi-actor interaction and balance the stakes on the global level (i.e., the aggregated behaviour: reaction to energy market situation and/or network operator needs) and on the local level (i.e. DER operational goals).

- **Autonomy and Privacy**: In most cases, different system parts are owned or operated by different legal persons, so the coordination mechanism must be suitable to work over boundaries of ownership. Accordingly, the power to make decisions on local issues must stay with each individual local actor.

These requirements ask for a distributed system, also referred to as a multi-agent system (MAS) for a number of reasons:

- In multi-agent systems a large number of actors are able to interact, in competition or in cooperation. Local software agents focus on the interests of local sub-systems and influence the whole system via negotiations with other software agents. While the complexity of an individual agent can be low, the intelligence level of the global system is high.
2.4 Smart Grid Visions

- Multi-agent systems implement distributed decision-making systems in an open, flexible and extensible way. Communications between actors can be minimised to a generic and uniform information exchange.

- By combining multi-agent systems with micro-economic principles, coordination using economic parameters becomes possible. This opens the possibility for the distributed coordination process to exceed boundaries of ownership. The local agent can be adjusted by the local stakeholder, and does not fall under the rules and conditions of a central authority. Further, a Pareto efficient system emerges, i.e. a system that optimises on a global level, while at the local level the interests of all individual actors are optimally balanced against each other.

2.4 Smart Grid Visions

So, the electricity infrastructure and its related market mechanisms must change into an intelligent infrastructure, a smart grid. This smart grid must be able to cope with increasing intermittency in electricity production and handle a fast growing electricity demand in an aging infrastructure. Further, it must be robust for a high number of micro-generators in the distribution networks. To do so, this smart grid must be able to:

1. Put the user in the center. The user, and the smart electricity consuming or producing devices around her, must be enabled to interact with the electricity system. What used to be called “the demand side” needs to be integrated in the network operation and energy markets. For a smart house, a smart office building or a smart industrial site, this means the ability to take part in scenarios such as: “give precedence to locally produced power”, “give precedence to green power from elsewhere” (e.g. off-shore wind), or “reduce consumption and/or increase production to relief the local network.”

2. Extend active network management to the distribution part of the physical infrastructure

3. Introduce a control paradigm robust for a high number of small interacting DER units, distributed generation, demand response and electricity storage. The new control paradigm must be able to aim for different, sometimes conflicting, goals of stakeholders in energy trade and supply on one hand and in network operations on the other.
2. Why “Smart” Electricity Networks?

Over the last few years, different public authorities have broadly cooperated with industry, R&D institutes and academia to formulate a vision on the future of the electricity infrastructure. To say something about the technology core needed for such a Smart Grid, it is interesting to look into these vision documents. In the next three sections we look into the vision of (i) the USA-based GridWise Alliance, (ii) the European Technology Platform SmartGrids, and (iii) the German E-Energy initiative.

2.4.1 GridWise vision

GridWise is a program initiated by the U.S. Department of Energy focused on the modernisation of the U.S. electricity infrastructure using information technology. Associated with the program is the GridWise Alliance, founded in 2003, a consortium of public and private stakeholders representing a broad range of the energy supply chain from utilities to large tech companies to academia to venture capitalists to emerging tech companies.

The next two subsections, quoting the alliance’s web site [31], describe its high-level vision on smart grids:

Defining a Smart Grid Future

“The electricity that powers everything from a single appliance to our vast, intricate national defense system is such an integral part of our daily lives that we rarely think about where it’s made or how it’s delivered. Today, it’s primarily generated at large, central fossil fuel plants, hydroelectric dams, and nuclear facilities. It then travels many hundreds of miles along an enormous, complex network of transmission and distribution lines and devices that crisscrosses our national landscape—called simply the grid. Tomorrow, we’ll need an even more complex and sophisticated infrastructure that will continue to power our digital economy but in a cleaner, more reliable, and more affordable way—a smart grid.

Stimulating the economic vitality of our nation and ensuring the continued safety and security of its citizens are compelling reasons to take a fresh look at how we operate our existing power system, as well as how we design and build new infrastructure components. To meet this massive, urgent challenge, we’ll need to tap the same ingenuity and innovation we channelled into building our existing grid many years ago. Fortunately, we’ve already made similar changes in other industries, using similar technologies and reaping similar benefits. Now, we must transform another industry—the electrical power generation and distribution system.”
Enter a Smart Grid

“To unlock the potential of a smart grid, we can choose from a multitude of hardware, software, and telecommunications tools. These technologies range from complex sensors that yield new and unique data and are woven into all aspects of the grid, to elegant user interfaces that give operators and consumers alike simple tools for making better decisions.

Specifically, a smart grid will:

- **Reduce peak demand by actively managing consumer demand:** The percentage of available appliances and equipment that can respond to both consumer and utility operator priorities continues to grow. The ability to manage power requirements in both directions—to the utility as well as from the utility—will reduce the need for power, especially during high-use periods like hot summer afternoons when the cost of producing and delivering power is extremely high.

- **Balance consumer reliability and power quality needs:** Although some uses of electricity require near perfect reliability and quality, others are almost insensitive to these needs. A smart grid will be able to distinguish the difference and adjust power reliability and quality accordingly at an appropriate cost.

- **Mine energy efficiency opportunities proactively:** A smart grid will furnish consumers and utilities with accurate, timely, and detailed information about energy use. Armed with this information, we can identify ways to reduce energy consumption with no impact on our safety, comfort, and security. We all gain a new level of understanding and insight into how our energy use affects our environment, along with the national economy and our own pocketbooks.

- **Improve overall operational efficiency:** A smart grid will become increasingly automated, and smart sensors and controls will be integral to its design and operation. Utility operators will be able to easily identify, diagnose, and correct problems, and will even have the capabilities to anticipate problems before they happen.

- ** Seamlessly integrate all clean energy technologies:** Electric vehicles, rooftop solar systems, wind farms, and storage devices will become a fundamental part of the grid. These clean energy technologies will generate not only energy and power, but serve many other vital functions as well. Although transparent to consumers and utilities, these technologies will bring vast value to society and our economy, and go a long way toward meeting our nations short- and long-term goals.
2. Why “Smart” Electricity Networks?

By smoothly engaging consumers and purposefully empowering utilities, a smart grid clearly holds the key to a healthy economy, a clean environment and a prosperous future."

2.4.2 European SmartGrids Vision

In 2005, the European Commission started the European Technology Platform (ETP) SmartGrids, representing all stakeholders in the electricity sector. The first aim of the platform was to formulate and promote a vision for the development of European electricity networks looking towards 2020 and beyond. In the next subsections, we quote sections of the platform’s vision document [26] describing the interaction of different subsystems in the future grid.

Shaping up for the future

“Throughout the development of the new grids, communication at every level is essential. Effective dialogue between stakeholders will ensure that relevant information influences the system design. The latest technologies will be incorporated into the network and the approach will remain flexible to accommodate further developments. Once the networks are up and running, two-way flows will exist between provider and user. This type of exchange has characterised the popularity of the internet.

Many factors will shape future electricity networks and the actions and decisions taken today will influence longer-term outcomes. It is therefore important to recog-
nise that a flexible approach and regular interaction with stakeholders is required to respond to future challenges and opportunities.

Future work should adopt a techno-economic system approach for a trans-European network. This calls for the development of:

- distribution grids accessible to distributed generation and renewable energy sources, either self-dispatched or dispatched by local distribution system operators;
- distribution grids enabling local energy demand management to interact with end users through smart metering systems;
- distribution grids that facilitate dynamic control techniques and high levels of power security, quality, reliability and availability;
- transmission grids with minimum negative side-effects on the environment and the society;
- secure transmission grids that can comply with different forms of generation including large and small, controllable and non-controllable, variable and intermittent sources;
- transmission grids that can accommodate central and non-central, multi-product markets”.

Internet-style inspiration

“One possible model for the electricity network of the future would be analogous to the internet, in the sense that decision-making is distributed and that flows are bidirectional. Applying this concept to the electricity networks would lead to control is being distributed across nodes spread throughout the system. Not only could the supplier of power for a given consumer vary from one time period to the next but also the network use could vary as the network self-determines its configuration.

Such a system would require advanced hardware and management protocols for connections, whether for suppliers of power, for consumers or for network operators. The market structures and regulatory mechanisms need to be in place to provide the necessary incentives.

This type of network would ease the participation of DG, RES, DSM and flexible energy storage and would also create opportunities for novel types of equipment and services, all of which would need to respect the protocols and standards adopted. New business and trading opportunities can be envisaged- based on new
power sources, new power consumption habits and new regulation, all of which favour cleaner and more efficient generation and consumption as well as the development of a flexible, multi-user connected network which establishes power and communication transfer possibilities among all players”.

New networks, new systems

“The realisation of such active distribution network technologies will allow radically new system concepts to be implemented. The two proposed examples are:

- Microgrids
- Virtual utilities

These are not fixed, discrete or unique solutions.

**Microgrids** are generally defined as low voltage networks with DG sources, together with local storage devices and controllable loads (e.g. water heaters and air conditioning). They have a total installed capacity in the range of between a few hundred kilowatts and a couple of megawatts. The unique feature of microgrids is that, although they operate mostly connected to the distribution network, they can be automatically transferred to islanded mode, in case of faults in the upstream network and can be resynchronised after restoration of the upstream network voltage.
2.4. Smart Grid Visions

2.4.3 Germany: E-Energy

In Germany, the Federal Ministry of Economics and Technology (BMWi) started a technology funding initiative called “E-Energy: ICT-based energy system of the future”. Since December 2008, six consortiums have been developing and testing core elements for an “Internet of Energy” in six independent model regions.

“The Internet of Energy interconnects the numerous stakeholders in the energy system, ranging from power generation and transportation companies to stakeholders in power distribution and consumption. Every appliance or unit that is connected to the power grid is added to the control system like a plug-and-play application. This results in an integrated data and power network featuring completely new structures and functions. Instead of the familiar electricity meter, this new sys-

**Figure 2.9:** “The Internet of Energy combines smart power generation, smart power grids, smart storage and smart consumption” [16].
tem uses digital measuring instruments known as ‘smart meters’. In the Internet of Energy, these meters no longer simply measure electricity consumption or the power fed into the grid for the purpose of invoicing, but also supply the intelligent E-Energy network nodes with the information they need to be able to automatically harmonise power generation, grid load and electricity consumption to a large extent. This helps reduce the demand for expensive electricity at peak times, ease the load on the electricity grids and maintain supply security.

The E-Energy network uses predictive systems that forecast the consumption and generation of electricity depending on weather conditions. Based on this information, pricing signals are then sent to ICT gateways in households and industry, on the one hand, and to the control systems of energy producers on the other hand. The electricity producers and consumers will behave in line with market conditions and react accordingly. Depending on settings previously made, the ICT gateways can coordinate when consumer loads are switched on, loop in small cogeneration heat and power plants or feed in electricity from storage units. The result is a new electronic ‘energy marketplace’ where customers can play a more active role as mini providers of electricity they generate themselves (through solar panels, for example), and where electricity is no longer simply traded. Rather, we will witness completely new services in this marketplace, such as ‘allow delayed switch-on’, ‘feed into grid in event of demand peaks’ or ‘only use in event of sunshine or high winds’.

In the E-Energy marketplace, power producers and consumers can also be rewarded for contributing to the secure, cost-effective and environmentally friendly provision of electricity. This, in turn, also helps reduce dependence on imported energy” [16].

2.5 The Internet as Metaphor for a Smart Grid

2.5.1 Desirable Properties of the Internet

The internet is used more and more as a metaphor for a smart electricity grid. Two of the three governmental policy visions described above explicitly mention the internet of energy. The internet has some interesting properties desirable in the smart electricity grid. To name a few:

- **User interaction and collaboration**: The smart electricity grid does not just connect consumer’s installations and generation units to a point of common coupling in the public network. The smart grid rather integrates them in the electricity system, it gets end-customers and their installations actively involved in the management of the electricity infrastructure. This is a strong analogy with the Web 2.0, where the user is in the center, in full interaction
and collaboration with others.

- **Network of networks:** The two-way power flows in the future electricity networks resemble the two-way data flows in the internet. With the introduction of distributed generation, power can be generated and consumed everywhere in the network. This allows for an internet-like topology of a network of networks. Local network segments provide their own supply with limited exchange of energy with the rest of the network. Then, comparable to the internet, network-operational decisions are taken on the local level.

- **Emergent self-organisation:** The internet is a complex network, a large collection of interconnected nodes exhibiting overall behaviour that cannot be explained by looking into the behaviour of individual nodes or links [67]. In complex networks, properties such as self-organisational and self-healing behaviours are emergent. Emergence is the way complex systems, patterns and behaviours arise out of a multiplicity of relatively simple interactions. The current electricity network is lacking these properties.

### 2.5.2 Emergence of Self-healing Behaviour

It is interesting to look a little deeper into the emergence of self-healing behaviour in the internet. A strong example of the self-healing capability of the internet, as described in [67], was seen after the suicide attack on the World Trade Center (WTC) in New York City on the 11th of September 2001. The WTC complex formed a major connection node in the internet, as three transatlantic data cables connected to the continental data network there. This connection center was located in WTC building 7, which was destroyed by debris from the collapsing towers. Further, in the vicinity of the WTC complex, an internet switching station and two internet exchange points were damaged. Since long before the attacks, Salus and Quarterman have been measuring the internet’s performance by monitoring the reachability of more than 1200 internet servers in the world [62]. At regular intervals, they send off ‘ping’ messages to these servers and record whether an acknowledgement message is received back. A reachability of 100% means that all servers in their list responded. A lower reachability means that some servers could not be reached, either because of these servers were down or due to a disrupted link in the communications path. Just after the attacks the reachability dropped by almost 9%. However, within half an hour, reachability rose again by 6%.

"This example illustrates two important properties of the internet. First, even when disrupting what would seem as a vital location in the Internet, such a disruption barely affects the overall communication capabilities of the network. Second,
2. Why “Smart” Electricity Networks?

The Internet has apparently been designed in such a way that it takes almost no time to recover from a big disaster. This recovery is even more remarkable when you consider that no manual repairs had even started, but also that no designer had ever really anticipated such attacks (although robustness was definitely a design criterion for the Internet). The Internet demonstrated emergent self-healing behaviour” [67].

2.6 An Internet of Energy?

The internet has been built with two assumptions in mind: scarcity of bandwidth, and fragility of communications channels. Being dependent on telephone-line-based data connections, the engineering of the early internet avoided reliance on anything beyond the own control. This put an emphasis on local management to cope with uncertainty of connections. “Every engineering decision was based on occasional connections, local management, and the knowledge that it was risky to rely on anything that was not controlled in-house”, according to blogger Toby Considine [15].

The smart electricity grid needs to cope with uncertainty and variations in production from wind and solar, and with increasingly unreliable and overloaded lines and cables. The engineering of the future electricity grid needs to prepare for intermittent energy sources distributed unevenly over an infrastructure of inadequate and expensive transmission and distribution connections. Considine again: “[w]e will have to make our energy decisions assuming occasional connections, local management of use, and the certain knowledge that it is risky to rely on anything that we do not manage in-house.”

Distributed decision making, a user-centric design that integrates end-user systems instead of just connecting them, emergence of self-organisation and self-healing properties. All properties of the internet as we know it and that would be desirable for the future electricity system. In the previous chapter, we defined six main requirements to the smart grid coordination mechanism: Openness, Privacy Protection, Scalability, Trade & Supply Functionality, Active Distribution Functionality and Integration of Renewable Energy Resources. Can these be realised by one-on-one mimicking of what happens in the internet? Is building a smart grid building an Internet of Energy? Certainly, the design approach as outlined by Considine and the high-level visions we have seen will be vital for a success. However, things aren’t that simple, the analogy does not hold while one goes down into the technical characteristics of the electricity infrastructure. Electricity ≠ Information, as we will see in the next chapter.
Chapter 3

Electricity ≠ Information

SYNOPSIS: Thus, the internet is a useful metaphor for the future intelligent electricity network: the internet of energy. However, the analogy does not hold when one goes down to the technical characteristics below the general vision. As electricity is not information, electricity networks are fundamentally different from computer networks. Electricity is continuous matter, distributed using a passive infrastructure that lacks storage capacity. This is, for instance, reflected in the mathematics used to model the two kinds of networks, but also in the way electrical power systems are organised. The operation of the physical subsystem is separated from that of the commodity subsystem, in which the energy product is traded. Interactions between the two sub-systems are limited, yet crucial.

In order to integrate end-customer side of the electricity system, currently only passively connected, four main approaches can be followed: top-down switching, centralised optimisation, price reaction and market integration. We argue that the market integration approach take precedence over the other three, for a number of reasons, and implements a truly intelligent system.

Thus, the internet is used as a metaphor for the intelligent electricity network, the internet of energy. This is a strong image when it comes to explaining the desired properties of the future smart grid: coordination by decentralised decision making, user participation, self-organising and self-healing behaviours, etc. The internet is a useful example of a well-performing complex network that demonstrates the desired features and is familiar to everyone. However, when one goes down to the technical characteristics below the general vision, the analogy does not hold anymore. As electricity is not information, electricity networks are different than computer networks. In this chapter we will discuss how.
3. Why is Electricity Different?

There are three main reasons why flow of electricity through a network is fundamentally different from information flowing through the internet. Firstly, the most important difference between information and electricity is the continuous nature of the latter. Electricity is a flow commodity, an infinitely divisible physical stream. Other examples of flow commodities are flows of gas or liquid such as natural gas, industrially-applied steam and water for heat transport or drinking. Secondly, electricity is mainly transported using passive networks, in which there is no way of directing the flow to follow a particular pathway through the network. Instead, the commodity follows the path of least resistance, possibly using a number of parallel trajectories. And thirdly, there is no way electricity can be stored in high quantities efficiently, neither in the network itself or at network nodes. These three differences make the electricity infrastructure fundamentally different from data networks, but also from those transporting discrete physical objects such as vehicles. In the following subsections, we will look into this further.

3.1.1 Passive Flow Networks

There are some special behaviours attached to transporting a continuous flow in a passive network:

- **Loop Flows:** In a passive network, a flow from a source to a sink will follow parallel trajectories whenever this is possible. The path with the lowest total flow resistance (i.e. the highest conductivity) will carry the main part of the flow. However, pathways of higher resistance will be loaded proportionally to their conductivity. This phenomenon is known as a loop flow. Figure 3.1 gives an example of this.

  This behaviour has great implications for network planning and day-to-day operations of the electricity grid. To illustrate this, consider the lines in the figure and suppose each of the seven lines has a maximum capacity of 73. Then, although the total sum of line capacity between nodes $P$ and $C$ would be 146, the transport capacity from $P$ to $C$ would be limited to 100.

  In December 2004 and January 2005, such a loop flow nearly caused a blackout in Northwestern Europe. An unexpected surplus of wind energy in the North of Germany flew to the South of that country via the neighbouring grids of The Netherlands and Belgium. The Dutch operator of the transmission network needed to take special measures to ensure the stability of the network [69].
3.1. Why is Electricity Different?

**Figure 3.1:** Power loop flows in an electrical network. *Left:* simple example electricity network with six nodes and seven lines. At node P electricity is produced, at node C it is consumed, while the other nodes are passive. *Right:* the physical flows resulting from producing 100 units at node P while consuming the same amount at node C. The (resistance) characteristics of all seven lines have been chosen equal, while, for the sake of the example, transport losses have been neglected.

- **Transport paths not following contract paths:** In directed networks, such as those of road transportation and packet-switched information flows, the transport path follows the contract path quite closely. In the field of logistics, for instance, a specific post packet shipped to a particular destination will, if all goes well, arrive at that location. In contrast, in electricity, the contract path does not dictate the actual flow of the commodity. Figure 3.2 gives an example of this in a simple example electricity network with two producers (P1, P2) and two consumers (C1, C2). A situation with two contract paths is shown in the middle of the figure: P1 sells an amount of 5 to C2, while P2 sells 4 to C1. The resulting physical flows are depicted in the right-hand side of the figure. Note that only 1 out of the 9 produced units flows physically to the contracted customer. In spite of this, all actors meet their contractual obligations. That the flows in the right subfigure are the result of the superposition of the contracted flows.

**Figure 3.2:** Contract paths and transport paths in electricity. *Left:* simple example electricity network with two producers (P1, P2) and two consumers (C1, C2). *Middle:* Example situation with two contract paths. *Right:* The resulting physical flows. For the sake of the example, transport losses have been neglected.
These special behaviours have implications for the way the electricity system is managed. There are two separate sub-systems with limited interaction: the physical infrastructure and the electricity markets. We will delve deeper into this separation in Section 3.2.

### 3.1.2 Absence of Storage

Unlike many other infrastructures, in electricity there is virtually no storage or buffering of the commodity in the network itself. In an electricity network, the supply/demand balance has to be maintained at all times to prevent instabilities, which could eventually result in a black-out. This means that, on a timescale of tens of seconds, the total supply in the system must equal total demand. On a timescale of seconds, some infrastructure-inherent storage is present due to the rotating mass of turbines in bigger power plants. The inertia of this mass allows for small deviations in the momentary supply demand balance. However, these small deviations need to be compensated for on a seconds to minutes timescale to prevent the system sliding towards a black-out.

Consequently, electricity needs to be produced at exact the same time it is consumed. This feature is unique to electricity. In Section 3.2.4 we will discuss the implications of this characteristic for the interaction between network management and electricity markets.

### 3.1.3 Outside to Inside Causality

The purpose of communication networks is getting messages from their source to their intended destination(s). Hence, the main operational process is message routing. For each node in the network, this involves defining what must be done if a message is received from source $A$ destined for node $B$. Here, the causal relations are from the inside behaviour to the outside behaviour. Efficient packet switching at the nodes gives an efficient loading of the data connections and, hence, leads to a good data throughput for the users at the terminal nodes.

In passive flow networks, routing is not the problem. When at a source $A$, a certain amount of the flow commodity is produced while at destination $B$ the same amount is consumed, the network takes care of the routing, completely automatically. The problem is rather to coordinate $A$ and $B$ to produce, and respectively consume, the same amount at the same time. Assuring the demand/supply balance is the key task in the operation of the electricity network. This task is constrained by the capacity of the individual links in the network. Overload situations must be avoided for all network components. Note that for passive flow networks the causal
3.1. Why is Electricity Different?

Figure 3.3: Outside to inside causality in passive flow networks: a change in demand at node $k$ results in a change in the flow through line $i$. Note that, contrarily, in a packet-switched data network the causality is from the inside to the outside: efficient switching at the inner nodes gives good data throughput at the terminal nodes.

relations are from the outside to the inside. Both subtracting and injecting the flow commodity at terminal nodes is an active deed of a network user. The combination of all these actions lead to a certain loading of the individual connections in the network. Figure 3.3 depicts this: the loading of a particular line in the network is influenced by the electricity exchanged with the network at a certain network node.

3.1.4 Continuous Mathematics versus Discrete Logic

Algorithms used in message routing and network analysis (Google) are rooted in discrete mathematics, with graph theory and discrete logic as main tools. The mathematics of passive flow networks is rooted in continuous mathematics.

As discussed above and depicted in Figure 3.3, a change in the external demand at a certain node may result in a change in the flow through each of the connection lines in the network. The influence of a subtraction at node $k$ (i.e. the local demand minus local supply at $k$) on the flow along line $i$ is given by the partial derivative:

$$ H_{i,k} = \frac{\partial z_i}{\partial d_k} \quad (3.1) $$

As each nodal demand $d_k$ has an potential influence on each line flow $z_i$, a complete steady state model of a flow network is defined by the matrix $H$, referred to as the network transfer matrix:

$$ z = Hd \quad (3.2) $$
Accordingly, the flow over one single line $i$ is given by:

$$z_i = \sum_{k=1}^{N_k} d_k \frac{\partial z_i}{\partial d_k}$$  \hspace{1cm} (3.3)

In these terms, the main electricity network’s operational goal of balancing demand and supply is formulated as:

$$\sum_{k=1}^{N_k} d_k + L = 0$$ \hspace{1cm} (3.4)

under the constraint of the individual line capacities:

$$|z_i| \leq z_{i,\text{MAX}}, \forall i$$ \hspace{1cm} (3.5)

where $L$ is a model for the total network losses.

### 3.2 Electricity Networks and Electricity Markets

The special nature of electricity has consequences for the way the highly-complex electricity systems of developed economies are organised. Where the energy market trade is liberalised, there is a separation between commodity trades and network operations, both performed in two separate sub-systems with limited, yet crucial, interaction.

#### 3.2.1 The Electricity System

The term *electricity system* is used to denote the collection of all systems and actors involved in electricity production, transport, delivery and trading. The electricity system consists of two subsystems: the physical subsystem, centered around the production, transmission, and distribution of electricity, and the commodity subsystem, in which the energy product is traded.

Figures 3.4 and 3.5 present a model\(^1\) of the electricity system. In this text, the financial flows that result from the electricity trade are referred to as the commodity transaction, to distinguish it from transactions related to the physical electricity flows. In these figures, the physical and commodity subsystems have been separated. Note that the two subsystems are related but they are not linked one to one. A generator with a constant output may have fluctuating revenues as a result of

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\(^1\)This model and its description is adapted from [79], Section 3.1. This adapted version has previously been published together with one of the original authors in [45]
variations in market price. Both subsystems need to operate within certain technical and regulatory constrains, such as safety limits, construction permits, operating licenses and emission permits for the physical sub-system, and competition law and market rules for the commodity subsystem. It is important to note that in the figures, for simplicity, different actors of the same type (such as different distribution system operators) are aggregated into one presented actor.

In the liberalised electricity market, several relevant parties can be distinguished (parties and their definitions are based on European regulations [25]):

- The **producer** is responsible for generating electricity (large power producers, as well as distributed generation (DG) operators who produce electricity with small-scale distributed generation).

- The **transmission system operator** (TSO) is responsible for operating the transmission system in a given area and, where applicable, its interconnections with other systems. It ensures the system’s long-term ability to meet reasonable demands for the transmission of electricity. To carry out these responsibilities, the TSO ensures the maintenance and, when necessary, the development of the transmission system. In this context transmission stands for the transport of electricity on the high-voltage interconnected system, the transmission grid. The TSO is also responsible for providing system services in his control area.
System services consist of balancing services (i.e., compensating the difference in the demand and supply, see also Section 3.2.4), reserve capacity (i.e., compensating shortfall in power generating capacity), power quality (e.g., frequency control), reactive power supply, and black start capability.

- The distribution system operator (DSO) is responsible for operating the distribution system in a given area and the connections to the transmission grid. It ensures the system’s long-term ability to meet reasonable demands for the distribution of electricity. To carry out these responsibilities, the DSO ensures the maintenance and, where necessary, the development of the distribution grid. In this context distribution means the transport of electricity on high-voltage, medium voltage and low voltage distribution systems with a view to its delivery to customers, but not including supply. The DSO is also responsible for system services, e.g., power quality.

- The supplier is responsible for the sale of electricity to customers (retail). Producer and supplier can be the same entity but this is not always the case. A supplier can also be a wholesale customer or independent trader who purchases electricity with the purpose to resell it within the system.

- The final customer purchases electricity for their own use and, in a liberalised market, is free to purchase electricity from the supplier of their choice. For different functions (lighting, heating, cooling, cleaning, entertainment, etc.) the final customer uses different electrical appliances.

### 3.2.2 The Physical Subsystem

The physical subsystem consists of all hardware that physically produces and transports electricity to customers as well as all equipment that uses the electricity. The structure of the physical subsystem is determined by the nature of the components that make up the electricity supply system: generators (large power producers and distributed generators), transmission network (TSO), distribution networks (DSOs) and loads (consumers) [76]. The physical subsystem is depicted in the lower part of Figure 3.4. The large power producers generate electricity that is fed into the transmission grid. Relation 1 represents the (regulated) agreement between the large power producer and the TSO. The power producer pays a connection charge (and sometimes also a use of system charge) for the transport of the produced electricity to the DSOs (2), who in turn, distribute it to the final consumer. Relation 5 represents the connection and use of system charges paid by the consumer to the DSO for the delivery of the electricity and system services. The figure shows that electricity generated by DG operators is directly fed into the distribution network based on
3.2. Electricity Networks and Electricity Markets

a (regulated) agreement between the DSO and the DG operators (3). The DG operator pays a connection charge and sometimes also a use of system charge to the DSO for electricity transport and for system services. Most of this electricity is then distributed to the consumer by the DSOs (5), but due to the growing amount of DG capacity, a local situation can occur in which supply exceeds demand. In this case, the surplus of electricity is fed upwards into the transmission grid (4), after which the TSO transports it to other distribution networks (2). The last relevant physical stream concerns the local consumption of DG electricity (6). This is the direct consumption of electricity produced on-site by a consumer, omitting the commodity purchase and sales process through the energy supplier.

3.2.3 The Commodity Subsystem

In contrast with the physical power streams, the economic transactions related to the commodity flow are merely administrative and depicted in the upper part of Figure 3.4. Its goal is an efficient allocation of costs and benefits, within the constraints imposed by the physical system. The commodity subsystem is defined as the actors involved in the production, trade or consumption of electricity, including their mutual relations, any supporting activities and regulation (adapted from [76]). The commodity subsystem controls the physical subsystem, but is constrained by it as well. Large power producers (7) and some large DG operators (8) offer the commodity on the wholesale market, where the commodity is traded between different actors. Large electricity consumers (e.g., industrial customers) can buy the commodity directly on the wholesale market (13). Next to those consumers, energy suppliers buy commodity in the wholesale market (9) on the basis of wholesale contracts to serve smaller consumers. The trade on the wholesale market provides a payment for the produced electricity. Additional to the wholesale market trade, the energy supplier extracts the commodity directly via (small) DG operators (10). The energy supplier subsequently delivers the commodity from the wholesale market and the DG operators to the consumers (12) who pay for it. As energy suppliers are often ‘long’ (i.e., they have contracted more commodity than they plan to offer to consumers), there is a commodity stream backwards to the wholesale market (11). Therefore, the energy supplier is a third party trader that offers commodity to the wholesale market.

In the situation that the energy supplier has accurately forecasted the actual amount of electricity which his consumers use, the received payment for the commodity (12) perfectly corresponds to the amount of delivered electricity (5). However, deviations from forecasted use or planned generation often occur, and, due to the failing of the mechanism to balance supply and demand on the short-term, they
create the need for an additional short-term balancing mechanism.

3.2.4 The Balancing Market

System operators and contractors have to estimate demand in order to ensure sufficient supply is available on short (seconds and minutes), medium (hours), and long (days, months, years) timescales. As the electricity system is liberalised, the market itself is responsible for matching supply and demand on the long and medium terms. As stated before, the electricity supply (output from all generators including national or regional import) must be controlled very closely to the demand. This has to be maintained on the timescale of seconds. Maintaining the short and medium term balance is the responsibility of the system operator, which for this purpose uses forecasts of electricity production and demand submitted by market players (called energy programs or physical notifications). Deviations between electricity demand and production during the actual moment of execution of the energy programs become visible to the TSO as an exchange of electrical power with neighbouring control areas, different from the agreed international or interregional exchange programs (involuntary or unintentional exchange). In this way, the TSO has insight
in the actual balance of the total system. In the case of shortage, the system is balanced by producing additional electricity (upward adjustment of production units) or making use of demand response (i.e., lower consumption). Currently, demand response is predominantly provided by industrial units larger than 5 to 10 MW. In the case of a surplus, production units are adjusted downwards.

In many European control areas, the liberalisation of the energy market has led to the establishment of a separate balancing market, apart from the wholesale and retail market. This market is controlled by the TSO, being the sole buyer. Access to the supply side of the balancing market is mainly limited to the large power producers, but DG operators (in particular large CHP-units) and energy suppliers also have access. Figure 3.5 shows the impact of the balancing market. The transactions that are less common in existing electricity markets are shown by dotted lines. As soon as a situation of shortage arises, the TSO corrects this by buying the lowest priced commodity offer in the balancing market (16). Most offers come from the large power producers (14), but sometimes DG operators (15, CHP units) or energy suppliers (18) offer balancing power as well. The TSO charges the energy supplier(s) which caused the imbalance (17) on basis of the (relatively high) price that it has paid on the balancing market. In the case of a surplus of produced electricity, the TSO accepts and pays the lowest bid in the balancing market for adjusting generating units downwards. So, the TSO sells the energy surplus in the system to the producer who regulates his generating units down. Energy suppliers causing this energy surplus (by having bought more energy on the wholesale markets than their customers are using) receive from the TSO the (relatively low) price the TSO received on the balancing market. Note that in both cases the energy supplier has a net loss. In the first case (when the supplier is short), a higher price is paid than the supplier would have paid earlier on the wholesale market. Since this balancing power is typically provided by units with high marginal costs, this power has virtually always automatically an higher price. In the second case (when the supplier is long), a lower price is received than the supplier paid earlier for the same energy on the wholesale market. As down-regulation of a running plant saves operational (e.g. fuel) cost, this price will be automatically lower than the wholesale market price for the same moment in time. This stimulates market players to make their forecasts of electricity production and demand as accurate as possible. These forecasts determine their trading volumes on the wholesale markets which are notified to the TSO in the energy programs mentioned above. The price differences between the wholesale and balancing markets give a strong incentive to act in accordance with these energy programs.

The responsibility to follow the own energy program of wholesale traded volumes applies not only to suppliers but to all parties active on the wholesale market.
Hence, if a large power producer does not comply with its contracts, e.g., when there is a malfunctioning of a generating facility, they must pay the balancing market prices as well. In Chapter 10 we come back to market trade operations by electricity suppliers when we look at integrating smaller DG and demand response in these operations.

### 3.2.5 System Support Services

Another relevant issue in the electricity system is the delivery of system support services or ancillary services, i.e., all services necessary for the operation of a transmission or distribution system. It comprises compensation for energy losses, frequency control (automated, local fast control and coordinated slow control), voltage and flow control (reactive power, active power, and regulation devices), and restoration of supply (black start, temporary island operation). These services, currently provided by generators and system operators, are required to provide system reliability and power quality.

### 3.3 Smart Coordination for the Smart Electricity Grid

As discussed in the previous chapter, demand response and response of distributed generation will be crucial for power systems management in the future smart electricity grid. Smart Coordination is needed for the Smart Electricity Grid. If this smartness isn’t going to be realised by mimicking the internet in an Internet of Energy, as we argued, what is it going to look like then? And what is ‘smart’ anyway?

#### 3.3.1 The Smart Energy Management Matrix

Throughout the world, there are a number of automatic response programs aimed at retail customers, i.e., households, small enterprises, etc. These programs are predominantly based on one-way signalling from the utility to consuming devices at the end-customer. However other approaches exist and are either in use of have been demonstrated. To classify different approaches and to reason about the properties of the different classes, I constructed the Smart Energy Management Matrix. This matrix classifies smart grid energy management approaches into four main categories. The matrix distinguishes if an approach takes decisions on local issues either locally or centrally, and whether the approach uses one-way or two-way communications. Figure 3.6 shows this matrix with four general classes of energy management approaches filled in: Top-down switching, Price Reaction, Centralised Optimisation
3.3. Smart Coordination for the Smart Electricity Grid

Figure 3.6: The four main categories of smart grid energy management.

and Market Integration. In the next four subsections we will look into these one by one.

3.3.2 Top-down Switching

This class contains the classical demand response programmes where typically in a certain grid area one device group is switched simultaneously. This is the simplest demand response approach and it has been used for decades in different parts of the world. One of the houses I rented as a student was part of such a programme. Every evening, at exactly 11 in the evening hours, a distinguished ‘click’ could be heard coming from a cupboard in the hall way. A ripple signal superposed on the mains sine wave sent out by the local utility company made a relay switch on our water boiler vessel. With our vessel, numerous other vessels in a same number of homes in the region were switched. If we used all warm water before 11, we had to take a cold shower before our night out.

This type of management is either switching devices ‘on’, or switching them ‘off’. Switching ‘on’ gives an external start of the operation cycle of devices such as my water boiler mentioned above and ice machines in hotels. This allows the utility to schedule these loads during off-peak hours. The switching ‘off’ category comprehends interrupting the operational cycle of household appliances such as
freezers and air conditioning systems, or industrial installations such as freezing houses and circulation pumps. The approach is simple and effective. The latter certainly from the perspective of the utility.

However, the approach has some drawbacks associated with it. To begin with, the approach ignores user preferences as illustrated by the shower example above. Further, there is the issue of consumer autonomy. A growing group of persons has problems with an outside authority directly influencing their direct living environment. From an outside point, something or someone decides what happens with the equipment in your house. On top of that, this approach ignores the state the device is in. In the case of a freezer, for instance, this state is the inner temperature and whether the cooling compressor is running or not. Ignoring the device state has two consequences:

1. The exact reaction of the response pool is uncertain as devices may be off already. In these cases, switching ‘off’ comes down to ‘preventing a device to switch on.’ In the freezer example, an ‘off’ signal is received while the compressor is not running at the time.

2. The approach is suboptimal as the response potential is used only partially. Due to the unknown device state, the minimal ‘off’ time needs to be based on a worst case scenario. In the freezer example, the worst case is switching at the moment when the freezer’s controller would switch on the compressor because the upper control temperature has been reached. In that case, the freezer can be kept from switching its compressor on until the freezer temperature reaches a value below the freezing point which is still considered safe. This worst case determines the minimal ‘off’ time. Consequently, freezers having a lower temperature at the time of switching could be switched off for a longer time, however, the central system is agnostic of this.

In sum, the problems associated with this approach are: the suboptimal use of the response potential, the uncertain system reaction and issues regarding consumer autonomy. As said, the top-down switching approach has been the first approach used in practice. From here, there are three different directions to move in, as the figure shows, each solving one or more of the issues described.

3.3.3 Centralised Optimisation

Moving side ways from top-down switching in the matrix, we enter the quadrant of Centralised Optimisation. In making this move, local decisions are still made centrally, however, communications are two-way communications here. Here we are in
3.3. Smart Coordination for the Smart Electricity Grid

the realm of the ‘omniscient’ central authority. An heavy optimisation engine over-
sees all flexible demand and supply in the smart grid cluster under consideration
(a virtual power plant, a local grid segment, etc.). Based on all relevant information
and taking into account the global and, hopefully also, local control goals, the op-
timiser searches for the best solution for the cluster. For this task, all relevant local
data needs to be communicated to the optimiser, while control signals or full control
schedules are communicated backwards.

As the optimiser has full information, it is able to utilise the full response po-
tential of the response cluster. And, as the optimiser outputs control signals, the
system-level reaction of the response cluster is known beforehand. The autonomy
issue of the top-down switching approach remains and, obviously, a privacy issue
is added. Further, communicating all relevant local information to a central point
limits the scalability properties of the approach.

3.3.4 Price Reaction

The price reaction approach is based on a one-way signalling of a dynamic price
(profile) to end-customers or his systems. This is also know as the ‘prices to devices’
approach. At certain time intervals, a new electricity price, or a price profile over the
coming hours is sent to an energy management system at the premises of the end-
customer. Then, either this price profile is displayed for the end-customer to react
to, or used by the management system to switch devices to reach the best reaction to
the prices. There are a number of reasons to choose for this approach. Among these
are: (i) simple one-way communications leading to low system complexity, (ii) no
issues regarding privacy or autonomy, and (iii) the availability of a dynamic price
profile from the wholesale market.

As compared to the top-down switching approach, two issues are solved now:
the autonomy issue and the suboptimal use of the response potential. The responsive
DER units of the end-customer are not externally switched, but rather respond
to an external price signal. Using this price signal, the operation of the DER device is
optimised economically by a local intelligent controller which is owned by and/or
under the control of the end-customer. This controller tries to operate demand dur-
ing low-priced periods, and supply at high-priced periods, taking the device state
and the user preferences into account. When the controller is well designed it is able
to unleash the full response potential.

The energy management solution itself does not introduce a privacy issue as
there is no data communicated to the outside world for this task. However, in order
to bill the customer according to the prices signalled, there has to be a digital elec-
tricity meter that measures with the same resolution as used for the price signal. If
the price signal has a resolution of 15 minutes, for instance, the meter data has to be collected in slots of 15 minutes as well. As this communicates only aggregated data on the level of the full house the privacy exposure is generally considered to be limited. Recent technology developments around automatic meter reading provide good solutions to further mitigate the privacy risks, such as by using encryption techniques and by separating the actual metering data from customer info. Hence, we do not consider privacy issues being associated with this approach.

Having solved two issues, one issue remains and another one is introduced. When using the price reaction approach, the reaction of a demand response pool to a certain price signal is still not known beforehand. Again, the ability of a device to react to a price signal highly depends on the particular state the device is in at that moment. As this information is not known centrally, the reaction of the pool as a whole is unknown. Further, in the long run, when this approach is used for a substantial group of customers, the approach will develop a market inefficiency. In western economies, more than 50% of the electricity is used by retail customers and smaller business-to-business customers located in distribution networks. Here, the —currently unused— potential for automatic response is high, and so will be the influence of this response on the market price of electricity. Consequently, when end-user systems are going to react to market prices on a bigger scale, without participating in these markets, the prices of these markets will not be right anymore. Hence, the wrong prices are signalled to the end-customers and the market becomes inefficient.

An ad-hoc solution to these two problems is a forecasting model for the demand pool’s reaction to a certain price signal. This model is then used for determining the right price to get a desired pool reaction. Note that this type of forecasting of demand response is harder than forecasting of demand patterns for big customer groups. The latter task is done in the current electricity system with an accuracy up to 98%. However, the responsiveness to a price signal of a demand pool depends on the available operational flexibility within the pool. This is highly dependent on the response history of the pool as the available flexibility tend to deplete when it is used. Consequently, for this forecasting problem it is much harder to reach an acceptable accuracy. So, expectedly, uncertainty will remain resulting in a market inefficiency.

3.3.5 Market Integration

The solution for the remaining issues of price reaction can be found in integrating flexible DER devices in the electricity markets. Then, one moves to the upper-right side of the matrix. Here DER devices engage in an automated market trade with
3.3. Smart Coordination for the Smart Electricity Grid

each other and with a representative of the global control stake which is automated as well. Communications are solely based on prices and energy volumes in a two-way fashion.

Analogous to what we have seen for the price reaction approach, the operation of DER devices is optimised economically by a local intelligent controller, again, owned by and/or under the control of the end-customer. This controller receives price information and tries to operate demand during low-priced periods, and supply at high-priced periods, taking the device state and the user preferences into account. So far, all is completely equal to the price reaction approach. What is different is the market interaction that precedes the broadcast of the price information. In this stage, the DER devices communicate their available flexibility together with their preferences and conditions to the electronic market. This might sound complicated, however, all this can be caught in a single market bid. Electricity consuming DER communicate their willingness to pay at this moment in time, while producing DER communicate the price for which they are willing to produce.

Due to these full market communications, reaction of the full response pool is known beforehand. All DER devices participating in the market have communicated their intended reaction to a range of price levels. As this information is known, it is known beforehand what the pool reaction to a certain price signal will be. Hence, the market prices will be automatically correct without a need to forecast. With this approach, demand response moves from influencing, with an uncertain overall response, into market-based control with the dynamic price as a control signal triggering a system reaction that is known beforehand. This is a particularly strong property of this approach. From the point of view of the end-customer, the local energy management system reacts on their behalf to outside price signals by engaging in a market trade. No direct outside control is involved here, as is the case in the centralised optimisation approach. However, from the central point of view, we are talking about control as the full reaction to a certain action to attain the global control goal is known beforehand. This is why this approach is known as market-based control or transactional control.

When implemented well, the market bids sent by DER devices can be aggregated together. When this is done for two devices, the resulting bid represents the preferences of the two devices together. The message size of the aggregated bid and of one single device bid are equal. Using this property, a highly scalable system can be obtained when, in a response cluster, bids are aggregated following a tree structure. The processing and communication time then scales with the height of the tree instead of with the number of DER devices participating. Further, the approach protects the end-customer’s privacy as the bids communicate only information about energy volumes and prices. When these bids are aggregated —on the
level of a house, a building or an industrial site— before communicated externally, the information exchanged is comparable to that of a metering system collecting near-real-time data as described for the price reaction approach above.

In sum, market integration approaches are able to use the full response potential, provide certainty about the momentary system reaction, realise an efficient market and protect the privacy of the end-customer who’s DER devices participate in the energy management task.

### 3.3.6 The Hot Spot in the Matrix

Now, where is the favourable —hot— spot in the Smart Energy Management Matrix? Figure 3.7 summarises the characteristics of the four quadrants. The lower-left quadrant is the only quadrant where it is not possible to unleash the full response potential. In the other quadrants it is possible to do so. The approaches that provide certainty about the expected system reaction are found in the right-hand side of the matrix. Then, the lower half scores a minus for the privacy and/or autonomy issues associated with these approaches. The approaches that connect to the electricity wholesale markets are found in the upper half of the matrix. Of these, approaches in the price reaction quadrant are not future proof, as a market inefficiency develops when a substantial number of customers is going to participate. So, the market integration approach forms the hot spot in the smart Energy Management Matrix.

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<thead>
<tr>
<th>Decisions on local issues made locally</th>
<th>Price Reaction</th>
<th>Market Integration</th>
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</thead>
<tbody>
<tr>
<td>+ Full Use of Response Potential</td>
<td>- Uncertain System Reaction</td>
<td>+ Full Use of Response Potential</td>
</tr>
<tr>
<td>- Market Inefficiency</td>
<td>+ No Privacy Issues</td>
<td>+ Certain System Reaction</td>
</tr>
<tr>
<td>+ No Privacy Issues</td>
<td></td>
<td>+ Efficient Market</td>
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<tr>
<td></td>
<td></td>
<td>+ No Privacy Issues</td>
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<table>
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<tr>
<th>Decisions on local issues made centrally</th>
<th>Top-down Switching</th>
<th>Centralised Optimisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Partial Use of Response Potential</td>
<td>- Uncertain System Reaction</td>
<td>+ Full Use of Response Potential</td>
</tr>
<tr>
<td>- Autonomy Issues</td>
<td></td>
<td>+ Certain System Reaction</td>
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<td></td>
<td></td>
<td>- Privacy and Autonomy Issues</td>
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<td>- Low Scalability</td>
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<tr>
<th>One-way Communications</th>
<th>Two-way Communications</th>
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<td>Figure 3.7: Pros and Cons for the four main categories of smart grid energy management.</td>
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</table>
3.3. Smart Coordination for the Smart Electricity Grid

3.3.7 When is a System ‘Smart’?

Since the early days of computing, the question if a machine can be intelligent has been addressed by philosophers and computer scientists alike. Alan Turing gave the kick off of the discussion in his famous 1950 paper “Computing Machinery and Intelligence”. However, the dispute has not been decided more than 60 years later. The main problem, carefully avoided by Turing, is the lacking definition of ‘intelligence’. Despite, “smart” and “intelligent” are labels frequently attached to technical artifacts. When a system gets such a label, generally, it is capable of the following [61]:

1. **Perception**: gathering information about the situation the system is in.

2. **Communication**: exchange of information with other entities: systems, agents or people.

3. **Reasoning**: capacity to do something with the gathered and received information. This includes planning, scheduling, forecasting and acting.

4. **Action Coordination**: cooperate with and perform joint actions with other entities.

Features 1 and 3 are individual capabilities, 2 and 4 social ones. A system showing only a subset —say features 1 and 2, or 1, 2, and 3— can be said to be ‘a little smart’. Following this, installing digital electricity meters (perception) and providing energy-usage feedback via a display installed in the customer’s home (communication) is not creating a smart grid. It is creating a ‘a little smart grid’.

Let’s go through our matrix with these criteria in mind. Of the four capabilities, top-down switching shows only the second: communication, and then only one-way. Centralised optimisation exhibits perception (gathering of information relevant for the optimisation task), communication (of info and control signals) and reason (at the level of the central optimiser). There is no action coordination as the optimiser is a central authority directly controlling remote devices. With some good will you can say that a smart central system steers dumb devices.

The price reaction approach has no perception on the central level, as this level is agnostic of what is going on at he level of the home and its devices. The local energy management system does have a local perceptional view. There is communication, only one-way. On the central level there is no reasoning nor action coordination. The going price (profile) of the wholesale market is taken and communicated to the local management systems. The latter do exhibit reasoning and action coordination...
on the level of the house\textsuperscript{2}. You could say that smart houses engage in a ‘little smart’ coordination mechanism, just opposite to what is the case in centralised optimisation.

When moving to a market integration approach, the house—which internally is a smart house in the price reaction approach—becomes externally smart as well. Communication becomes two-way and richer in order to coordinate the local actions within the house with that of other smart houses using market mechanisms. Global control goals are articulated via the electronic market in a way similar to the market interaction in which the smart homes engage. So, following the capability criteria for intelligent systems, the market integration approach is the only one to yield a truly intelligent system from top to bottom.

3.3.8 What’s Next?

The rest of this thesis explores a specific realisation of a smart coordination system for the smart electricity grid following the approach of market integration. The next part, Part II, describes and reinforces the theoretical underpinnings for this system.

\textsuperscript{2}Or the commercial building, or the industrial site. In the remainder of this document we restrict to houses for reasons of readability.
Chapter 4

Decentralised Market-based Control

SYNOPSIS: The three non-functional requirements defined – Openness (R1), Privacy Protection (R2) and Scalability (R3) – direct towards the technology of Multi-agent Systems (MAS). MAS theory provides a paradigm for designing open, flexible, scalable, and extensible ICT systems aimed to operate in highly-complex environments. In a MAS, large numbers of software agents are able to interact. On the system level, intelligence of a well-designed MAS can be high, even while the complexity of individual agents remains low. Complex, intelligent, behaviour emerges as a result of a multiplicity of relatively simple agent interactions. This emergence of system-level intelligence can be achieved efficiently using electronic markets, which provide a framework for distributed decision making based on microeconomics. Using market mechanisms, agents collectively make decisions to allocate limited resources within the agent society. This process is known as resource allocation. Market-based Control comes into existence when the agents in a MAS each control a physical process and compete on an electronic market for a scarce input resource needed to attain the control goal of each individual process (e.g. keep a temperature within limits). As compared to centralised optimisation, the market-based approach has a number of advantages. Communications are uniformly based on market information. This results in an open system based on a communication protocol that is easily standardisable and doesn’t include specific local data. Further, due to its distributed nature, MBC has better scalability properties as well.

MULTI-AGENT SYSTEMS (MAS) is a widely-used engineering paradigm for distributed systems development. In Part I of this thesis, we argued that the smart electricity grid needs to be designed as a distributed system. We argued further that the nature of electricity is such that solutions used in other complex infrastructures, such as the internet, cannot be transferred one-on-one to the electricity domain. In Part II, we focus on the theoretical foundations on which
the future electricity grid’s control system should be built. As we will see, the defined non-functional requirements for Openness, Privacy Protection and Scalability direct in a natural way to the technology of Multi-agent Systems (MAS). In this chapter, we introduce Decentralised Market-based Control as a subclass of MAS. In market-based control, agents in a MAS are competing for (one or more) resources on an equilibrium market whilst performing a local control task (e.g., classical feedback control of a physical process) which requires those resources as an input.

In the first two sections, we introduce multi-agent systems technology and electronic markets as a special form of MAS technology. In section 4.3 we introduce how interaction of control agents with an electronic market leads to Market-based Control (MBC). Section 4.4 discusses different protocols for market systems, including the distinction between price-based and utility-based market communications. This distinction is important for later chapters. Section 4.5 gives an example of price-based MBC and section 4.4 describes a number of existing MBC algorithms.

4.1 Multi-agent Systems Technology

A multi-agent system (MAS) is a software system implemented as a collection of interacting autonomous agents [51]. A software agent is a self-contained software program that acts as a representative of something or someone (e.g., a device or a user). A software agent is goal-oriented: it carries out a task, and embodies knowledge for this purpose. For this task, it uses information from and performs actions in its local environment or context. Further, it is able to communicate with other entities (agents, systems, humans) for its tasks.

A commonly-used definition of an agent [81]:

**Definition 4.1.1.** An agent is “an encapsulated computer system that is situated in some environment and can act flexibly and autonomously in that environment to meet its design objectives”.

Wooldridge and Jennings elaborate on several aspects in this definition [82]: “Agents are:

1. clearly identifiable problem-solving entities with well-defined boundaries and interfaces;
2. situated (embedded) in a particular environment over which they have partial control and observability—they receive inputs related to the state of their environment through sensors and act on the environment through effectors;
3. designed to fulfill a specific role—they have particular objectives to achieve;
4. autonomous — they have control over both their internal state and their own behaviour;

5. capable of exhibiting flexible problem-solving behaviour in pursuit of their design objectives, being both reactive (able to respond in a timely fashion to changes that occur in their environment) and proactive (able to opportunistically adopt goals and take the initiative).”

In multi-agent systems (MAS), a large number of such agents are able to interact. Locally-situated agents focus on the interests of local sub-systems and influence the whole system via interactions with other software agents. MAS theory provides a paradigm for designing open, flexible, scalable, and extensible ICT systems aimed to operate in highly-complex environments [40]. The use of local intelligence allows to keep local information locally. The intelligence level of a well-designed MAS the global system can be high, while the complexity of individual agents is relatively low. This phenomena is referred to as emergence. Emergence in multi-agent systems is the way complex behaviour arises on the system level as a result of a multiplicity of relatively simple agent interactions. A MAS can be designed to exhibit specific emergent behaviour. In that case, property number 5 in the list of agent properties above, is of less importance, as the system-wide intelligence is rooted in the interactions of high numbers fairly simple software agents.

Figure 4.1: Canonical view of a multi-agent system (adapted from [40]).
4.2 Electronic Markets

Emergence of system-level intelligence can be achieved by using electronic markets. Electronic markets provide a framework for distributed decision making based on microeconomics. Using electronic markets, the interactions of individual agents can be made highly efficient. Microeconomics is a branch of economics that studies how economic agents (i.e., individuals, households, and firms) make decisions to allocate limited resources, typically in markets where goods or services are being bought and sold. One of the goals of microeconomics is to analyse market mechanisms that establish relative prices amongst goods and services and allocation of limited resources amongst many alternative uses. A distinctive feature of microeconomics is that it aims to model economic activity as an interaction of individual economic agents pursuing their private interests [49, 74]. Note that in economics, the term agent—an actor in an economic interaction—has been used long before software agents were invented.

Whereas, economists use microeconomic theory to model phenomena observed in the real world, computer scientists use the same theory to let distributed software systems behave in a desired way. Market-based computing is becoming a central paradigm in the design of distributed systems that need to act in complex environments. Market mechanisms provide a way to incentivise parties (in this case software agents), that are outside the sphere of direct control, to behave in a certain way [18, 63]. A microeconomic theory commonly used in MAS is that of general equilibrium. In general equilibrium markets, or exchange markets, all agents respond to the same price, that is determined by searching for the price that balances all demand and supply in the system. From a computational point of view, electronic equilibrium markets are distributed search algorithms aimed at finding the best trade-offs in a multidimensional search space defined by the preferences of all agents participating in the market [78, 85]. The market outcome is Pareto optimal, a social optimal outcome for which no other outcome exists that makes one agent better-off without making other agents worse-off.

4.3 Market-based Control

As stated in this chapter’s introduction, in Market-based Control, agents in a MAS are competing for (one or more) resources on an equilibrium market whilst performing a local control task (e.g., classical feedback control of a physical process) that needs those resources as an input. In several early publications on market-based control, the example of climate control of buildings with many office rooms has been used [14, 35, 84]. As depicted in Figure 4.2, offices are attached to a pipe
4.3. Market-based Control

through which cold air is distributed to the individual office rooms. Incidentally, this control problem originated from a XEROX PARC office building in California, where the aim was to improve comfort management by a market approach during the summer period. During hot summer days, the offices at the end of the air distribution pipe were overheating when the afternoon sun shone on the side of the building where these offices were located.

![Diagram of building climate control problem](image)

**Figure 4.2:** Building climate control problem [84].

In this setting, at each office the room temperature is measured and the preferred temperature (the setpoint) is read from a user-adjustable dial. On the level of a single office room, the control problem is to determine the amount of cold air needed to keep the room temperature in a reasonable band around the setpoint. Here, we look into three control system configurations, solving this control problem for each room. Two of these are able to spread the burden of overheating over all rooms.

- **Local Control:** Each office room is equipped with a standard local controller, such as an on/off controller or a PID controller. An on/off controller will either completely open or close the air supply valve in order to keep the room temperature between certain limits around the setpoint $T_{set}$, say, between $T_{set} - 0.5^\circ C$ and $T_{set} + 0.5^\circ C$. This type of temperature control is rather common in room thermostats and also in domestic appliances such as freezers and refrigerators. A so-called PID controller is able to modulate the position of the valve in order to fine control the temperature. This commonly used controller type adjusts the amount of supplied air based on Proportional, Integration and
Decentralised Market-based Control

Derivation (PID) terms of the control error. The control error is the deviation of the actual temperature from the setpoint. We will come back to PID control in Chapter 5.

- Central ‘Omniscient’ Optimisation: All local information on room temperatures and set points is transferred to a central optimiser. The central optimiser solves the resource allocation problem such that, in case of scarcity of cold air, all rooms deviate evenly from their desired temperature. When desired, weighting factors can be attached to each of the rooms to prioritise them. For instance, when the junior underassistant’s office is allowed to warm up more than the CEO’s boardroom.

- Market-based Control: A software agent is associated with each of the rooms. This agent maps the local information on temperature and setpoint into a market bid. In this bid the agent expresses preference information: what amount of cold air it ideally would like to receive, plus its (un)willingness to deviate. Then all agents engage in a market negotiation with each other until the general equilibrium is reached. Alternatively, the agents let a market operator (the electronic market) calculate the equilibrium directly, with identical result. The market outcome is the allocation of the scare resource, cold air, among all agents. When the willingness to deviate is equal over all agents, all rooms deviate evenly from their desired temperature. Unfortunately for the junior underassistant, here, a similar prioritising mechanism is possible by allowing the CEO’s agent to express a lower deviation willingness than the underassistant’s agent.

In Chapter 5, a proof is given that Central ‘Omniscient’ Optimisation is equivalent to Market-based Control. The market-based approach, however, has a number of advantages over the centrally optimised one. Firstly, there is an advantage regarding openness and flexibility. In the market-based control case, the communications between each agent and the electronic market is based on uniform messages expressing market information. Each agent maps its relevant local information onto a market bid to be sent off to the market. In contrast, in the centrally optimised approach all relevant information needs to be known at the central level in order to optimise over all local and global control goals and constraints. In the office building example, all local processes are of the same type and the information that needs to be exchanged with each agent is limited to the measured and desired temperature. However, in complex real-world applications there will be a great pluriformity in control processes and the information to be exchanged may include multivariate state histories, process characteristics, and local control constraints. Having a uniformed way of communication is a prerequisite for open and flexible systems. In
the cases of Market-based Control, each new type of local process to be controlled, having its own local peculiarities, can be added to the system without changing the communication protocol. In contrast, in case of centralised control, this means tailoring the communications and the central optimiser to include the new process.

Secondly, there is the question of scalability. A number of electronic market algorithms exist that are able to run in a distributed manner. These algorithms are multi-agent systems in themselves, running over a series of computing devices. Their logical structure is designed to minimise computing and communication overhead. This is a vital feature when the number of local control tasks grows to a high value. Then, a centralised approach—communicating all relevant local information to a single central point—will rapidly reach scalability limits with respect to computational complexity and communication overhead.

4.4 Protocols for Market-based Control

4.4.1 Price-Based and Utility-Based Market Communications

In economics, preferences of individual agents can be described using either utility functions or demand functions. Consequently, market protocols for electronic markets may be based on these two ways of modelling agent preferences.

Utility is a measure of relative happiness or satisfaction, a way to rank different goods in accordance with the preferences of an individual. If \( x \) denotes a quantity of a certain good, a utility function \( u(x) \) assigns a numerical value expressing the individual’s preferences for owning that quantity of the good. Utility gives the relative satisfaction: the higher the value the higher the satisfaction. The good \( x \) may be indivisible (e.g. shorts, jeans, or bass guitars) or quantities of a continuous resource (e.g. alcohol, cacao, or electricity).

A demand function gives the amount of a certain commodity an agent wishes to consume (or produce) given the price of the commodity. In fact, a demand function is an indifference curve for the commodity and money. A particular point on the function, say at price \( p_1 \), reflects the individual’s indifference for having either an amount of money of \( p_1 \) or having the commodity in an amount of \( d(p_1) \), where \( d(p) \) denotes the demand function. Demand functions form the basis under Walras’s general equilibrium theory, and, therefore, are sometimes referred to as Walrasian demand functions. From a given utility function, the corresponding demand function can be obtained by taking the first derivative.

A utility value has meaning only in comparison to other utility values. Therefore, utility-based market protocols can be used only when all agents in the market system fall under one single authority (owner, operator, etc.) that parameterises the
individual agent utility levels. To refer back to the example of the CEO and the junior underassistant: if the latter is allowed to turn up its agent’s utility level for reaching the exact right room temperature, the allocation system does not prioritise properly. Then, the system falls back to the original situation of local control prone to overheating certain offices. So, the relative utility levels of all agents in such a system need to be determined at design time, or, alternatively, set by the person operating or supervising the system. Consequently, this type of electronic market is more suitable for solving resource allocation problems in settings where reaching a system-level optimum clearly takes precedence over local agent gains. These include building management, industrial plant optimisation, or bandwidth allocation in computer networks, to name a few.

In contrast, price-based markets are more suitable for e-Business settings, where the control architecture is distributed over a number of separate legal entities and, consequently, local agents act more independently and competitively. Here, design decisions regarding the local control systems are made independently of each other. At run time, the market price dynamics, and the local agent’s willingness to pay, automatically align the preferences of the local control agents in the market system. In the case of the assistant and the CEO from the example above, the CEO’s agent can be given more (virtual) budget to accomplish its comfort control task than the assistant’s. When the assistant adjusts its agent to negotiate a better comfort at a higher cost, it will quickly run out of budget resulting in a worse comfort level. It is important to note that, whether —in a specific application— the price has a monetary value or is virtual and solely used as a coordination signal depends on the particular implementation and on the business case behind it.

When using price-based electronic markets, one must make sure that the market is competitive. A market is competitive when there are so many buyers and sellers participating that none of them has the capacity to influence market prices significantly. This is opposed to monopoly or oligopoly market situations. In competitive markets individual agents are price takers which means that agents take prices as externally given (exogenous). This reflects their limited market power. An agent is said to be self-interested when it tries to maximise its utility in every possible way. In a competitive market, the dominant strategy for self-interested agents is to bid truly, i.e. reflecting the true preferences of the agent. A dominant strategy is the best strategy an agent can follow regardless of the strategies of the other agents in the market. A demand function is rational when it is decreasing in \( p \). For electronic equilibrium markets, bid rationality is generally a prerequisite for participating agents, as a unique equilibrium point cannot be guaranteed otherwise.
4.4.2 Existing Market Protocols, A Short Overview

Because of the described advantages, electronic markets are studied in computer science fields such as multi agent systems and electronic commerce. The flow resource allocation line of research yielded a number of algorithms. Here, we give a short overview of the most important results.

Wellman [78, 13] published a distributed algorithm for solving multi-commodity flow problems. The algorithm, coined WALRAS, is based on the basic constructs for defining computational market structures of the French economist Léon Walras (1834–1910). Ygge and Akkermans published a highly efficient market algorithm for flow commodity markets in time-critical environments [83, 85]. In their COTREE algorithm, the market algorithm itself is distributed, in the form of a combinatorial tree, which makes the algorithm highly scalable with respect to the number of participating agents. Further, this in an any-time algorithm that can be stopped at any iteration and still produce a feasible allocation (i.e. with balanced demand and supply.) This algorithm has been used in field experiments of agent-based comfort management in large buildings [41, 39].

Whereas Ygge and Akkermans improved the scalability of flow resource allocation algorithms with respect to the number of market participants, Carlsson and Andersson published an algorithm that improves scalability with respect to temporal interdependencies in agent’s preferences [12]. Markets with time-dependent goods are a special case of multi-commodity markets. In this algorithm, agents can express dependencies in a tree-structured bid. In this way, dependencies between commodities on the market are handled in a tractable way. In conclusion, a broad range of good possibilities exists from which we can select a suitable market protocol for control.

4.5 Price-Based Control: A Typical Example

In a typical price-based market-based control problem, there are several producing and/or consuming agents as well as an auctioneer agent. Each market round, the producers and consumers create their market bids and send these to the market agent. These bids are ordinary, or Walrasian, demand functions \( d(p) \), stating the agent’s demand \( d \) at a price of \( p \). The demand function is negative in the case of production. After collecting all bids, the market agent searches for the equilibrium price, i.e. the price at which the market clears. This price is broadcast to all agents, who can determine their allocated production or consumption from this price and their own bid. Finally, all producing agents feed their allocated production into the flow network while all consuming agents extract their consumption from it.
Figure 4.3 shows an example of price forming in a (single-commodity) general equilibrium market with four agents. The demand functions of the individual agents are depicted in graph (A). There are two consuming agents, whose demand decreases gradually to zero above a certain market price. Further, there are two producers whose supply, above a certain price, increases gradually to an individual maximum. Note that supply is treated as negative demand. In a control setting, the position of the inflexion point is typically determined by the current process state. The solid line in (B) shows the aggregate demand function. The equilibrium price $p^*$ is determined by searching for the root of this function, i.e. the point where total demand equals total supply. The value of each agent’s demand function at this price is given in Table 4.1, Situation 1.
4.6. What’s Next?

The MAS technologies of Market-based Resource Allocation and Market-based Control form the basic toolbox for our search into a coordination mechanism for the smart grid. Before we can apply this toolbox, there are a number of theoretical questions to answer. The first is about optimality of Market-based Control. As said, there are good reasons to choose for the distributed solution that MBC provides. However, how does it perform in comparison with common and well known optimisation methods that aren’t distributed?

Then there are two theoretical questions regarding application in the liberalised energy market, where functions of commodity trade are separated from network management functions. How can a system that in it’s essence is based on market trade mechanisms be suitable for network management? And if it is possible to

### Table 4.1: Agent demand levels for the two situations described in the text. Situation 1 corresponds to Figure 4.3, situation 2 to Figure 4.4.

<table>
<thead>
<tr>
<th>Situation 1</th>
<th>$p^*$</th>
<th>$d_1(p^*)$</th>
<th>$d_2(p^*)$</th>
<th>$d_3(p^*)$</th>
<th>$d_4(p^*)$</th>
<th>$\sum d_a(p^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>92.7</td>
<td>-99.99</td>
<td>15.15</td>
<td>-5.56</td>
<td>90.41</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Suppose the commodity traded in this example is electrical power. Further, suppose the first agent is associated with a unit for combined heat and power generation (CHP), e.g. used to heat a public swimming pool. While serving the local heat demand, the unit produces electricity at the same time. Its local control goal is to keep a large water-filled heat buffer between two temperature limits. This buffer serves heat demand coming from subsystems such as space heating of the pool hall and heating of the pool water. In the situation depicted by Figure 4.3, the CHP unit runs at full capacity. Its produced electricity is consumed by the two consuming agents and its produced heat is heating up the buffer.

Suppose that some time later, the heat buffer temperature is approaching the upper temperature limit. Then, the agent’s need to produce heat —and, thus, its willingness to deliver electricity to the other agents— will be much lower. Now, the agent wants to produce electricity only if it gets a really good price for it and updates its bid accordingly. Figure 4.4 and Situation 2 in Table 4.1, show the new situation. Due to the change in demand function of the first agent, the equilibrium price rises to 109.8. This causes the consuming agents to lower their intake, for agent 2 virtually to zero. The resulting demand is met entirely by the production of agent 4.
4. Decentralised Market-based Control

combine these two functions in one mechanism, does one end up with a system that is still scalable? In the next three chapters we present novel theoretical work providing answers to these questions.
Chapter 5

Optimality of Market-based Control

SYNOPSIS: When Market-based Control is going to be applied to a critical infrastructure such as the electricity network, it is desirable to have a good theoretical insight in the method. To address the research question regarding Optimality of Market-based Control (Q1), the theoretical foundations of distributed market-based control have been assessed. A novel theory has been developed which integrates multi-agent microeconomic market theory with control theory. The central result of this work is a general market theorem that proves two important properties of market-based control: (i) computational economies with dynamic pricing mechanisms are able to handle scarce resources for control adaptively in ways that are optimal locally as well as globally (‘societally’); and (ii) in the absence of resource constraints the total system acts as collection of local independent controllers that behave in accordance with conventional control engineering theory. This gives theoretical evidence that market-based control is ‘outcome equivalent’ to centralised optimisation as was perviously only empirically shown for a particular exemplar problem. This formal result provides the theoretical underpinnings for the market-based control system design we present further on.

MARKET-BASED CONTROL COMBINES multi-agent systems with local control, as we have seen in the previous chapter. Local control agents are competing for (one or more) resources on an equilibrium market whilst performing a local control task (e.g., classical feedback control of a physical process) that needs those resources as an input. When Market-based Control (MBC) is going to be applied to a critical infrastructure such as the electricity network, it is desirable to have a good theoretical insight in the method. Therefore, we are looking into the important question of the optimality of Market-based Control in this chapter.

In a simulation study into a particular exemplar problem, Ygge and Akkermans demonstrated the result equivalence of market-based control and ‘omniscient’ centralised optimisation [84]. The exemplar problem used is the building comfort man-
5. Optimality of Market-based Control

A management problem, as discussed in section 4.3. This work was a reaction on work by Huberman and Clearwater who concluded from simulations using the same exemplar problem that MBC was better than local control [14, 35]. Note that the comparison with centralised optimisation is a better one as that method uses data exchange from and to the local control task which is the case for MBC as well. Purely local control does not have this ability. From their simulation study, Ygge and Akkermans conclude that 'local information plus market communication produces global control'.

This is an important result as it gives an empirical indication of the optimality of MBC. Apparently, centralised optimisation and MBC yield the same outcomes, while the latter has clear advantages regarding openness, privacy protection and scalability as we argued in the previous chapter. The outcome equivalence between MBC and centralised optimisation can be seen as a form of emergence, which we defined earlier on as the way complex systems, patterns and behaviours arise out of a multiplicity of relatively simple interactions. Then, if simulations point to this important equivalence, can theoretical evidence be found for it? Hence, we introduce a research subquestion into the theoretical properties of economically interacting control agents:

**Q1. Optimality of Market-based Control:** Consider an interactive society of a large number of agents, each of which has an individual control task. Is it possible to provide mathematical proof of the optimality of the control strategy that interactively emerges from this agent society with respect to both local and global control performance criteria?

The work presented in this chapter provides a general market theorem for agent-based microeconomic control. This theorem formally proofs the findings of Ygge and Akkermans for a significant class of local controllers, namely, PID control. The theorem is based upon a unification of formalisms from microeconomic theory and control theory. First, a conceptual framework is outlined how one can unify these rather different types of theory in a natural and general way (Section 5.1). A central result is the derivation (Section 5.2) of a general equilibrium market theorem for multi-agent based control. It provides a microeconomic extension of conventional control theory that shows how computational economies with dynamic pricing mechanisms can achieve system control goals— in an emergent fashion, by forms of adaptive distributed intelligence— that are both individually and globally optimal. We then consider some special cases that allow to derive analytical results (Section 5.3), for the market outcome, the equilibrium price, and their impact on individual agent control strategies. The theory presented in this chapter has various generalisations to distributed solutions for advanced forms of optimal and adaptive control. These are briefly discussed in Section 5.4.
5.1 Microeconomic Markets and Control Theory

Consider an interactive society of a large number of agents, each of which has an individual control task. What kind of control strategies will interactively emerge from this agent society, and how good are these with respect to both local and global control performance criteria? There are two, very different but well-formalised theories that can be brought forward to model this problem setting: control theory and microeconomic theory. The conceptual picture, then, is that agents are negotiating and trading with each other on an electronic marketplace in order to acquire the resources that they need to achieve their individual control action goals, as indicated in Figure 5.1.

Microeconomic theory is able to tell us, presupposing given agent utilities or demands, at what price needed resources can be acquired, and what their allocation over the agents will be. However, it lacks the notion of a goal: the purpose or reason for which the resources are put to use by the agents (and this will ultimately determine what and how many resources are needed and demanded) falls outside the scope of market economic theory.

Control theory, however, gives an operational handle on this important issue. It tells us what the amount of resources (the process input variable, $r$, seen in Figure 5.2) must be if we want to reduce the deviation (state error variable $x$) of the pro-

Figure 5.1: Handling of scarce resources in a society of control agents.

Figure 5.2: Standard control theory feedback loop to control the dynamic behaviour of a process
cess output state \( (o) \) from a desired goal state of the system (the setpoint \( o_{set} \)). Controller design means quantitatively specifying this input-output, i.e. resource-goal, relationship. As there are many different types of controllers, this can be done in several ways [3, 53]. The simplest way to do this is Proportional-Integral-Derivative (PID) control, the type of control most widely used in industrial control applications. PID control is a form of feedback control that attempts to minimise the state error by calculating a corrective action as a weighted sum of three sub-actions. Firstly, the proportional term determines a reaction to the current error magnitude. Secondly, the integral term is an action to the sum of recent errors and, thirdly, the derivative term is an action dependent of the rate of change in the current error. Three associated gain constants define how strongly each of the tree terms accounts to the controller’s corrective action. The general equation of the PID control strategy is given later on in equation (5.1).

What is common to all types of control is that they embody some mechanism to compute the needed goal-resource relation. On the other hand, control theory lacks the notion of an economy of resources that is able to adequately allocate scarce resources in a societal context. This is a gap that can be filled by microeconomic theory, as it gives us a way to compute the resource-price relation. If we combine microeconomic and control theory, we are able to treat the complete goal-resource-price triad for control in a distributed fashion, enabling a full cost-benefit calculation for resources desired in the light of individual agent goals. In this way, these two theories are unified as depicted in Figure 5.3.

![Figure 5.3](image_url)

**Figure 5.3:** Microeconomics and control engineering unified in multi-agent theory.
5.2 Microeconomic Control Theorem

This section describes the microeconomic control theory in formal detail for one significant class of local controllers, namely, PID control. The assumption is that each individual agent represents a local PID controller. The building control problem (Figure 4.2) is a case in point: commercial building management systems include a large number of local PID controllers. The aim is to derive what the system as a whole will look like if all local controllers are able to communicate, and especially how it will react globally as well as locally if control resources are scarce at the system level.

5.2.1 Model

The general equation expressing the PID control strategy is

\[ r(t) = K^P x(t) + K^I \int_0^t dt' x(t') + K^D \frac{dx}{dt} x(t). \] (5.1)

Here, \( r(t) \) is the input resource variable, \( x(t) \) is the output state error variable, and the \( K \) are the gain constants. In market terms, \( r \in \mathbb{R} \) implies that we are dealing with an infinitely divisible resource.

Now, let us consider a large collection \( \alpha = 1, \ldots, N \) of independent local PID controllers (in the building example, one local controller for each room in the office building; so \( N \) may run in the hundreds or even thousands). Each local controller follows the PID control rule of Eq. (5.1), which can be more concisely written in operator notation as

\[ r_\alpha = O_\alpha x_\alpha, \] (5.2)

where \( O_\alpha \) is a linear operator operating on the local error state variable \( x_\alpha \). As a matter of convenience, the dependence on \( t \) is not indicated explicitly.

Interpreted in agent terms, the PID control rule Eq. (5.1) and its alternative form Eq. (5.2) state the resource amount \( r_\alpha \) that a controller agent \( \alpha \) needs if it wants to achieve its goal state (setpoint) by eliminating the state error \( x_\alpha \). The PID control rule thus defines the agent’s local demand function without taking possible resource constraints into account. If, on the other hand, the total resource is constrained, it is traded on an automated marketplace that thus serves as a resource allocation mechanism. Economic issues such as this scarce-resource situation are not addressed in conventional control, and this is the added value of our market-based approach.

Assume an agent society in which each individual agent \( \alpha \) represents a local independent controller, which has to negotiate with other agents in a marketplace in order to obtain its desired resource \( r_\alpha \). In particular, there may occur a situation
of scarce resources, in the sense that the total available resource at a certain time \( t \) is smaller than the sum total of the requested resources \( \sum_{\alpha=1}^{N} r_{\alpha} \) as given by Eqs. (5.1) or (5.2). In this new constrained situation, how are the available resources going to be distributed? What is the optimal situation for each agent locally, and how will agents adapt their local control strategies? What is the global control strategy that emerges in this agent society?

**Definition 5.2.1.** Let each independent local PID controller be represented by an agent \( \alpha \), whereby its utility function is defined by

\[
u_{\alpha} = f_{\alpha}(r_{\alpha}),
\]

where \( f_{\alpha} \) is a strictly concave function of \( r_{\alpha} \) that is twice continuously differentiable (on a suitable interval \( |r_{\alpha}| \leq |R_{\text{unc}}| \)), and that has its maximum at the local resource value \( r_{\alpha} = O_{\alpha}x_{\alpha} \) as given by the PID control equations Eq. (5.1) or, equivalently, Eq. (5.2). Furthermore, suppose that the total available resource is scarce, so that we have

\[
0 \leq \sum_{\alpha=1}^{N} r_{\alpha} = R_{\text{max}} \leq \sum_{\alpha=1}^{N} O_{\alpha}x_{\alpha} \quad \text{def} = R_{\text{unc}}.
\]

Finally, let all agents be self-interested utility maximisers and let them be competitive (i.e. price takers).

The latter equation says that \( R_{\text{unc}} \) is the total ‘free’ demand of all agents taken independently, as implied by the sum total of the PID control equations in a situation with an unconstrained supply of resources. But, there may be a smaller cap \( R_{\text{max}} \) on the total available resource if it has to be shared by the agent society (as is the case with the cooling power in the smart building example). The total demand \( R_{\text{unc}} \) by the individual agents in the unconstrained case derives from local information (according to Eq. (5.2)), whereas the resource limitation to \( R_{\text{max}} \) is the result of a supposed external action or situation. One has the design freedom to choose any agent utility function \( f_{\alpha} \) within the confines of Definition 5.2.1.

### 5.2.2 Theorem

**Theorem 5.2.1.** Assuming the agent utility functions and behaviours given by Definition 5.2.1, the following statements hold:

\footnote{Depending on the physics of the problem, \( R_{\text{unc}} \) might be either positive or negative. Here, a positive \( R_{\text{unc}} \) is assumed for simplicity. If it happens to be negative, the statements and derivations that follow still hold (just introduce auxiliary resource variables that are the negatives of the above ones).}
5.2. Microeconomic Control Theorem

A. There exists a resource allocation $r^*_\alpha$ that is a global maximum to the optimisation problem: \[
\text{Max} \sum_{\alpha=1}^{N} f_\alpha(r_\alpha) \text{ subject to the resource constraint } \sum_{\alpha=1}^{N} r_\alpha = R^{max}, 
\]
and this global maximum is unique.

B. The same resource allocation $r^*_\alpha$ is identical to the competitive equilibrium of a market in which each individual agent maximises its utility $f_\alpha(r_\alpha)$ within its budget, whereby the market is clearing (i.e. $\sum_{\alpha=1}^{N} r^*_\alpha = R^{max}$) and $p^*$ is the market clearing price.

C. The resource allocation $r^*_\alpha$ obtained as outcome of this competitive equilibrium market is Pareto optimal (i.e. there exists no other allocation that is better or neutral for all agents).

5.2.3 Proof

Proof. Statement A follows directly from Definition 5.2.1 and standard optimisation theory (see for example Ibaraki and Katoh [36], Ch. 2; Fletcher [28], pp. 216-218; Mas-Colell et al. [49], pp. 50-51, 314-327, 945, 962). A standard method to find the constrained maximiser in an optimisation problem is to set up the Lagrangian $L$ for problem A, as follows

\[
L = \sum_{\alpha=1}^{N} f_\alpha(r_\alpha) + p \left( R^{max} - \sum_{\alpha=1}^{N} r_\alpha \right), \tag{5.5}
\]

and solve the equations $\frac{\partial L}{\partial r_\alpha} = 0$ and $\frac{\partial L}{\partial p} = 0$. The latter immediately yields the constraint equation $\sum_\alpha r_\alpha = R^{max}$. The former gives $\frac{\partial L}{\partial r_\alpha} = p$ for all $\alpha$: the marginal agent utilities all have the same value $p$ at equilibrium. The resource allocation $r^*_\alpha$ that satisfies these equations solves the (global) optimisation problem of statement A. Now, following the definition of (partial) competitive equilibrium (e.g. [49], p. 314-318) and including the agent budget constraints, we find that the local utility maximisation problem for each individual agent on the market of statement B is:

\[
\text{Max} \left[ f_\alpha(r_\alpha) - p^* \cdot r_\alpha + \text{const},_\alpha \right]. \tag{5.6}
\]

As a result, the same first-order equations hold for the market problem B and the optimisation problem A, whereby at the market clearing point the resource constraint holds. Hence, the Lagrangian parameter $p$ equals the market clearing or equilibrium price $p^*$, and the optimal resource allocation $r^*_\alpha$ of problem A is also the solution to the competitive equilibrium market problem of statement B. This proves statement B. Statement C now immediately follows from the first fundamental theorem of welfare economics ([49], pp. 325-327). □
The market theorem for agent-based control is a key contribution of this chapter. It has weaker assumptions and is much stronger than the corresponding result in [84]. It also holds in the *multicommodity* case (hence, for the case of state-feedback control). In fact, it expresses a rather general statement about the relationship between global optimisation and competitive market problems. The optimisation problem of statement A reflects how a central controller, that oversees all local control agents, will look at the situation in a hierarchical, top-down manner. In contrast, the market problem of statement B represents the situation through the eyes of the individual agents in a bottom-up and emergent fashion. The market theorem then shows that there is an *outcome equivalence* between the two approaches. Moreover, statement C says that the resulting resource allocation \( r^* \) is optimal both locally and globally, in other words, it is optimal for each agent individually as well at the agent society level.

### 5.3 Analytical Results for a Society of Control Agents

The general statements of the previous section can be extended to analytical results if we consider some special cases that throw further light on the characteristics of microeconomic control by PID agents. Namely, the simplest utility function that satisfies the requirements of Theorem 5.2.1 is a quadratic one (note that simple utility functions like these *do* make practical sense in real-life applications such as smart buildings [84, 7]):

\[
    u^Q_{\alpha} = -\frac{1}{2w_{\alpha}}(r_{\alpha} - O_{\alpha}x_{\alpha})^2, \tag{5.7}
\]

where \( w_{\alpha} \overset{\text{def}}{=} \frac{1}{c_{\alpha}} \) is a weight factor \( > 0 \) that may be different for each agent. The weight factor may be used to express individual preference differences (a higher \( w \) makes the utility function sharper and a lower one makes it broader, so that the agent more/less easily makes concessions in its utility maximisation) and/or to express some social hierarchy (the CEO’s boardroom is probably seen as more important to serve than the junior underassistant’s office); \( c \) can be seen as a measure for the agent’s willingness to make concessions. The differences in strictly physical characteristics (such as size) are already catered for through the \( O_{\alpha}x_{\alpha} \) term in the utility equation.

This form of the utility function allows us to analytically solve the Lagrangian equations for the constrained market optimisation:

\[
    \frac{\partial L^Q}{\partial r_{\alpha}} = 0 \Rightarrow r_{\alpha} = O_{\alpha}x_{\alpha} - c_{\alpha} \cdot p^Q \tag{5.8}
\]
Through this equation, we have derived an explicit expression for the agent’s demand function when available resources are scarce (compare with Eq. (5.2) for the unconstrained case). Then, using the resource constraint equation and Eq. (5.4) gives the market outcome at equilibrium:

\[ p^*_Q = \frac{(R_{unc} - R_{max})}{\sum_{\alpha=1}^{N} c_{\alpha}}, \]  

and

\[ r^*_\alpha = O_\alpha x_\alpha - \frac{c_{\alpha}}{\sum_{\alpha=1}^{N} c_{\alpha}} (R_{unc} - R_{max}). \]  

The latter equation is actually a generalised version of the central control solution constructed by [84].

There are some special cases of Eq. (5.10) that are of interest to show explicitly. The first case is that all agents are equal in the sense of having equal weights:

\[ \forall \alpha : c_{\alpha} = 1 \Rightarrow r^*_\alpha = O_\alpha x_\alpha - \frac{1}{N} (R_{unc} - R_{max}), \]  

and

\[ p^*_Q = \frac{1}{N} (R_{unc} - R_{max}). \]  

This equation says that if all agents are equal, they all have to take the same absolute cut in resources.

A second interesting case is when the agents’ preferences are proportional to their unconstrained demand \( O_\alpha x_\alpha \). Then we get:

\[ \forall \alpha : c_{\alpha} = O_\alpha x_\alpha \Rightarrow r^*_\alpha = O_\alpha x_\alpha \left( \frac{R_{max}}{R_{unc}} \right). \]  

Note that in this case we have:

\[ \forall \alpha : c_{\alpha} = O_\alpha x_\alpha \Rightarrow p^*_Q = \left( \frac{R_{unc} - R_{max}}{R_{unc}} \right). \]  

This is another elegant result: if all individual preferences are proportional to free demand, each agent gets the same relative cut in resources. In control terms, all PID gain constants are multiplied with the same factor \(< 1\), equal to the overall relative resource reduction.

The above analytical results are useful in their own right, because one has the agent design freedom to choose the utility function. Hence, it is convenient to take the simplest one (viz. the quadratic form) that does the job. In addition, they are helpful in the microeconomic interpretation of large-scale distributed control.
5. Optimal of Market-based Control

Namely, by looking at the proof of Theorem 5.2.1 and the subsequent discussion on market protocols in Sec. 5.2, it follows that the Lagrangian multiplier $p$ is naturally interpreted as the going market price. Its value at the optimal resource allocation $r^*_\alpha$ equals the market equilibrium price $p^*$.

If we apply this interpretation to the above analytical results, we see that the market clearing price for constrained PID control is proportional to $(R^{\text{unc}} - R^{\text{max}})$, in other words, to the ‘cut’ applied to or shortage in the total available resource. In the unconstrained case, the equilibrium price is zero (which is natural because the resources then are ‘for free’, in other words, there is no premium price on top of a given external price). Thus, the unconstrained situation of conventional control (independent, non-communicating local controllers) is the limiting case of the constrained control problem, where there is no resource cut. We also see that the reduction of the resource for each agent relative to its initial ‘free’ demand (according to the standard PID control rule) is proportional to the resource shortage.

5.4 Implications and Generalisations

5.4.1 Top-down control or bottom-up markets?

Let us reconsider Equation (5.10). It has the form of a PID control rule extended with a term reflecting resource constraints. By summing over $\alpha$ it is easily seen that it incorporates the resource constraint (both sides always sum to $R^{\text{max}}$). Moreover, it also covers the unconstrained case (because then $R^{\text{max}} = R^{\text{unc}}$, so that the term with the weight factors $w$ equals zero, and we are left with Eq. (5.2)).

Hence, Equation (5.10) actually gives the recipe for the design of a central controller that behaves under resource constraints in a way equivalent to the decentralised market approach to PID control [35, 84]. These equations show that a hierarchical central controller needs global access to the following information: (1) all local PID control rule information (i.e. all $C_\alpha x_\alpha$, in order to be able to construct $R^{\text{unc}}$); (2) all local weights $w_\alpha$; (3) the value of $R^{\text{max}}$. This formalises what Huberman and Clearwater’s ‘omniscience’ means. The central controller then can correctly instruct each local controller with the proper (changed) PID rule when the total resource is constrained, and can simply leave them alone in the unconstrained case. This extends the previous partial results by [84] to general PID control.

Note that the direct explicit construction of the central controller fully depends on whether an analytical solution of the constrained optimisation equations can be found. This is only possible due to the special choice of a quadratic utility. It is not straightforward or even possible in the general case, whereas the decentralised market approach will always work properly (according to Sec. 5.2). Thus, the distributed
microeconomic approach to control is more flexible and more generally valid than hierarchical control.

This completes the general theory of microeconomic control as applied to large-scale PID control. It also settles some conjectures and outstanding questions in the literature regarding the capabilities and added value of market-based control versus central conventional control. In brief, this chapter demonstrates:

**For resource-constrained large-scale PID control, we have shown how to construct a Pareto-optimal agent-based market solution (Sec. 5.2, market theorem statement B and C).**

**There also exists a central hierarchical controller of which the outcome is identical to the multi-agent based solution (Sec. 5.2, market theorem statement A).**

**The computational economy can always be constructed in the general PID case, and suitable market protocols have been given (Sec. 5.2). In contrast, a direct explicit construction of the central controller is only possible in a few special cases (Sec. 5.3). In the general case, a computational market approach is needed (or at least a functionally equivalent optimisation algorithm).**

### 5.4.2 Microeconomic control as an online adaptive strategy

It is noteworthy to point out that the market-based control solution effectively controls the local PID controllers, but generally it is not itself a PID controller. (This is only true in the special case of quadratic utility functions and linear demand functions of the control agents, see Sec. 5.3).

In essence, microeconomic control is a special type of *adaptive* control. It embodies an, online and self-organising, adaptation of the local control strategies when overall resource limitations come into play. The results of this paper have been derived for the general case of PID control. They can, however, be generalised to other, more sophisticated types of control (outlined in Sec. 5.1). For example, all results of the present paper readily carry over to state-feedback control, whereby the market is turned into a multicommodity market.

The distributed microeconomic approach presented is also applicable to optimal control whereby a chosen performance index is optimised over a whole time period. In that case, the negotiation rounds are inherently intertwined with iterative internal optimisation computations by each local control agent, which is, on its turn, responsible for a (possibly large) multidimensional dynamic subsystem. Moreover, each such subsystem itself may be handled in a fully decentralised fashion, by representing each local variable (single dimension) by an agent. This leads to a coupled hierarchy of computational economies. This is actually a quite natural architecture.
in advanced application scenarios, such as the management of multi-building sites or city neighbourhoods. Online supply-demand matching of power over several regions at the national and international level is another example. These are currently all very relevant applications of distributed intelligence, both from a business, policy, and technical perspective. Distributed agent-based microeconomic control offers an effective as well as conceptually natural decentralised computational framework.

Thus, the microeconomic control theory of this paper can be generalised in several directions, representing a diversity of other, richer or more comprehensive, agent societies for control:

- multiple state dimensions and control variables can be handled simultaneously;
- different types of control design and strategy can be covered, whereby ‘conventional’ control theory is preserved and integrated into the agent actions;
- dynamic physical environments and models, including nonlinear ones, can be treated;
- a mix of markets and hierarchies for control is possible;
- forms of bounded rationality may be covered (e.g. satisficing, anytime market algorithms, relevant for scenarios dealing with emergencies or critical events);
- different kinds of agent intentionality can be handled — including utilities that are not strictly self-interested, thus going beyond the societal limitations of competitive markets.

5.5 Conclusion

The work presented in this chapter provides a formal proof that:

Market-based distributed control and centralised ‘omniscient’ optimisation are equivalent.

The agent-based microeconomic control approach presented here yields a formalism plus a decentralised, bottom-up computational framework that enables new forms of large-systems control that are: (i) optimal, (ii) adaptive, and (iii) economically aware. It has been designed such that it takes full advantage of existing control engineering and theory. It provides the theoretical underpinnings for, and subsumes, multi-agent based control applications developed so far. It moreover generalises to
computational economies for other types of control, thus providing the formal foundation for an even wider range of distributed intelligence applications in large-scale industrial control.

5.5.1 Relevance to Computer Science

This finding contributes new knowledge to the computer science knowledge base. In the existing literature, this outcome equivalence had been demonstrated for a specific simulated case only.

5.5.2 Relevance to Electrical and Control Engineering

This new knowledge is useful for engineering market-based control systems in general. Centralised optimisation is used in a wide variety of engineering problems. However, there are number of problems associated with its use that are solved by using MBC. The proven equivalence between the two approaches makes it safe to solve these problems without compromising the functionality of the control system at hand. To recall: MBC uses an open, uniformed communication protocol that doesn’t require detailed local information to be communicated, and has a better computational and communication complexity. In our application for coordination in the electricity grid, the first means that far more DER devices can contribute to the coordination task. The latter means that no detailed local information about the DER device and its usage by its private owner is externally communicated. Further, by using MBC the local device isn’t steered directly by an external authority. Contrarily, there is an agent working on behalf of the owner to minimise electricity costs and/or maximise electricity revenues.

5.5.3 What’s next?

This chapter provides an important formal proof of the optimality of Market-based Control. As we have seen, in MBC, local control agents mutually negotiate a scarce resource needed for their control task on an electronic market, which is a form of resource allocation. Now we change our focus to the way this resource actually ends up at the location of the individual control task. As these resources are generally flow resources (electricity, fluids, gases, etc.), a flow network must be in place to distribute the resource.

In the next two chapters we will look into resource allocation in flow networks. Capacity constraints are an issue in industrial flow infrastructures, and this is also the case in the ageing electricity networks of our western society under the “electrification of everything”. In Chapter 6, we set out to introduce locational pricing in the
theory of resource allocation of flow resources. Then, in Chapter 7, a novel fast algorithm is introduced tailored for the task of congestion management in distribution networks.
Chapter 6

Network Feasibility in Resource Allocation

SYNOPSIS: The MAS research line resource allocation of flow commodities is highly relevant for our research question. This research line is primarily focussed on efficient algorithms for assigning flow resources (i.e. infinitely divisible streams) to different applicants under scarcity. The state-of-the-art in this research line does not provide algorithms that are able to consider the characteristics of the underlying transport network. In applying these, one implicitly assumes the network has virtually infinite capacity. It would be desirable if algorithms for allocation of flow resources would yield so-called network feasible solutions, i.e. allocation solutions that obey the characteristics of the underlying flow network. On the other hand, power systems economics provides a framework called Locational Marginal Pricing (LMP) which runs an electricity wholesale market while considering line capacity constraints and energy losses in the electricity transmission network. In answer to the research question regarding Network Feasible Solutions in Resource Allocation (Q2), it has been investigated how LMP can be introduced in MAS. The contribution of this work is threefold. Firstly, the LMP framework is reformulated and expanded into a general applicable MAS framework. Secondly, it is shown that, under the common condition of demand and supply elasticity, the constrained optimisation problem posed by the framework has a unique solution and a search in the parameter space will converge to that solution. Thirdly, a distributed market algorithm that solves the constrained optimisation problem is provided.

ANOTHER RESEARCH LINE in MAS important for our smart grid system design is resource allocation of flow commodities. A flow commodity is a physical stream that is infinitely divisible. Apart from electricity, examples of flow commodities are physical flows of gas or liquid. Resource allocation is the process of assigning resources in an economic way to applicants taking into account the availability of the resources and the preferences of the applicants.
This research line is primarily focussed on efficient algorithms for this type of allocation problems (see section 4.4). Major advances have been made towards algorithms with high scalability regarding both the number of participating agents and the number of commodities. However, these algorithms do not consider the characteristics of the underlying transport network. In applying these, one implicitly assumes the network has virtually infinite capacity. In Electrical Engineering terms: the network is assumed to be a "copper plate". The interaction between passive flow networks and resource allocation algorithms is not yet described in MAS terms. It would be desirable if algorithms for allocation of flow resources would yield network feasible solutions, i.e. allocation solutions that obey the characteristics of the underlying passive flow network. Surprisingly, this white spot in Computer Science can be filled in using knowledge from the Power Engineering field. Power systems economics provides a framework called Locational Marginal Pricing (LMP) which runs an electricity wholesale market while considering line capacity constraints and energy losses in the electricity transmission network. Hence, the following research subquestion:

Q2. Network Feasible Solutions in Resource Allocation: How can algorithms for allocation of flow resources be extended to yield network feasible allocation solutions obeying characteristics of passive flow networks? How can the mechanism of locational marginal pricing from the field of power systems economics be formulated in computer science terms?

So, we seek for a general approach from a computer science point of view that provide network feasible solutions for all types of flow networks. Accordingly, the flow networks we focus on in this chapter are not limited to electricity networks. Apart from capacity constraints and network losses, changes in the amount of commodity stored in the transport network itself is a network characteristic relevant to certain application cases. In a gas network, for instance, the amount of gas stored inherently in the network varies with the average network pressure. In the work presented in this chapter we:

1. translate the framework of locational marginal pricing [65] from the field of power systems economics into computer science. In this reformulation, we:
   (a) omit modelling details oriented towards bulk transmission and wholesale trade of electricity;
   (b) bring the framework into multi-agent systems theory where agents communicate their preferences in the form of demand functions; and
   (c) generalise the framework to be applicable for all flow commodities, such as gasses, liquids and electricity.
2. show that, under the common condition of demand and supply elasticity, the constrained optimisation problem posed by the framework has a unique solution and a search in the parameter space will converge to that solution; and

3. provide a distributed market algorithm that solves the constrained optimisation problem.

The market algorithm can be regarded as a generalisation of electronic equilibrium markets. Under network capacity constraints, it finds solutions that are feasible for the underlying passive flow network. In non-constrained networks, its solution is equal to the general equilibrium market outcome.

In generalising the framework for all flow commodity types, a price component has been included for storage of the commodity inherently in the network itself. Generally, network inherent storage is possible in case of gas or liquid flows, where the amount of material stored in the network is influenced by the average system pressure. Further, the framework includes a price component for transport losses. For material flows in the gas or liquid phase, transport losses are pressure-driven (e.g. filtration or permeation of pipes and connections). For electrical energy these are Ohmic losses: dissipation of electrical energy into heat in network components such as cables and transformers.

Section 6.1 introduces the concept of locational pricing through an augmentation of the example presented earlier in Section 4.5 and gives a brief overview of related work. Section 6.2 defines formal models for network and connected agents. These models are used in the theoretical framework for locational pricing as defined in Section 6.3. Section 6.4 analyses search space and convergence properties of the constrained optimisation problem posed by the framework. Section 6.5 gives the distributed market algorithm that searches for a solution to this optimisation problem. The latter section also demonstrates the algorithm for a medium-sized network. Section 6.6 concludes the chapter.

6.1 The Concept of Locational Pricing

6.1.1 “A Typical Example” Revisited

Here, we start by revisiting the typical example of Section 4.5 describing the price forming in a single-commodity general equilibrium market with four agents. The demand functions of the individual agents, originally depicted in Figure 4.3 are reproduced in Figure 6.1 (A). Now, suppose these agents are located in the H-shaped flow network shown in Figure 6.2. Each of the four end nodes accommodates one of the agents. The individual agent demands $d_k(p^*)$, that are subtracted from the
network, are indicated at the corresponding nodes. The two intermediate nodes are just connection points and accommodate no additional demand or supply. Then, the resulting commodity flows through the network connections are as indicated in the figure. The subnetwork on the left-hand side is a net producer of the commodity which results in a strong flow to the net-consuming right part of the network.

Now, focus on line 3, connecting the left and right parts of the network. The price reaction of the left and right subnetwork are respectively given by:

\[
\begin{align*}
    d_{\text{left}}(p) &= d_1(p) + d_2(p) \\
    d_{\text{right}}(p) &= d_3(p) + d_4(p)
\end{align*}
\] (6.1) (6.2)

In Figure 6.1 (B), these two aggregated demand functions are added to the original

---

**Figure 6.1:** (A) Demand functions of the four agents in the example. (B) Solid line: The aggregate demand function and resulting unconstrained equilibrium price. Other lines: Aggregated demand curves for both sides of the capacity constrained line and the locational prices to solve the line overloading (see text).
6.1. The Concept of Locational Pricing

Figure 6.2: Resulting network flows through an H-shaped network when the agents of Figure 6.1 are located in the endnodes. Note that supply is indicated by negative demand.

Table 6.1: The network feasible line flows of the described example (with all flow directions equal to those in Figure 6.1).

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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>$z_1$</td>
<td>$z_2$</td>
<td>$z_3$</td>
<td>$z_4$</td>
<td>$z_5$</td>
</tr>
<tr>
<td>85.00</td>
<td>60.00</td>
<td>25.00</td>
<td>38.07</td>
<td>63.07</td>
</tr>
</tbody>
</table>

The figure. Note that, per definition, $d_{right}(p^*) = -d_{left}(p^*)$, and $|z_3| = |d_{left}(p^*)|$. This is indicated in the figure by the vertical black line at $p = p^*$. In words, at the equilibrium price, the excess supply in the left subnetwork equals the excess demand in the right subnetwork, and is equal to the flow through the interconnection.

Now, suppose line 3 has a maximum capacity: $z_{3,\text{MAX}} = 25$, in which case the general equilibrium solution overloads this line more than threefold. Any market-based method to solve this constraint violation has to follow the general modus operandi of market-based systems (as described in section 4.1), i.e. to incentivise actors —that are not necessarily under direct control— to participate in a particular way. The way to do that, in this case, is to create a price difference over this line in such a way that the agents on both sides respond to relieve the line. The two price levels must be chosen such that (i) total demand equals total supply, and (ii) the line flow is equal to its maximum. For this specific example, the prices $p_{\text{RIGHT}}$ and $p_{\text{LEFT}}$ indicated in Figure 6.1 (B) accomplish this. The resulting line flows are shown in Table 6.1. Note that the two conditions are met: $d_{right}(p_{\text{right}}) = -d_{left}(p_{\text{left}})$, as can be seen in the figure, and $|z_3| = |d_{left}(p_{\text{left}})| = |z_{3,\text{MAX}}|$, as is indicated in the table.
6. Network Feasibility in Resource Allocation

6.1.2 Related Work on Locational Pricing

Two early introductions of the concept of locational pricing for networked services were published in the beginning of the 1970s. Then, William Vickrey introduced the concept in an essay on responsive pricing of utility services, such as telephone services, road usage and energy delivery [75]. Few years later, Carson Agnew described a model for varying congestion tolls in highway and communications networks [2].

Both in computer science and in power systems economics the notion of locational pricing is used to solve a number of network-related problems. Without the aim to provide a complete overview, we will briefly discuss the usage of the concept in both fields.

Locational Pricing in Computer Science

Locational pricing plays an important role in different solutions to problems related to data network (e.g. internet) topologies, routing and pricing. An example of this is work by Mullen and Wellman that describes a computational market model for information services distributed over a data network [50]. Their focus is “on the economic problem of when and where to establish mirror sites for the more popular information services. Competitive agents choose to set up mirrors based on going prices for network bandwidth, computational resources and the information service.”. Another example is work done by MacKie-Mason and Varian, who describe a basic economic theory of pricing congestible network resource such as an ftp server, a router, a Web site, etc. [48]. They examined the implications of “congestion pricing” as a way to encourage efficient use of network resources. An overview of the development of costs and pricing schemes for data infrastructure usage, against the history of that for other infrastructures, can be found in [52].

Further, the concept has been used in auction algorithms for solving the classical linear network flow problem and its various special cases such as shortest path and max-flow problems [6, 5]. These solutions are targeting networks where objects can be routed via a specific pathway through the network.

Locational Pricing in Power Systems Economics

Important work on locational pricing was done within the field of electrical power systems economics. During the 1980s, Bohn et al. developed a comprehensive theory for spot pricing of electricity [8, 9]. The book Spot Pricing of Electricity that resulted from this research became a standard work in this field [65]. Their approach became known as locational marginal pricing (LMP).
6.1. The Concept of Locational Pricing

Currently, LMP is increasingly applied in management of electrical power infrastructures at the level of bulk generation and transmission of electricity. For instance, in the transmission grid area known as the PJM Interconnection (USA), congestion problems in the high-voltage transmission network are being solved using LMP since 1998. This grid area encompasses the transmission grid of the states of Pennsylvania, New Jersey and Maryland (hence the abbreviation PJM) and all or parts of 10 other US States. In this area, the wholesale electricity markets and transmission system power flow analysis are coupled in order to use pricing to allocate scarce transmission capacity. At times of sufficient transmission capacity, the system works as a coordinated and transparent spot market. When the transmission system is constrained, the spot prices can differ substantial across the 13 states [33]. LMP has been implemented in a similar manner in Chile and New Zealand.

Comparable pricing mechanisms are used to optimise the utilisation of transmission system interconnectors between countries in Europe. In the Nordic countries, this is known as market splitting as the common Nordpool wholesale market is split into two or more loosely-coupled markets when interconnection capacity is constrained [47]. In the rest of Europe, individual countries have had national electricity wholesale markets since the liberalisation of the electricity markets at the end of the last millennium. The European transmission system operators (TSOs) and national market operators are currently adopting a LMP-based market model, similar to that of the Nordic countries [24]. As, in contrast to the Nordic situation, this model aims at coupling previously separated markets, the mechanism has been coined market coupling.

In [30], it is shown for the UK electricity system, that moving from uniform prices to optimal locational prices could raise social welfare, lower vulnerability to market power and would also send better investment signals. On the other hand, it would create politically sensitive regional gains and losses.

6.1.3 How are passive flow networks different?

As stated in the introduction of this chapter, current electronic market algorithms for flow commodities do not take the characteristics of an underlying flow network into account. However, the concept of locational pricing is used in multi-agent systems as described in section 6.1.2. Are these results not directly applicable to flow commodity networks? The answer lies in the type of network addressed. Real-world industrial applications of flow resource allocation use passive transport networks. We touched this topic earlier on when we described the special nature of the electricity infrastructure in section 3.1. In these networks, there is no way of directing the flow to follow a particular path. Instead, the commodity flows via the path(s)
of least resistance, possibly via a number of parallel trajectories, from the point of injection to the point of subtraction as we have seen. In a network of a given topology, and with given resistance characteristics, the actual flows through the network depend entirely on commodity injections and subtractions at the network nodes. The flow characteristics in these networks are fundamentally distinct from those in actively switched networks, such as packet-switched data networks and road transportation networks. Hence, to get network feasible solutions from flow-commodity resource allocation algorithms in computer science, other mechanisms need to be introduced.

6.2 Network and agent models

6.2.1 Network Model

We model a flow network by a directed graph $G = (V, E)$, with $V = \{v_1, v_2, \ldots, v_{N_n}\}$ a set of network nodes and $E = \{e_1, e_2, \ldots, e_{N_l}\}$ a set of directed lines with associated flow characteristics. The lines are directed in order to define the positive flow direction. So, a negative flow value for a particular line indicates a flow against the defined line direction. Note that this differs from the commonly used conventions for directed graphs in mathematics, in which it is not possible to follow a pathway against defined line directions. Each line $i$ is defined by a tuple $e_i = (h_i, t_i, r_i, z_{i,\text{max}})$, where:

- $h_i, t_i \in V, h_i \neq t_i$ are the head and tail nodes joined by the line. The positive flow direction is defined to be from head $h_i$ to tail $t_i$. A negative flow value indicates a flow from tail to head.
- $r_i$ is the resistance of $e_i$.
- $z_{i,\text{max}}$ is the flow capacity of the line, the maximal allowable flow through $e_i$.

There is a flow model $\mathcal{F}$ mapping graph $G$ to a network transfer matrix $H$: $H = \mathcal{F}(G)$. This matrix holds the relation between the subtractions $d_k$ (local demand minus local supply)\(^1\) at nodes $\{v_k \mid k = [1, N_n - 1]\}$ and line flows $z_i$ at all lines $e_i$:

$$z = Hd$$

(6.3)

The individual matrix elements $H_{ik}$ represent the influence of the subtraction at node $v_k$ on the flow along line $e_i$: $H_{ik} = \partial z_i / \partial d_k$. In other words, it gives the flow

\(^1\)Throughout this text, ‘demand’ and ‘subtractions’ are defined positively. Supply can be seen as negative demand and injection as negative subtraction.
through $e_i$ as directly caused by the total net demand at $v_k$. Accordingly, the flow along a line $e_i$ is given by:

$$z_i = \sum_{k=1}^{N_n} \frac{\partial z_i}{\partial d_k} d_k$$

(6.4)

Note that, in (6.3), vector $d$ holds the demand at all nodes except node $v_n$. Likewise, this particular node, referred to as the swing node, has no corresponding column in $H$. This is a common property for network matrices describing a closed conservation-of-matter system in physics, as the full matrix is singular by definition. The swing node is generally indicated with a star ($\ast$). So:

$$d_{N_n} = d^\ast$$

(6.5)

For a given set of nodal subtractions $\{d_k | k = [1, N_n - 1]\}$, $d^\ast$ follows from the conservation-of-matter property:

$$d^\ast = -\left[\sum_k d_k + L + \Delta S\right]$$

(6.6)

where $L$ equals the total network losses and $\Delta S$ denotes the change in the amount of commodity stored in the network itself. The magnitude of $L$ and $\Delta S$, if they exist at all, depend on the underlying physics of the commodity in question. We will discuss both $L$ and $\Delta S$ in greater detail later on.

### 6.2.2 Agent model

There is a set of agents $X = \{x_1, x_2, \ldots, x_{N_n}\}$, each agent $x_k$ representing the demand and/or supply at node $v_k$. The agent holds a demand function $d(p)$ stating the agent’s demand against resource price $p$. Each agent must act as a rational trader, i.e. its demand function $d_k(p)$ is continuous and monotonically decreasing.

### 6.2.3 Network-agnostic market clearance

The set of agent demand functions define an allocation problem. As the set of agents represents a closed system, the problem is finding an allocation of the flow commodity at hand over all agents that balances demand and supply. When ignoring the network, the allocation problem is solved by finding the general equilibrium price $p^\ast$ such that:

$$\sum_{k=1}^{N_n} d_k(p^\ast) = 0$$

(6.7)
Under these conditions, market clearance is established, i.e. total demand equals total supply in the agent set. According to the general equilibrium theory in microeconomics, the general equilibrium solution is *Pareto* optimal, a social optimal outcome for which no other outcome exists that makes one agent better-off without making other agents worse-off [49]. From a computational point of view, electronic equilibrium markets are distributed search algorithms aimed at finding the best trade-offs in a multidimensional search space defined by the preferences of all agents participating in the market [78].

When using this network-agnostic solution to the allocation problem, one implicitly assumes (i) the network has infinite capacity, (ii) the network-inherent storage stays stationary and (iii) network losses are negligible.

### 6.2.4 Flow Model

A complete discussion of network flow analysis methodologies is beyond the scope of this document. Hence, we briefly discuss a general steady-state flow model here, following [65]. Congestion management in flow infrastructures is a process that takes place on a time scale of minutes, so, a steady-state model is sufficient for this purpose. The model described here is used later on to indicate the role of the flow model in the market algorithms described.

The flow model \( \mathcal{F} \) maps the graph \( G \) to a network transfer matrix: \( H = \mathcal{F}(G) \). Here, the two important properties of \( G \) are its topology and the resistance values \( r_i \) of the graph’s edges \( e_i \in E \). Incidence matrix \( A \) with size \((N_n - 1) \times N_l\), represents the graph topology and is defined as:

\[
A_{ik} = \begin{cases} 
1, & \text{if } h_i = v_k \\ 
-1, & \text{if } t_i = v_k \\ 
0, & \text{Otherwise}
\end{cases} \quad (6.8)
\]

Resistance matrix \( R \) with size \( N_l \times N_l \), is defined as:

\[
R_{ij} = \begin{cases} 
r_i, & \text{if } i = j \\ 
0, & \text{Otherwise}
\end{cases} \quad (6.9)
\]

From these two matrices the transfer matrix can be calculated as follows:

\[
B = (A^T R^{-1} A)^{-1} \quad (6.10)
\]

\[
H = R^{-1} AB \quad (6.11)
\]

Each column \( k \) of \( H \) describes the flow path of the commodity subtracted at node \( v_k \) from the swing node. The flow values resulting from equation (6.3) can be
regarded as a superposition of all nodal demands being transported from the swing node to the point of subtraction. Figures 6.3 and 6.4 illustrate this for a triangular network, composed of three nodes and three lines. The former figure shows the corresponding network transfer matrix. The latter visualises the superposition of flows caused by individual nodal subtractions. The left side of the figure shows the resulting flows for subtractions $d = (-1, 1)^T$, in a network model without losses and inherent storage. The resulting flows can be regarded as a superposition of two effects, as shown in the right side of the figure. Firstly, injecting commodity at node 1 and the resulting flow to the swing node, and secondly, a subtraction at node 2, resulting in a flow from the swing node.

### 6.3 Locational Marginal Pricing Framework

Equation 6.7 in section 6.2.3 gave the general equilibrium equation for an network-agnostic market clearing process. Now, the challenge is to generalise this market into one that does take the characteristics of the underlying network into account. These network characteristics may have three aspects relevant to this process. Firstly, the commodity flow $z_i$ through each line $i$ will have a maximum allowable flow $z_{i, \text{MAX}}$. Secondly, the total network flow may—depending on the physics of the commodity type—induce network losses $L$, and, thirdly, the amount of commodity stored in the network itself may—again, commodity type dependent—change at a certain time. Changes in *inherent storage* are denoted by $\Delta S$. 

![Triangular network with corresponding transfer matrix $H$. The positive line directions are shown by the arrows in the line labels. Node 3 is chosen to be the swing node and the resistances of the individual lines are chosen to be equal.](image-url)
Figure 6.4: Network flows as a result of demands $d_1 = -1$ and $d_2 = 1$ (right). Superpositional decomposition of these flows into $d = (-1, 0)^T$ (top left), and $d = (0, 1)^T$ (bottom left).

When these network characteristics are accounted for, the market-based optimisation in (6.7) generalises to finding a set of locational prices $(p_1, p_2, \ldots, p_N)$, one for each network node $k$, such that:

$$\sum_{k=1}^{N_n} d_k(p_k) + L + \Delta S = 0$$  \hspace{1cm} (6.12)

$$|z_i| \leq z_{i,\text{MAX}}, \forall i$$  \hspace{1cm} (6.13)

The first equation ensures market clearing: the total demand and supply in the network, plus the total network losses $L$, plus the change in inherent network storage $\Delta S$ must equal to zero. The set of inequalities (6.13) gives a line capacity constraint for each individual line in the network. Note that these equations reduce to the general equilibrium equation (6.7) when transport losses and inherent storage are neglected or absent and all line capacities are sufficient. In that case, all nodal prices $p_k$ become equal to the general equilibrium price $p^*$.

A decomposition of the locational prices $p_k$ into specific components completes the framework. Each component enforces the market outcome to obey one aspect in
the equations (6.12) and (6.13). The price decomposition is defined by:

\[ p_k(t) = \lambda(t) \text{ [Market Clearing Component]} + \eta_{C,k}(t) \text{ [Line Capacity Component]} + \eta_{L,k}(t) \text{ [Network Losses Component]} + \eta_S(t) \text{ [Network Storage Component]} \]

(6.14)

Note that, in general, the demand functions of individual agents are changing over time. Hence, the time-dependency of the market price and its components in (6.14). However, we omit the time dependency from here on for reasons of readability.

Using this pricing scheme, the locational prices in a flow network at a certain time depend on:

- **Demand & Supply**: The total demand and supply in the network, subject to the preferences of all individual agents.
- **Network**: The availability of flow capacity, plus, depending on the physical characteristics of the flow commodity, network losses and/or changes in the amount of commodity stored in the network itself.
- **Spatial demand/supply distribution**: The specific locations of production and consumption in the network.

In the next subsections we will discuss the four price components in detail.

### 6.3.1 Market Clearing Component

The Market Clearing Component \( \lambda \) is the commodity price component used to balance the total demand and supply in the system. This component is equal for all agents attached to the network; there is no locational aspect in this component. In the absence of line capacity constraints, losses and inherent storage, \( \lambda \) is equivalent to the general equilibrium price.

### 6.3.2 Line Capacity Component

The Line Capacity Component \( \eta_{C,k} \) is a price mechanism to allocate the use of scarce network capacity [65]. The component becomes large in magnitude when the maximum capacity of network lines is being approached. This is one of the price components that brings locationality into the pricing scheme: the magnitude of \( \eta_{C,k} \) is dependent on the location in the network and can be different for each network.
node $k$. Each $\eta_{C,k}$ is chosen in such a way that all network flow magnitudes are less than or equal to the maximum capacity of the individual network connections, obeying (6.13).

Assume in a network one line, line $i$ with flow $z_i$, is overloading. We treat that line’s transport capacity as a scarce resource and let a price mechanism allocate its use among the agents. In this case of the single overloaded line $i$, $\eta_{C,k}$ is given by:

$$\eta_{C,k} = \theta_i \frac{\partial z_i}{\partial d_k}$$

(6.15)

Thus, the price component at network node $k$ resulting from this overloaded line $i$ is equal to some term $\theta_i$ multiplied by the incremental flow through $i$ as caused at node $k$. A market clearing mechanism is used to find an appropriate value for $\theta_i$. So, during price forming, $\theta_i$ is adjusted until consuming and producing agents respond by changing their usage or production so that the line overload does not occur.

Equation (6.15) gives $\eta_{C,k}$ for the situation where only line $i$ overloads. The full equation becomes:

$$\eta_{C,k} = \sum_{i=1}^{N_l} \theta_i \frac{\partial z_i}{\partial d_k}$$

(6.16)

where $N_l$ is the number of lines in the network. Naturally, $\theta_i$ needs to be nonzero, only if line $i$ would be overloaded otherwise. Hence the condition:

$$|z_i| \leq z_{i,\text{MAX}} \leftrightarrow \theta_i = 0, \forall i$$

(6.17)

Dependent on the sign of the partial derivative term, $\eta_{C,k}$ can be positive or negative. Those locations $k$, where an increase in demand $d_k$ leads to a decrease in flow $z_i$, have a negative $\eta_{C,k}$. Since both producers and consumers at $k$ are having the same locational price $p_k$, and increasing demand at $k$ will have an equal effect as decreasing supply at $k$, both producers and consumers have equal incentive to respond to prevent the line overload. Further, note that actors having a higher ‘network distance’ from an overloaded line will have a lower influence on the flow over that line. Hence, their $\partial z_i/\partial d_k$ is lower and, accordingly, their incentive to respond is lower.

### 6.3.3 Transport Network Losses

One of the special phenomena occurring when flow commodities are transported is the loss of commodity. A resource allocation method must take these losses into account. If not, the theoretical commodity balance found by the method will yield commodity imbalance in practice. Naturally, the losses add to the total demand
6.3. Locational Marginal Pricing Framework

in the network. Losses can be incorporated in the market search by considering the
associated costs, which are equal to the loss magnitude \( L \) times the commodity price
\( \lambda \). As different network locations will face different losses, different network nodes
\( k \) may have different magnitudes for \( \eta_{L,k} \).

The marginal cost for network losses at location \( k \) is given by [65]:

\[
\eta_{L,k} = \lambda \frac{\partial L}{\partial d_k} \tag{6.18}
\]

where \( L \) equals the total network losses at time \( t \). Thus, the network losses price
component at node \( k \) is equal to the commodity price multiplied by the incremental
system losses as caused at \( k \). When the losses of an individual line depend on the
actual line flow, then \( L = \sum_i L_i[z_i] \), and (6.18) can be expanded into:

\[
\eta_{L,k} = \lambda \sum_{i=1}^{N_l} \frac{\partial L_i[z_i]}{\partial z_i} \frac{\partial z_i}{\partial d_k} \tag{6.19}
\]

6.3.4 Network Inherent Storage

For specific flow commodities there is a certain amount of the commodity contained
in the flow network. The stored amount may change over time, when the total feed-
in to the network is unequal to the total feed-out. The magnitude of \( \Delta S \) is the result
of the spatial distribution of demand and supply in the network.

Price component \( \eta_S \) is defined as:

\[
\eta_S = \lambda \Delta S \tag{6.20}
\]

Since \( \Delta S \) cannot be accounted to specific nodes, as is the case with network losses,
the cost (or benefit) of the storage changes are accounted for regardless of location-
ality.

6.3.5 The Locational Price

Substituting the above results in (6.14) yields:

\[
p_k = \lambda + \sum_{i=1}^{N_l} \theta_i \frac{\partial z_i}{\partial d_k} + \lambda \frac{\partial L}{\partial d_k} + \lambda \Delta S \\
= \lambda \left( 1 + \frac{\partial L}{\partial d_k} + \Delta S \right) + \sum_{i=1}^{N_l} \theta_i \frac{\partial z_i}{\partial d_k} \tag{6.21}
\]
6. Network Feasibility in Resource Allocation

6.4 Analysis

6.4.1 Search Space and Convergence

In market-based resource allocation, each agent’s demand function $d_a(p)$ is generally required to be continuous and monotonically decreasing. A general equilibrium search (6.7) tries to find a root of the aggregate demand function $\sum d_a(p)$, which is also a continuous, monotonically decreasing function. Thus, if a solution exists (i.e. there is sufficient elasticity in supply and demand), this is a unique equilibrium point and the search is guaranteed to converge to it.

In our case, price forming is a search in a space of $(N_l + 1)$ dimensions. This search space is defined by $(\lambda, \theta_1, \theta_2, \ldots, \theta_N)$. Any set of values for these parameters yields a set of locational prices $(p_1, p_2, \ldots, p_N)$ according to equation (6.21). These prices must be chosen such that the market clears (6.12) and the line capacity constraints (6.13) are met.

The $\lambda$ price component determines the supply/demand balance in the network. By substituting the locational price equation (6.21) in the commodity balance constraint (6.12) while omitting $L$ and $\Delta S$, the search space along the $\lambda$-dimension is obtained:

$$\sum_{k=1}^{N_k} d_k \left( \lambda + \sum_{i=1}^{N_l} \theta_i \frac{\partial z_i}{\partial d_k} \right) = 0 \quad (6.22)$$

Since all $d_k$ are continuous and monotonically decreasing, the left-hand side of this equation shares these properties. Consequently, if for a given set of $\theta_i$ values there exists a $\lambda$ such that total demand equals total supply, this solution is unique and a search in $\lambda$ will converge to it.

Each individual $\theta_i$ ensures the line capacity constraint of one line is met. To assess its convergence properties, suppose we vary $\theta_i$ while $\lambda$ and all other $\theta$-values remain stationary. Then, for all nodes $k$ with $H_{i,k} = \partial z_i / \partial d_k \neq 0$, an increase in $\theta_i$ will result in a change in nodal demand in a direction opposite to the sign of $H_{i,k}$. In short:

$$\frac{\partial z_i}{\partial d_k} > 0 \Rightarrow p_k \uparrow_{\theta_i} \Rightarrow d_k(p_k) \downarrow_{\theta_i}$$

$$\frac{\partial z_i}{\partial d_k} < 0 \Rightarrow p_k \downarrow_{\theta_i} \Rightarrow d_k(p_k) \uparrow_{\theta_i}$$

where $\uparrow_{\theta_i}$ denotes “continuously and monotonically increasing in $\theta_i$.” The first step follows from the nodal price definition (6.21), the second from the requirement of demand functions to be defined as continuously and monotonically decreasing.
Both $H_{i,k}$ and $d_k(p_k)$ influence flow $z_i$, according to (6.4), such that:

$$
\begin{align*}
\frac{\partial z_i}{\partial d_k} > 0 & \quad \Rightarrow \quad z_i \downarrow \theta_i \\
\frac{\partial z_i}{\partial d_k} < 0 & \quad \Rightarrow \quad z_i \downarrow \theta_i 
\end{align*}
$$

Thus, for every node with a nonzero influence on $z_i$, an increase in $\theta_i$ will result in a decrease in $z_i$. Consequently, if any line $i$ is overloaded, there is a unique value for $\theta_i$ where $z_i = z_{i,max}$. As $z_i$ is continuously and monotonically decreasing in $\theta_i$, a search will converge to this solution, provided there is enough elasticity in those demands $d_k(p_k)$ for which $H_{i,k} \neq 0$.

### 6.4.2 Combining Locational Pricing and Flow Analysis

Due to the swing node’s absence in the network transfer matrix $H$, some special features arise that are important when solving the optimisation problem:

#### Market Clearing

The demand of the swing node can be computed in two distinct ways, denoted here as $d^{*1}$ and $d^{*2}$, respectively. The first one follows from the flow analysis. Taking (6.6), and assuming the swing node has the highest node number, yields:

$$
\begin{align*}
\tilde{d}^{*1} & = - \left[ \sum_{k=1}^{N_n-1} d_k(p_k) + L + \Delta S \right] 
\end{align*}
$$

Secondly, the swing node demand follows from the local demand function and the local price:

$$
\tilde{d}^{*2} = d_k(p_k), \text{ with } k = N_n
$$

It may be clear that $\tilde{d}^{*1} = \tilde{d}^{*2}$ must hold in a sound solution to the optimisation problem. Consequently, any set of prices $p_k, k = 1 \ldots N_n$ that results in equal values for $\tilde{d}^{*1}$ and $\tilde{d}^{*2}$ complies with the commodity balance constraint (6.12).

#### Swing Nodal Price

Being the balancing item in the flow calculation, demand or supply at the swing node has no modelled influence on any flow in the network. This is logically as
subtractions at all other nodes are modelled to be flowing from this node. One could state that the flow model assumes:

$$\frac{\partial z_i}{\partial d^*} = 0, \quad \forall i$$  \hspace{1cm} (6.25)

Substituting above equation in (6.21) and using the expanded loss component (6.19) yields the swing node price:

$$p^* = \lambda (1 + \Delta S)$$  \hspace{1cm} (6.26)

So, while the demand or supply at the swing node has no effect on the network flows, its local price has no effect on line congestions and line losses. The price at the swing node only depends on those price components that have no associated locational aspects.

In case the network exhibits no or negligible inherent storage, as is the case with electricity, the swing node price becomes:

$$p^* = \lambda$$  \hspace{1cm} (6.27)

**Losses and Line Capacity Components**

As described in section 6.2.4, the result of a load flow calculation is a superposition of all nodal demands being transported from the swing node. The $H$-matrix describes the flow paths from the swing node to every individual node. As a result, for a node $k$, all $H_{i,k} = \frac{\partial z_i}{\partial d_k}$ values for lines $i$ that are not part of a possible flow path between node $k$ and the swing node are equal to zero. As a consequence, the losses component $\eta_{L,k}$ for any node $k$ is the price for the losses of transporting the demand at $k$ from the swing node. Similarly, the line capacity price component $\eta_{C,k}$ is only influenced by the lines that are in a possible flow path between $k$ and the swing node.

### 6.5 Market Algorithm for Network Feasible Solutions

In this section we describe a novel agent-based market algorithm that solves the constrained optimisation problem described above. For reasons of clarity—but without loss of generality—we omit the price components for losses and inherent storage in the descriptions. Both characteristics can be added easily by implementing models for $L$ and $\Delta S$ and incorporating these in the code lines where the nodal prices are calculated.
6.5. Market Algorithm for Network Feasible Solutions

6.5.1 Algorithm Description

The algorithm is distributed over three types of agents: an Auctioneer Agent, a Node Agent for every node and a Line Agent for every line. The Auctioneer is responsible for concerting the optimisation process in consecutive market rounds. Further the Auctioneer searches for the $\lambda$ value that clears the market, i.e. minimising the difference between equations (6.23) and (6.24). The individual Line Agents determine their own $\theta_i$ value in order to solve capacity constraint violations, if any. The Node Agents communicate their preferences for consumption or production of the commodity at the start of each market run. Afterwards, they receive their nodal price and implement their allocation. We assume the presence of only one consuming and/or producing agent per node. When more agents are present at one node the Node Agent becomes an aggregator of all connected agent’s preferences. Below we give pseudocode for all three agent types.

The pseudocode of the \textsc{AuctioneerAgent} is given by:

\begin{verbatim}
AUCTIONEERAGENT(H, NodeAgentList, LineAgentList)
  ϵ ← 0.0001
  while True
do
    WaitNextMarketRound()
    Send(BidReq, NodeAgentList)
    D ← Receive(Bids, NodeAgentList)
    λ ← EQUILIB-PRICE(D)  # First guess.
    θ: row vector of $\theta_i$ values.
    θ[i] ← 0, i = 1...N_l  # First guess.
    repeat
      λ: search for commodity balance.
      λ_old ← λ
      λ ← FINDZERO(F-LAMBDA($\lambda$, Θ, H, D), λ)
      δ_λ ← ABS(λ_old − λ)
      # Request new $\theta$ from line agents.
      Send(ThetasReq, LineAgentList, λ, Θ)
      Θ_old ← Θ
      Θ ← Receive(Thetas, LineAgentList)
      δ_Θ ← MAX(ABS(Θ_old − Θ))
      until MAX(δ_λ, δ_Θ) < ϵ
    P ← $\lambda + \Theta \ast H$  # array of nodal prices
    # Communicate prices to the node agents.
    for k ← 1 to N_n
do
      Send(Price, NodeAgentList[k], P[k])  # Signal market round end to line agents.
    Send(MarketReady, LineAgentList)

We start the description of the code by making some general remarks important
for all given code:

- **Agent Communications:** The agents communicate using the message passing procedures `SEND` and `RECEIVE`. The first takes a message ID as a first parameter (e.g. `BidREQ`), a (list of) Agent ID(s) as a second followed by an optional list of parameters to be send along with the message. `RECEIVE` blocks operation until the specified message is (or messages are) received. It has two possible forms, receiving either a message of one single agent or receiving messages from a list of agents. The latter form returns the received parameters in an array.

- **Demand Function:** The demand function data structure is not specified in detail. A possible form is an array of tuples \((p, d)\). For computational reasons, the chosen structure must allow for fast aggregation of demand functions by adding price-wise. Evaluation of a demand function \(d\) for a given price is denoted in the pseudocode as \(d(p)\). For the tuple-based data structure, this would involve interpolation between two tuple values. For reasons of simplicity this is not included in the pseudocode.

- **Root Finding:** The procedure `FINDZERO` implements a univariate root finding algorithm. The call:
  \[
  x \leftarrow FINDZERO(F(x, y, z), x_0)
  \]
  searches for a root of the function \(F\) with \(x\) as free parameter. The search starts at \(x_0\) and parameters \(y\) and \(z\) are considered to be constant during the search.

The `AUCTIONEERAGENT` requests for the demand function of all `NODEAGENT` instances at the beginning of each market round. Using these functions and the network transfer matrix \(H\), which is given to as a parameter to the Auctioneer, a search for \(\lambda\) and \(\theta_i\), \(\forall i\) is started. As a first guess \(\lambda\) is set to the general equilibrium price and all \(\theta\) values are set to zero. In the `repeat` loop the agent consecutively searches for the \(\lambda\) value that gives commodity balance for current \(\theta\) values and requests the Line Agents for \(\theta\) updates. When this optimisation ends, the nodal prices are sent to the individual Node Agents.

The objective function for the \(\lambda\) optimisation is:

\[
F\text{-LAMBDA}(\lambda, \Theta, H, D)
\]

1. \(\triangleright\) Calculate nodal price vector \(P\)
2. \(P = \lambda + \Theta \ast H\)
3. \(\triangleright\) Swing-nodal demand from load flow.
4. \(d^1 \leftarrow \sum_{k=1}^{N_{n-1}} D(k||P||k)\)
5. \(\triangleright\) Swing-nodal demand from demand function.
6. \(d^2 \leftarrow D[N_{n}](\lambda)\)
7. \(\triangleright\) Goal: \(d^1\) equal to \(d^2\)
8. \text{return } d^1 - d^2
The Node Agents are assumed to operate some process that produces or consumes the commodity. Their demand function will be influenced by the state of that process. Upon request by the Auctioneer, the agents compose their bid and send it to both the Auctioneer and all Line Agents. The Line Agents use the bids for calculating their expected line flow.

\[
\text{NODEAGENT}(\text{AuctioneerAgent, LineAgentList})
\]

1. while True
2. do
3. REceive(BidReq)
4. \( d = \text{COMPOSEBid(ProcessState)} \)
5. SEND(BID, AuctioneerAgent, d)
6. SEND(BID, LineAgentList, d)
7. \( p \leftarrow \text{REceive(Price)} \)
8. CONSUMEALLOCATION(d(p))

The pseudocode for the LINEAGENT is:

\[
\text{LINEAGENT}(i, H, z_{i,\text{MAX}}, \text{AuctioneerAgent, NodeAgentList})
\]

1. \( \triangleright \) Select the 'own', i-th, row from \( H \)
2. \( H_i \leftarrow H[* , i] \)
3. while True
4. do
5. \( D \leftarrow \text{REceive(BIDS, NodeAgentList)} \)
6. repeat
7. \( [\lambda, \Theta] \leftarrow \text{REceive(THETAREQ)} \)
8. \( \triangleright \) Calculate nodal price vector \( P \)
9. \( P = \lambda + \Theta * H \)
10. \( \triangleright \) Calculate the line flow \( z \)
11. \( z_i = H_i * D(P) \)
12. if \( |z_i| < z_{i,\text{MAX}} \)
13. then \( \theta_i \leftarrow 0 \)
14. else \( \triangleright \) find \( \theta \) to solve overload
15. \( \theta \leftarrow \text{FINDZERO}(F-\text{THETA}(\theta_i, i, \lambda, \Theta, H_i, D, z_{i,\text{MAX}}), \Theta[i]) \)
16. \( \text{SEND(THETA, AuctioneerAgent, } \theta) \)
17. until PeekNextMsg() = \text{MARKETREADY}
18. \( \triangleright \) Consume peeked \text{MARKETREADY} message
19. Dummy \( \leftarrow \text{REceive(MARKETREADY)} \)

The objective function for the \( \theta \) optimisation is given by:
6. Network Feasibility in Resource Allocation

Table 6.2: Line flows for the General Equilibrium and Network Feasible solutions.

<table>
<thead>
<tr>
<th></th>
<th>( z_1 )</th>
<th>( z_2 )</th>
<th>( z_3 )</th>
<th>( z_4 )</th>
<th>( z_5 )</th>
<th>( z_6 )</th>
<th>( z_7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE</td>
<td>1.4</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>1.8</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>NF</td>
<td>1.0</td>
<td>0.4</td>
<td>0.6</td>
<td>0.4</td>
<td>1.0</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( z_8 )</td>
<td>( z_9 )</td>
<td>( z_{10} )</td>
<td>( z_{11} )</td>
<td>( z_{12} )</td>
<td>( z_{13} )</td>
<td>( z_{14} )</td>
</tr>
<tr>
<td>GE</td>
<td>2.4</td>
<td>0.8</td>
<td>0.5</td>
<td>2.1</td>
<td>1.2</td>
<td>0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>NF</td>
<td>1.0</td>
<td>1.0</td>
<td>0.7</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

F-\( \text{THERA}(\theta_i, i, \lambda, \Theta_i, H_i, D, z_i, \text{MAX}) \)

1. \( \triangleright \) Calculate line flow \( z_i \) for this \( \theta_i \)
2. \( \Theta[i] \leftarrow \theta_i \)
3. \( P = \lambda + \Theta * H \)
4. \( z_i = H_i * D(P) \)
5. \( \triangleright \) Goal: \(|z_i| \) equal to \( z_i, \text{MAX} \)
6. if \( z_i > 0 \)
7. \( \text{then return } z_i - z_i, \text{MAX} \)
8. \( \text{else return } z_i + z_i, \text{MAX} \)

6.5.2 Example

Figure 6.5 gives an example algorithm outcome. Each of the lines has a capacity constraint of 1. All demand is located in the four nodes to the far left, while all supply is at the four nodes far right. All demand functions are S-shaped (i.e. sigmoidal) with the inflexion point at varying price levels between 5 and 15. The maximum demand per node is 2 for consuming nodes and –2 for producing nodes. It can be seen from the figure that in the network feasible (NF) solution the nodal prices are such that neither of the line flows exceeds the limit of 1. In the general equilibrium (GE) solution, six of the 14 lines are overloaded as shown in Table 6.2.

6.6 Conclusion

Current methods for market-based allocation of flow resources ignore transport network characteristics and constraints. This limits their applicability in larger-scale industrial applications, which often are distributed over a large regional area and use congested transport networks. In this chapter, we introduced the concept of locational marginal pricing in passive flow-commodity networks to the discipline of Computer Science. Building forth on the Locational Marginal Pricing framework in power systems economics, we formulate a general-applicable Multi-agent Systems
framework for finding network-feasible solutions in commodity flow networks. The framework describes a pricing scheme that enforces the electronic equilibrium market to find solutions that are feasible for the underlying transport network, i.e. obeying network constraints and accounting non-constraining network characteristics such as network losses and network-inherent storage. This pricing scheme is generally applicable to all types of flow resources. We have shown that, under the common condition of demand and supply elasticity, the constrained optimisation problem posed by the framework has a unique solution and a search in the parameter space will converge to that solution. Further, this chapter presents an algorithmic method for finding this transport network feasible solution in market-based flow resource allocation, and the algorithm has been demonstrated for a medium-sized

Figure 6.5: Example network feasible market result. The maximum line capacity is set to 1 for each line.
example network.

6.6.1 Relevance to Computer Science

This work adds new capabilities to the existing algorithms for resource allocation. There is a large literature base on resource allocation in switched networks transporting discrete objects (e.g. streams of data packets in information networks or streams of vehicles in road networks). This thesis adds a new network/stream combination to this knowledge base, namely passive flow networks and continuous flow commodities.

6.6.2 What’s next?

For our focus field of the future smart electricity network, this is an important result as, now, market-based control can be used in the electricity grid without treating the grid as a copper plate. However, LMP has been designed for the interaction between the electricity wholesale markets and the high-voltage transmission networks. As the distribution part of the infrastructure is much finer grained the standard LMP algorithm is less suitable to be used there. In the next chapter a solution is provided for this problem by introducing a fast algorithm tailored for the task of congestion management in distribution networks.
Chapter 7

Locational Pricing in Radial Networks

SYNOPSIS: Locational marginal pricing is an important mechanism for our research goal. LMP gives means to utilise DER flexibility for system-level balancing and for active management of the distribution networks simultaneously. However, LMP has been designed for the electricity transmission networks, where scalability is less of an issue. In electricity distribution, both the number of network nodes as well as the number of connected actors to be involved is much higher. This results in an heavier computational burden when applying LMP to these networks as the LMP algorithm scales badly with the number of network nodes. The work performed to answer the research question regarding Locational Pricing in Radial Networks (Q3) investigated how to reduce this computational complexity by making use of the differences in topology between distribution and transmission networks. In the distribution part of the electricity infrastructure, networks are predominantly operated in a radial, acyclic, topology. Flow calculations in radial networks are quite straightforward, as subtractions or injections at a certain node have a one-on-one influence on the flow through the lines between the root of the tree and that node. Making use of this property, a fast algorithm for locational marginal pricing (LMP) in radial networks has been developed. The algorithm makes only two passes through the network to come to a network feasible power flow at each network location. Accordingly, the method yields a local power flow that is (i) within the local line capacity constraint, and (ii) accounts for network losses.

AS MENTIONED BEFORE, the “electrification of everything” will put a major strain on the (low to medium voltage) distribution networks. In the future, congestion management will be a standard ingredient of a more active management of these networks. So, there is a need to use locational marginal pricing in distribution networks. Originally, however, LMP has been designed for the interaction between the electricity wholesale markets and the high-voltage transmission networks. Electricity distribution networks are different in nature than the
transmission networks as their number of network nodes and connected actors is much higher. The LMP algorithm does not scale well with regard to the number of nodes in the network, which gives a problem when applied to the distribution level in the electricity system.

Another difference between the distribution and transmission networks is their topology. Where transmission networks are generally operated in a meshed topology, the distribution networks are predominantly operated in a radial, non-cyclic, topology. Naturally, for reasons of security of supply, these networks are built such that each group of customers can be reached via more than one network route. However, in normal operation, the network is generally switched such that only one route is used at the time. Power flow analysis, the calculation of power flows through a known network given all production and consumption at the network’s nodes, is quite straightforward in radial networks. This observation leads to the following research subquestion:

Q3. **Locational Pricing in Radial Networks:** How can algorithms for Locational Marginal Pricing in non-cyclic passive flow networks take advantage of this topological property to find solutions against a lower computational burden?

In this chapter, we present a fast algorithm for determining network-feasible locational marginal prices in acyclic networks. The proposed algorithm builds forth on a idea of bid function transformations as briefly sketched by Hommelberg et al. [34]. The algorithm propagates demand functions from the leaves of the tree to the root (swing node) in the first phase and back-propagates the nodal prices to the leaves in the second phase. In the first phase, the demand functions are transformed according to the local network characteristics: line capacities and transport losses. These transformations take place when a demand function is transferred from one end of a specific line to the other, hence the used term propagation. The propagation process ensures that a demand function associated to a specific location in the network is network feasible. A network-feasible demand function yields for any price a local flow that is (i) within the local line capacity constraint, and (ii) accounts for network losses. Note that, in the previous chapter, we described locational marginal pricing (LMP) in passive flow networks from a computer science point of view. There, we gave a general description for all possible types of flow commodities, including liquid and gas flows. Here, we will focus on electricity and, thus, we will omit network inherent storage.

Section 7.1 outlines the algorithm, Section 7.2 gives a formal description and Section 7.3 gives an example using a six-bus network. In Section 7.4, some variants of the algorithm are discussed. One of the variants is used in a field validation as will be described in Chapter 13, Section 13.4. Section 7.5 concludes the chapter.
7.1 Method Outline

7.1.1 Radial Networks

Here, we reuse the network and agent models as described in section 6.2. In short, we model a flow network by a directed graph \( G = (V, E) \), with \( V = \{v_1, v_2, \ldots, v_N\} \) a set of network nodes and \( E = \{e_1, e_2, \ldots, e_N\} \) a set of directed lines. Each line \( e_i \) has defined flow characteristics: \( z_{i, \text{max}} \) giving the maximal allowable line flow and \( r_i \) giving the resistance of the line. For each line the positive flow direction is from head to tail. Each node has an agent associated, representing the (net) demand and supply in that node. The agent holds a demand function \( d(p) \) stating the agent’s demand against resource price \( p \). Further, each agent must act as a rational trader, i.e. its demand function \( d_k(p) \) is continuous and monotonically decreasing. Please, refer back to 6.2 for more details.

We define an acyclic network a network without any cycles regardless the direction of the lines. In an acyclic network, there is no pathway starting at some node \( v_k \) and following a sequence of lines for each line either in the positive or negative direction that eventually leads back to \( v_k \) again. This type of network is also referred to as a tree or a radial network. We refer to the subtree rooted in node \( k \) as subtree \( k \). We assume the swing node (\( v_{N_0} \) or \( v^* \)) is the root of the tree structure, with all lines directed away from the root, i.e. for each line the head is closer to the root than the tail. Accordingly, the positive flow direction is from root towards the leaves. Further, we assume there is only power demand or supply in the leaves. This is without loss of generality as demand or supply in any non-leaf node can be modelled by a line from that node to a leaf accommodating the demand and/or supply of the tree node.

Note that, in acyclic networks, all \( H_{ij} \) elements of the network transfer matrix \( H \) (as described in 6.2.1) are either 1 or 0, as there exists only one unique path between each node and the swing node. This means that subtractions or injections at a certain node only influence the flow through the lines between the root of the tree and that node. As a result, the flow through a certain line \( i \) connecting a sub tree rooted at node \( k \) to the rest of the network is equal to the net demand in that subtree. So, if the concentrated demand function of that sub tree is known, all possible line flows through \( i \) (dependent on the local price at \( k \)) are known. Consequently, it is known for which nodal prices the line \( i \) will be overloaded and what the line losses in \( i \) are for each nodal price. The proposed algorithm is based on altering the concentrated demand function such that the line capacity constraint will be met at all times and line losses are accounted for.
7.1.2 Propagation of Capacity Constraints

Assume that line $i$ has node $k$ as tail node and $j$ as head node and, thus, connects subtree $k$ to the rest of the network via node $j$. Let $a_k(p)$ be the concentrated demand function representing all demand and supply in the subtree. Then, all prices $p_k$ for which $|a_k(p_k)| > z_{i,\text{max}}$ will overload line $i$. To prevent this, $|a_k(p)|$ is limited to $z_{i,\text{max}}$ for exactly these prices. An example of this alternation is shown in figure 7.1. The resulting demand function is network sound for line $i$ and is propagated over this line. In this way, only the network-sound contribution of subtree $k$ to the system-level demand/supply balance is taken into account in the price forming at the swing node.

In the second phase of the algorithm, when the price is propagated back from the root to the leaf nodes, the nodal price $p_k$ is determined from the nodal price at $j$ as shown in figure 7.2. Input to this process are the original, untransformed, demand function $a_k$ and price $p_j$. The figure shows three distinct cases:

(A): Price $p_j$ does not cause line overloading. Price $p_k$ is set to $p_j$.

(B): Price $p_j$ will result in an overloading demand level. Price $p_k$ is set to the price that results in a demand equal to the line capacity $z_{i,\text{max}}$.

Figure 7.1: Demand function propagation accounting for the line capacity of line $i$: for the prices where demand or supply exceeds line capacity $z_{i,\text{max}}$, it is limited to the value of $z_{i,\text{max}}$. 
7.1.3 Propagation of Line Losses

Again, think of a subtree $k$ in an acyclic network connected by line $i$ to node $j$. Now, the question is to transfer the demand function $a_k(p)$ of the subtree into one incorporating the line losses in line $i$. For a given flow $z_i$, the losses in $i$ are known, as the line resistance $r_i$ is known for each line. Further, for each price $p_k$, this flow equals to $a_k(p_k)$. So, the line losses in $i$ are directly dependent on $p_k$. Consequently, creating a network-sound demand function with regards to losses comes down to adding the expected losses to the demand function at node $k$, as shown in figure 7.3.

For losses, there is no price back-propagation procedure. The losses in all lines in the network are incorporated in the total aggregated demand function at the root node. This ‘extra’ demand in the system results in a higher swing-nodal price as
compared to the situation in which the losses are neglected. This higher price causes a decrease in demand, which results in lower losses, and an increase in supply, such that the remaining losses are covered.

### 7.2 Formal Algorithm Description

The algorithm is distributed over four types of agents. Leaf Agents are representing the demand and supply in the leaves of the network tree. Line Agents are performing the demand function propagation and the price back propagation over the network line it represents. Node Agents are concentrating all incoming bids of the locally connected subtrees and passing it on towards the tree root. Finally, there is one unique Root Agent that does the market clearing.

The algorithm uses four different algorithmic operators:

- **PROPAGATE**: used by line agents to keep a demand function network sound while transferring it over the network line to the next node towards the root node.

- **CONCENTRATE**: used by the network node agents (including the root agent) to concentrate incoming demand functions.
7.2. Formal Algorithm Description

- FINDROOT: root finding function used to determine the nodal price at the swing node.
- PRICEBACKPROP: price back-propagation function used by each line agent to determine the nodal price at its tail end.

7.2.1 Propagate

The propagate operator propagates a concentrated demand function at a given node \(v_k\) over the first line, denoted \(e_i\), in the path between \(v_k\) and the root, i.e. \(v_k\) is the tail of \(e_i\). The operator accounts for the line capacity and network losses. The propagated demand function \(a_k(p)\) for a line capacity constraint is calculated as:

\[
\overline{a}_k(p) = \begin{cases} 
  z_{i,\text{max}} & z_{i,\text{max}} < a_k(p) \\
  a_k(p) & -z_{i,\text{max}} \leq a_k(p) \leq z_{i,\text{max}} \\
  -z_{i,\text{max}} & a_k(p) < -z_{i,\text{max}} 
\end{cases} \quad (7.2)
\]

while the propagated demand function for line losses can be calculated as

\[
\pi_k(p) = a_k(p) + l_i a_i^2(p) \quad (7.3)
\]

where \(l_i\) is the loss factor, which is a function of the line resistance \(r_i\). Naturally, the propagation in (7.2) and (7.3) can be combined in one operator.

7.2.2 Concentrate

The concentration operator concentrates, for a given node \(v_k\), the local demand function \(d_k(p)\) and the demand functions \(\overline{a}_i(p)\) propagated into the node. The node receives incoming demand functions from all connected lines directed away from it. The concentrated bid at node \(v_k\) is calculated as:

\[
a_k(p) = \sum_{i : e_i \in Y_k} \overline{a}_i(p) \quad (7.4)
\]

where \(\overline{a}_i(p)\) is the demand function propagated to \(v_k\) over line \(e_i \in Y_k\). \(Y_k\) is defined as:

\[
Y_k = \{ e_i | h_i = v_k \} \quad (7.5)
\]

the set of lines directly connected to \(v_k\) and directing away from the root of \(G\).
7.2.3 Swing Nodal Price

The price at the swing node ($v_{N_n}$) is chosen such that the market at the swing node is in equilibrium:

$$a_{N_n}(p_{N_n}) = 0$$  \hspace{1cm} (7.6)

where $a_{N_n}(p)$ is the concentrated demand function for the swing node.

7.2.4 Price Back Propagation

The price at the swing node is then propagated back along each line in the tree network using the price-back-propagation operator. This operator determines the nodal price for each node $v_k$. Consider a node $v_k$ directly connected by line $e_i$ to node $v_j$, with $v_j$ being the head and $v_k$ the tail of the line. Then, $v_k$ gets its nodal price back-propagated from node $v_j$. When $v_j$ has a back-propagated price $p_j$, then for the propagation in (7.2), $p_k$ is calculated as:

$$p_k = \begin{cases} p_j & |a_k(p_j)| \leq z_{i,\text{max}} \\
 p_k : a_k(p_k) = z_{i,\text{max}} & a_k(p_j) > z_{i,\text{max}} \\
 p_k : a_k(p_k) = -z_{i,\text{max}} & a_k(p_j) < -z_{i,\text{max}} 
\end{cases}$$  \hspace{1cm} (7.7)

7.2.5 Agent Pseudocode

The agents communicate using message passing procedures SEND and RECEIVE. The first takes a message ID as a first parameter (e.g. BidREQ), an Agent ID (List) as a second followed by one or more optional parameters to be send along with the message. RECEIVE blocks operation until the specified message is (or messages are) received. It has two possible forms, receiving either a message of one single agent or receiving messages from a list of agents. The latter form returns the received parameters in an array.

The Leaf Agent

The pseudocode of LEAFAGENT is quite straightforward. After reception of a bid request, it composes its bid according to its current preferences. The bid is sent off to the Line Agent associated with the line connected to the agent’s node. After reception of the resource price the agent consumes its allocated power given by $d(p)$.
7.2. Formal Algorithm Description

LEAFAGENT(Line)

while TRUE
  do
    ▷ First Phase:
    RECEIVE(BidReq, Line)
    d = COMPOSEBid(Preference)
    SEND(Bid, Line, d)
    ▷ Second Phase:
    p ← RECEIVE(Price, Line)
    CONSUMEALLOCATION(d(p))

The Line Agent

The line agent keeps the local concentrated demand function network sound by incorporating the line characteristics for flow capacity and losses. Further the line agent determines the nodal price at its tail node.

LINEAGENT(HeadNode, TailNode)

while TRUE
  do
    ▷ First Phase:
    a ← RECEIVE(Bid, TailNode)
    π ← PROPAGATE(a)
    SEND(Bid, HeadNode, π)
    ▷ Second Phase:
    p_j ← RECEIVE(Price, HeadNode)
    p_k ← PRICEBACKPROP(p_j)
    SEND(Price, TailNode, p_k)

The Node Agent

The Node Agent holds a list of lines connecting the node to subtrees, referred to as its child lines. Further it holds the ID of the line agent connecting the node to its parent node. In the first phase of the algorithm, the node agent concentrates all incoming bids and passes it on towards the tree root. In the second phase, the agent receives its nodal price from the parent line and passes this to its child lines.

NODEAGENT(ChildLineList, ParentLine)

while TRUE
  do
    ▷ First Phase:
    A ← RECEIVE(Bid, ChildLineList)
    a_k ← CONCENTRATE(A)
    SEND(Bid, ParentLine, a_k)
    ▷ Second Phase:
    p_k ← RECEIVE(Price, ParentLine)
    SEND(Price, ChildLineList, p_k)
The Root Agent

Each iteration, the Root Agent starts with waiting for a trigger for a next market round. This trigger can be coming from a timer or some external event. After the trigger, the root agent starts the whole market process in the tree of agents by requesting a bid from the leaf agents. Eventually, this leads to the reception of propagated demand functions from all child lines. Then, the root agent determines its own nodal price by concentrating these bids and performing a search for the function root. This price is passed back to the child lines.

Pseudocode for ROOTAGENT:

```
ROOTAGENT(ChildLineList, LeafAgentList)
1 while TRUE
2   do
3     ➤ First Phase:
4     WAITNEXTMARKETROUND()
5     SEND(BIDREQ, LeafAgentList)
6     A ← RECEIVE(BID, ChildNodeList)
7     ➤ Second Phase:
8     a_n ← CONCENTRATE(A)
9     λ ← FINDROOT(a_n)
10    SEND(PRICE, ChildNodeList, λ)
```

7.3 Example

Consider the island network in Figure 7.4, which contains a swing generator $S$, an industrial load $R_I$ and two identical districts $A$ and $B$, represented by the buses $B_5$
7.3. Example

and $B_6$ respectively. Each district contains a load ($R_A$ and $R_B$) and a generator ($G_A$ and $G_B$). The districts are connected to a common bus $B_2$ by lines $e_4$ and $e_5$. Bus $B_2$ is connected to bus $B_1$ by a long line $e_1$. It is assumed that all loads and generators in the network have flexibility to some extent. In this example, only active power is being considered, thus no voltage levels and reactive power are taken into account. Each load and generator is represented by a leaf agent that buys or sells electricity against the marginal costs of the load or generator. The root agent of this network resides at bus $B_1$ and there are concentrators at buses $B_2$, $B_5$ and $B_6$. Four
cases have been considered and the results are shown in table 7.1\(^1\). Additionally, the demand functions of the individual leaf agents, as well as the transformed and non-transformed aggregated demand functions of the node agents in the four cases have been plotted in Figure 7.5.

To provide a reference, the example network was first calculated without any constraints and thus, the market clearing price of 5.75 was the same for the global and local markets.

The second case considered a capacity flow limit of the line \(e_{4}\), which was implemented by using the propagation operator as defined in (7.2). The maximum capacity for this line was set to \(z_{5,\text{max}} = 15\). As a result, the global market price has decreased with respect to the reference case, while the local market price in district \(A\) has increased. In the reference case the load on line \(e_{4}\) was 24.06, which violates the maximum capacity that exists for that particular line. With the price increase, the production has increased and the demand decreased, such that the load on the line is exactly 15. Consequently, district \(A\) demands less electricity on the global market, making the price in the unconstrained districts to go down.

The third case considered significant energy losses on line \(e_{1}\) with respect towards the reference of Case 1, i.e. there were no other constraints in the network, using the operator in (7.3), with \(l_{1c} = 2 \cdot 10^{-3}\). The losses in line \(e_{1}\) were 24.41, which were mainly compensated by an increase of production of generators \(G_A\) and \(G_B\). A positive side effect of this, is that the net demand and load on line \(e_{1}\), and thus the losses in this line are lower then what they could have been if no locational pricing would have been applied.

In the last case, the capacity limit on line \(e_{4}\) and the losses in line \(e_{1}\) were intro-

\(^1\)The units of power and price in this example have been left out on purpose to increase the readability.
duced simultaneously in the example network. Consequently, the concentrator at $B_2$ propagates an already propagated demand function, thus including the optimisation of the capacity limit within the optimisation of the line losses. The results are not surprising. In district $A$, the capacity limit is dominant and also affected the amount of line losses in $e_1$, which were 10.59.

7.4 Variations

7.4.1 Propagation of Non-Network Constraints

Many other constraints can also be introduced. For example, grid operators want to minimise the aging behaviour of a transformer, as it degrades faster for higher loads resulting in decreased lifetime. The investment costs for such a replacement can be postponed if peak loading of the station can be avoided. A transformation on the demand function can be used to charge degradation costs to the end-customer. Hence, the end-customer gets a financial incentive to shift its demand from times of peak load to times of off-peak load. Another example would be if a household must pay taxes over the imported and exported electricity. If the supply and demand within the household is matched more frequently, the net import and export is reduced thus decreasing the amount of taxes to be paid. This is especially financially beneficial if market clearing prices show relatively small fluctuations compared to the tax rate.

7.4.2 Load Management Based on Measurements

The algorithm described above requires the incoming bid curve to represent the complete set of devices connected the subtree rooted in the node under consideration. Because of this complete information, there is no need for measuring the line loads, as the expected load is represented by the concentrated bid already. However, in practice there might be reasons not to include all grid-connected devices in the energy management system. One could, for instance, decide to include only the flexible, manageable devices into the energy management system. Then, the expected load does not follow from the demand function. So, a variant is needed in which the available line capacity is determined through a load measurement.

Figure 7.6 shows this variant again using a line $i$ connecting subtree $k$ to the rest of the network at node $j$. The variant is again divided into two phases:

(A) Demand function propagation when the load measurement reveals an overload on line $i$. The excess load is given by $z_{i,ex}$. The propagated demand function is lowered by this value over the full price range.
7. Locational Pricing in Radial Networks

Figure 7.6: Demand function propagation accounting for line capacity based on a measured overload. See text for a detailed description.

(B) Back-propagation of $p_j$ to node $k$. The allocation for subtree $k$ is given by $\bar{a}_k(p_j)$, where $\bar{a}_k$ is the propagated demand function. Nodal price $p_k$ is set such that this allocated amount of is consumed at $k$.

Note that the figure depicts the situation of a net demand in subtree $k$. In case of an overloading net supply, the curve is shifted downwards. Consequently the resulting $p_k$ is lower than $p_j$.

We will come back to this variant in section 13.4, where we validate this method in a field situation.

7.5 Conclusion

This chapter presents a novel fast algorithm for locational pricing in non-cyclic passive flow networks. As is the case with normal LMP algorithms, the algorithm yields locational prices such that all network flows are within the local line capacity constraints, while the total supply and demand in the network is balanced and network losses are accounted for. The topology of the agents that constitute the algorithm is equal to that of the physical network. The algorithms’ processing flow runs through
this tree-shaped topology of agents twice: first from its leaves to its root (swing node) and then from the root back to the leaves. This results in a fast algorithm that scales with the height of the tree.

7.5.1 Relevance to Computer Science

This finding adds new capabilities to the existing algorithms for resource allocation. The algorithm builds forth on the locational pricing framework formulated in answer to research question 2. Using particular properties of tree-shaped flow networks, the algorithm solves the locational marginal pricing problem in a computing time that scales with the height of the network tree.

7.5.2 Relevance to Industrial Engineering

Radial flow networks are widely present in industry. Virtually all industrial piping networks are radial. So, the algorithm is usable in a wide variety of infrastructures transporting and distributing gasses or liquids where the commodity as well as the infrastructural capacity is shared between concurrent uses.

7.5.3 Relevance to Power Systems Engineering

In the current Power Systems Engineering practice, LMP is implemented at the level of transmission networks and wholesale electricity markets. In electricity distribution, both the number of network nodes as well as the number of connected actors to be involved is much higher. This results in an heavier computational burden when applying LMP to these networks. However, in the distribution part of the electricity infrastructure, networks are predominantly operated in a radial, acyclic, topology. So, this algorithm is very suitable for active management of distribution networks. The algorithm fits into a liberalised setting, where network operation and energy delivery are unbundled, as it combines global coordination, such as VPP operations, with local network management. The method yields a local power flow that is (i) within the local line capacity constraint, and (ii) accounts for network losses.

7.5.4 What’s Next?

Based on the non-functional requirements of the needed coordination mechanism for the future electricity grid, we chose to look into Multi-agent Systems as a technology basis. Especially existing knowledge around Market-based Control and Resource Allocation is pivotal for the desired mechanism. In the Theory Part of this
document, we described this existing knowledge in Chapter 4, while important insight has been added to this knowledge base in Chapters 5 to 7. The newly generated knowledge centers around optimality of MBC and obtaining network-feasible solutions from resource allocation algorithms.

Now, it is time to get creative with the tools at hand and craft a mechanism that integrates numerous small-to-medium-sized DER in balancing at a system level and network management at a local level. In the next part, we present our system design and reason about strategies for DER devices participating in an electronic market.
Part III

Innovation Concept
Chapter 8

The PowerMatcher

**Synopsis:** Based on the theories in Part II, a general-purpose market-based control mechanism for large DER clusters has been designed and implemented. This multi-agent system, coined PowerMatcher, comprises four types of software agents. The first two types, named Auctioneer and Concentrator, implement a distributed electronic market. The third type is the Local Device Agent which trades on this market on behalf of a DER device. The last one, the Objective Agent, enables external control actions rooted in application-specific business logic. The system yields locational prices when Concentrator Agents perform bid transformations. By design, the PowerMatcher ensures three of the six requirements of the coordination mechanism: requirements R2 (Privacy Protection), R1 (Openness for DER) and R3 (Scalability). The first two are ensured by the data protocol used in the communications between the agents. This protocol is uniform for all agents and solely based on market information. Local information specific to DER devices is not included in the communications. Scalability is ensured by design through choices in the market design and agent topology.

The SMART GRID needs a coordination mechanism able to involve numerous small electricity consuming and producing units in the operation of the electricity system as a whole. As we have seen in the opening chapters, there are three main drivers behind this need. Firstly, the transition to sustainability will increase the variability of uncertainty at the supply side of the electricity system. Secondly, the electrification of everything puts a big strain on our ageing electricity networks. Active management of the distribution networks – the part of the grid holding the highest cumulative capital investment – will defer reinforcements and pro-long asset lifetimes. Finally, the trend towards distributed generation forces us to rethink the current balancing paradigm of centralised control of a few large generation units in order to follow electricity demand.

The three main non-functional requirements (Openness, Privacy Protection and Scalability) led us to a particular toolbox of technologies and methods. This toolbox
The PowerMatcher consists of the Multi-agent Systems design paradigm, algorithms for Market-based Control and Resource Allocation, as well as Locational Marginal Pricing. In computer science terms, using these, one is able to build scalable coordination systems in which local control agents situated in a networked environment compete for a flow commodity needed for their control tasks. The design task at hand is to apply these in a meaningful way to craft the coordination mechanism for the future electricity grid. The results of performing this design task are described in this chapter.

This chapter describes The PowerMatcher, a general-purpose coordination mechanism for balancing demand and supply in large clusters of Distributed Energy Resources (DER, distributed generation, demand response, and electricity storage connected to the distribution grid). These ‘clusters’ can be electricity networks with a high share of distributed generation or commercial trading portfolios with high levels of renewable electricity sources, to name a few. 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 and tested in simulations and field experiments [46, 77, 43, 59, 58, 57, 73, 44]

This chapter is structured as follows: Section 8.1 gives an overview of the systems design of the PowerMatcher. We describe the logical structure of the agent society, detail the roles of the different agent types and describe the communications between these agents. Section 8.2 gives a classification of DER devices according to controllability. In Section 8.3 we argue how the PowerMatcher meets the three non-functional requirements by design. This is followed by a proof-of-principle simulation study into the cluster-level behaviour of a PowerMatcher cluster (Section 8.4). Section 8.5 concludes the chapter.

8.1 A Tree-Structure of Agents

8.1.1 Logical Structure and Basic Agent Roles

Within a PowerMatcher cluster, the 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 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. More detailed descriptions of the agent roles are as follows:

- **Local device agent**: Representative of a DER device. A control agent which tries to operate the process associated with the device in an economically optimal way. This agent coordinates its actions with all other agents in the cluster.
by buying or selling the electricity consumed or produced by the device on an electronic market. In order to do so, the agent communicates its latest bid (i.e., a demand function, see Section 4.5) to the auctioneer and receives price updates from the auctioneer. It uses this received price, together with its latest bid, to determine the amount of power the agent is obliged to produce or consume.

- **Auctioneer agent**: Performer of the price-forming process. The auctioneer concentrates the bids of all agents directly connected to it into a single bid, searches for the equilibrium price and communicates the price update back whenever there is a significant price change.

- **Concentrator agent**: 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 to the auctioneer. In the opposite direction, it passes price updates to the agents in its sub-cluster. This agent uses ‘role playing’. On the auctioneer’s side it mimics a device agent: sending bid updates to the auctioneer whenever necessary and receiving price updates from the auctioneer. Towards the sub-cluster agents directly connected to it, it mimics the auctioneer: receiving bid updates and providing price updates. A Concentrator may
(or may not) be associated with a component of the physical electricity infrastructure, such as a transformer. Then, the agent is able to do congestion management and account for local network losses by performing bid curve transformations.

**Objective agent**: Agent that gives a cluster its purpose. In absence of an objective agent, the goal of the cluster is to balance itself, i.e., it strives for an equal supply and demand within the cluster itself. Depending on the specific application, the goal of the cluster may be different. If the cluster has to operate as a virtual power plant, for example, it needs to follow a certain externally provided setpoint schedule. Such an externally imposed objective can be realised by implementing an objective agent. The objective agent interfaces the agent cluster to the business logic behind the specific application.

The logical agent structure follows the CoTree algorithm [83]. By aggregating the demand functions of the individual agents in a binary tree, the computational complexity of the market algorithm becomes $O(lg a)$, where $a$ is the number of device agents. In other words, when the number of device agents doubles it takes only one extra concentrator processing step to find the equilibrium price. Furthermore, this structure opens the possibility for running the optimisation algorithm distributed over a series of computers in a network complimentary to power systems architectures. We discuss the issue of scalability further in Section 8.3.2.

### 8.1.2 Basic Device Agent Functionality

For a DER unit to be able to participate in a PowerMatcher cluster, its associated agent must communicate its momentary bid curve or demand function to the Auctioneer. As described before, this function defines the DER’s electricity demand $d(p)$ for a given price $p$. An offer to produce a certain amount of electricity against a certain price is expressed by negative $d(p)$ values. As a convention, throughout this text we refer to these functions as a bid, even when (part of) the function expresses a production offer.

Let’s focus on an agent for an electricity-consuming device, say a freezer. A simple block model of the thermal process of a freezer cell and its external influences is depicted in Figure 8.2. Input to the process model is the boolean control variable $\alpha_{on/off}$, switching the freezing element on or off. Further, the temperature in the freezing cell is influenced by two environment variables: the ambient temperature ($T_{amb}$) and a usage pattern ($\rho_{usage}$). The latter represents usage events such as door opening & closing and goods being placed in or removed from the cell.

The control goal is to keep the inner cell temperature within the temperature
8.1. A Tree-Structure of Agents

Figure 8.2: Freezer block model

band given by: $T_{\text{max}}$ and $T_{\text{min}}$, the maximum inner cell temperature and the minimum inner cell temperature, respectively. In a conventional freezer, this is achieved by a standard on/off-controller with hysteresis. When participating in a PowerMatcher cluster, this conventional controller is replaced by a device agent. The goal of the agent is, again, to keep the cell temperature between the given limits, with an additional goal to consume in low-priced periods as much as possible.

Figure 8.3 gives the three basic bid shapes for the freezer. When the cell temperature is below its minimum (left), the freezing element must be switched off. Accordingly, the device agent sends a Must Off bid. Similarly, when the cell temperature is above its maximum (right), the agent sends a Must On bid. The agent is forced to accept any price in order to get the cell temperature back within its limits. When the cell temperature is within limits (middle), the agent has the flexibility to switch on or off the element dependent on the electronic market price. Since the freezer element can either be switched on or off the agent’s bid is a step function: bidding either for the freezer’s nominal power or for a power of zero. The position of the step flank reflects the agent’s willingness to pay. When the cell temperature is still in the lower part of the temperature band, the agent is only willing to consume when the price is really low. However, when the temperature rises, the agent’s will-

Figure 8.3: Three basic demand functions of a freezer.
Ingeness to pay increases with it. So, available flexibility is directly dependent on the device state (here the cell temperature), and the position of the step flank in the agent’s bid directly reflects that. In order to optimise its strategy, the agent needs to have market-knowledge, as the notion of what defines a “high price” or a “low price” is crucial in the agent’s bidding strategy. We will come back to this aspect in Chapter 9, where we further investigate bidding strategies of DER agents.

8.1.3 Auctioneer and Concentrator Functionality

The core functionality of the auctioneer and the concentrators is to run the electronic market allocating the electrical power resource to the local device agents. The electronic market solves this allocation problem by finding the general equilibrium price $p^*$ such that:

$$\sum_{a=1}^{N_a} d_a(p^*) = 0 \quad (8.1)$$

where $N_a$ is the number of local device agents and $d_a(p)$ the demand function of agent $a$, stating the agent’s demand or supply at a given price $p$.

The task of summoning all device agent’s demand functions is divided over all concentrator agents and the auctioneer agent, here jointly referred to as market agents. Each market agent $k$ summons the demand functions received from their attached agents. These functions originate from two different sources: (1) the device agents directly attached to $k$, and (2) the concentrator agents directly attached to $k$.

The concentrated bid of $k$ is calculated as:

$$a_k(p) = \sum_{j: x_j \in X_k} d_j(p) + \sum_{i: i \in Y_k} a_i(p) \quad (8.2)$$

where $X_k$ is the set of local device agents directly connected to $k$ and $Y_k$ is the set of concentrator agents directly connected to $k$.

If $k$ is a concentrator agent, it passes $a_k(p)$ on to the higher-level market agent it is attached to. If $k$ is the auctioneer, it uses $a_k(p)$ to find the equilibrium price $p^*$ such that the market is in equilibrium:

$$a_k(p^*) = 0 \quad (8.3)$$

Note that, in the latter case, $a_k$ is the concentrated demand functions over all device agents:

$$a_k(p) = \sum_{a=1}^{N_a} d_a(p) \quad (8.4)$$

and that substitution of (8.4) in (8.3) yields the general market equation (8.1).
8.2. Classification of DER Controllability

In this way, the Auctioneer and the Concentrator collectively implement an electronic market that is agnostic of the underlying electricity network and, thus, is assuming a network with “copper plate” properties. This is sufficient for those use cases that can be operated independently of the physical grid. Running a commercial virtual power plant to be active on the electricity wholesale market for balancing is an example of such a use case. For those uses cases in which the underlying network needs to be considered in the electronic market’s outcomes, Concentrator variants have been implemented that use bid curve transformations, as defined in Chapter 7. Using these, active distribution management functions can be performed such as congestion management and minimisation of network losses.

8.1.4 Communication Timing

The agents communicate in an event-based manner. Device agents update their bids whenever there is a change in the system state significant enough to justify a bid update. Typically, device agents update their bid once every few minutes or longer. Concentrators, in turn will not update their bid unless subsequent updated bids from lower agents result in a significant change in their concentrated bid. Likewise, the auctioneer will only communicate a new price after a considerable price change. In this way, coordination on a timescale of minutes is realised with low volumes of communicated data.

8.2 Classification of DER Controllability

From the viewpoint of supply and demand matching, DER devices can be classified in six classes according to their controllability characteristics. Below we describe each class and the basic agent strategy associated with it:

- **Stochastic operation devices**: devices such as solar and wind energy systems of which the power exchanged with the grid behaves stochastically. In general, the output power of these devices cannot be controlled, the device agent must accept any market price.

- **Shiftable operation devices**: batch-type devices whose operation is shiftable within certain limits, for example (domestic or industrial) washing and drying processes. Processes that need to run for a certain amount of time regardless of the exact moment, such as assimilation lights in greenhouses, ventilation systems in utility buildings and circulation pumps in swimming pools. The total demand or supply is fixed over time. This class consists virtually only
of electricity consuming devices. The agent strategy is to shift electricity consumption to time periods of low(er) prices.

- **External resource buffering devices**: devices that produce a resource, other than electricity, that are subject to some kind of buffering. Examples of these devices are heating or cooling processes, whose operation objective is to keep a certain temperature within two limits. By changing the standard on/off-type control into price-driven control allows for shifting operation to economically attractive moments, while operating limits can still be obeyed (see Figure 8.4). Devices in this category can both be electricity consumers (electrical heating, heat pump devices) and producers (combined generation of heat and power).

- **Electricity storage devices**: conventional batteries or technologies such as flywheels and super-capacitors coupled to the grid via a bi-directional connection. Grid-coupled electricity storage is widely regarded as a future enabling technology allowing the penetration of distributed generation technologies to increase at reasonable economic and environmental cost. Grid-coupled storage devices can only be economically viable if their operation is reactive to a time-variable electricity tariff, as is present in the PowerMatcher concept. The agent bidding strategy is buying energy at low prices and selling it later at high prices.

- **Freely-controllable devices**: devices that are controllable within certain limits (e.g., a diesel generator). The agent bidding strategy is closely related to the marginal costs of the electricity production.

- **User-action devices**: devices whose operation is a direct result of a user action. Domestic examples are: audio, video, lighting, and computers. These devices are comparable to the stochastic operation devices: their operation is to a great extent unpredictable and has no inherent flexibility. Thus, the agent must accept any market price to let them operate.

In all described device categories, agent bidding strategies are aimed at carrying out the specific process of the device in an economically optimal way, but within the constraints given by the specific process. In section 9 we will have a more detailed look into agent strategies.

### 8.3 Requirements Met by Design

As described in the introduction chapter (notably section 1.6.3), Market-based Control has been selected as our base technology as it builds complex ICT systems that
are, amongst others, open, scalable and capable of hiding specific local information. Hence, three of the six requirements (as defined in section 1.3) have been firmly rooted in the design of the PowerMatcher: Openness (R1), Privacy Protection (R2) and Scalability (R3).

### 8.3.1 Design for Openness and Privacy Protection

Both openness and privacy protection are ensured by the design of the communication protocol between the software agents of the PowerMatcher. All inter-agent communications are minimised to a generic message based on market information which hides specific local information. The former ensures openness to a wide variety of DER, while the latter is important for privacy protection. Further on, in Part IV, we seek empirical support of the openness claim. As the privacy claim is hard to validate further in an empirical way, we look closer into this issue in the remainder of this subsection.

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**Figure 8.4:** Operation shifting in a cooling process whilst obeying process state limits.
On the level of a private home, for instance, each PowerMatcher message communicated outwards represents a market bid of all (flexible) electricity producing and consuming devices within the home. This is aggregated information comparable to that communicated by remotely readable electricity meters. Hence, a comparable privacy protection level applies for the PowerMatcher. Furthermore, all local decisions are being taken locally in the PowerMatcher. So, there is no outside authority switching devices of end-customers. Instead, the end-customer’s devices are equipped with an agent which is under their control. The agent tries to buy and/or sell electricity against a good price on behalf of its owner. In this way, the flexibility potential is provided as a valuable service from the end-customer’s premises to the smart grid, without a direct interference by an outside system or party.

Based on the above, we state that the Openness (R1) and Privacy Protection (R2) requirements have been met by design. As indicated, we seek further empirical evidence for the claim of Openness in Part IV.

8.3.2 Design for Scalability

In the design of the PowerMatcher a number of choices have been made to meet the important requirement of scalability. The three main scalability choices are: the use of a pool market, one-shot communications and distributed aggregation of demand functions.

Pool Market vs Peer-To-Peer Trading

In an electronic market of software agents, agents could negotiate in a peer-to-peer manner. Then, each agent has the ability to negotiate with all other agents. The exact equilibrium price $p^*$ would be reached when all buyers negotiate with all sellers and, thus, everyone has complete information. On the other hand, an auctioneer could act as a market operator. Then, all buyers and sellers communicate with the auctioneer only. The auctioning process starts with the auctioneer calling off a price. Then, all buyers and sellers state to the auctioneer the amount they are willing to sell or buy of the commodity under consideration for that price. The auctioneer sums up all amounts to see if the market clears. Then a higher price is called in case of excess demand, and a lower price if there is excess supply. The auctioneer iterates through this process until the market-clearing price $p^*$ is found. This procedure is known as the tatonnement process. Note that the market outcome is equal to the case in which all participants hold complete information, however, without the necessity for each participant to communicate with each of the others.
8.3. Requirements Met by Design

**Trusted Auctioneer: One-shot Communications**

Note that, in the case described above, each buyer or seller \( a \) needs to have his own demand function \( d_a(p) \) in mind. When the auctioneer calls off price \( p_x \), each buyer and seller states his preferred amount for that price, given by \( d_a(p_x) \). Note further, the auctioneer has to be trusted by all actors participating in the pool market in order to let him play the role as a middleman. When the auctioneer is trusted, the number of communication steps between auctioneer and all participants can be reduced drastically if the full demand functions are communicated at once. Then, the iterative process of finding the clearing price by the auctioneer does not include any further communication with participants. The whole process reduces to a one-shot communication of \( d_a(p) \) of all \( a \) to the auctioneer, followed by a communication-free clearing price search by the auctioneer and again a one-shot communication of the resulting price \( p^* \) to all participants.

**Distributed Concentration of Demand Functions**

Introducing one-shot communications drastically limits the number of communication steps in the process. However, now, the auctioneer is the hub in the electronic market wheel. All demand functions need to be communicated to one single point in order to run the market. When the number of agents participating in the market grows further, this system again runs into a communication complexity problem when the auctioneer cannot handle all communications fast enough. The solution to this problem lies in the electronic market algorithm. The price search involves the summation of all \( d_a(p) \) into a concentrated demand function \( \sum d_a(p) \) and finding the equilibrium price \( p^* \) for which this concentrated function equals to zero: \( \sum d_a(p^*) = 0 \). The calculation of the concentrated bid and the subsequent communications can be distributed over a number of concentrator agents. Then, a number of concentrator agents collect the demand functions of a mutually exclusive subset of market participants and calculates the concentrated bid for this subset. The result is communicated further toward the auctioneer. At the top of the structure, the auctioneer does the last concentration step and searches for the equilibrium price.

Imagine a market with 1 million market participants and a market structure having an auctioneer and two layers of concentrators of 100 and 10,000 pieces respectively. The auctioneer and each of the concentrator agents communicate with 100 agents in the layer directly below it, which is a low complexity communications task. Further, concentration of bids happens in parallel within each concentrator layer. When the number of market participants doubles, the whole structure below the auctioneer is duplicated and one extra concentrator is added. This hardly adds to the overall computation and communication complexity.
In chapter 15, we seek for empirical support for the scalability claim.

8.4 Proof of Principle: Cluster-level Behaviour

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.

Imagine a small island with a local electricity network with no connection to a greater network. The village of this island has 10 houses. Half of the houses are heated by heatpumps, the other half by micro-CHPs. Apart from the heatpumps, the energy consumption within the houses is inflexible and following standard household load profiles. Further, on the island there is a wind-diesel combination delivering that part of the momentary electricity demand not supplied by the CHPs. This combined unit is operated to balance the island system. When the local demand is higher than the total CHP and wind turbine production, the diesel generator is regulated to maintain the momentary system balance. On the other hand, when local demand is lower than the CHP and wind generated power, the wind turbine is curtailed and regulated to balance the network.

In a small-scale proof-of-principle simulation, the impact of the PowerMatcher was analysed for the hypothetical island system described above. The simulation has been carried out for two distinct cases:

1. Reference Case. This is the business as usual scenario. The heating systems

<table>
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<th>Type</th>
<th>$P_{\text{max}}$</th>
<th>Number</th>
<th>P/C</th>
<th>Flex?</th>
</tr>
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<tr>
<td>Diesel generator</td>
<td>15 kW</td>
<td>1</td>
<td>P</td>
<td>yes</td>
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<tr>
<td>Wind Turbine</td>
<td>30 kW</td>
<td>1</td>
<td>P</td>
<td>no</td>
</tr>
<tr>
<td>Micro CHP</td>
<td>1 kW</td>
<td>5</td>
<td>P</td>
<td>yes</td>
</tr>
<tr>
<td>Heat pump</td>
<td>0.7 kW</td>
<td>5</td>
<td>C</td>
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</tr>
<tr>
<td>Household Load</td>
<td>1.1 kW</td>
<td>10</td>
<td>C</td>
<td>no</td>
</tr>
</tbody>
</table>
8.4. Proof of Principle: Cluster-level Behaviour

Figure 8.5: Power Output of the 30 kW wind turbine over the two-day simulation period.

Figure 8.6: Diesel generator output power for the reference case (solid line) and the coordinated case (dashed line) over the two-day simulation period.
are controlled by a standard thermostat on/off controller. The system is balanced entirely by the wind-diesel system.

2. Coordinated Case. In this case the micro-CHPs and the heat pumps (HPs) are coordinated by the PowerMatcher. The multi-agent system tries to match CHP production and HP consumption with the inflexible demand and supply of the households and wind turbine respectively. Any net surplus or shortage is still balanced by the wind-diesel combination.

Table 8.1 gives the characteristics of the units used. The wind turbine output followed the measured production profile of a real-world turbine (Figure 8.5). The heating systems, i.e. the micro-CHPs and the heat pumps, were used for space heating alone. At this stage, hot tap water demand was left out of the scope of the simulation. The heat demand was generated using a basic thermal model of a house. The main external variable of this model is the outside temperature, which was set to follow a standard reference pattern. The household electricity consumption followed a standard residential load profile. Goal of the simulation is to give a proof of principle of the coordination mechanism, illustrating the cluster-level behaviour.

The simulation spans a period of two days. In the coordinated case, the local device agents for the HPs and CHPs make use of the inherent energy buffer in the
inner space of the houses to shift the heating operation, while comfort levels are maintained throughout the simulated time period. The HP agents try to heat the homes in the low-priced periods while the CHPs seek the high-priced periods. Figure 8.7 gives the price on the electronic market for the simulation period. The resulting price is influenced by a number of factors: (i) the momentary wind power availability, (ii) the momentary household electricity demand, and (iii) the available operational flexibility of the micro-CHPs and the HPs.

Figure 8.6 gives output power of the diesel generator in the two cases. Note that in the coordinated case the diesel generator is only operated in the high-priced periods. Then, the needed generation capacity cannot be provided by the rest of the cluster resulting in high prices and, in turn, utilisation of the generator. Comparing the two cases, two important effects can be seen from the figure:

1. The total production of the diesel generator is lower in the coordinated case (approx. 40%).
2. The peak load served by the diesel generator is lower in the coordinated case (approx. 45%).

These figures show a better utilisation of the wind power capacity on the island in the coordinated case. Responsive demanders, heat pumps in this case, were shifted towards periods of high wind and low demand. At the same time, distributed generators, micro-CHPs in this case, were shifted to periods of high demand and low wind generation. The 40% reduction in diesel-produced electrical energy is an important result as the environmental footprint of the island’s electricity system is improved. More wind power is consumed and the turbine has been curtailed less. The second effect is important from an investment point of view. If the peak load on the diesel system is lower, the unit’s design capacity can be lower which leads to a lower investment cost.

8.5 Conclusion

The PowerMatcher has been designed as a general-purpose market-based control mechanism for large DER clusters. This multi-agent system comprises four types of software agents each having a clear function in the system. By design, the PowerMatcher complies with three of the six requirements to the coordination mechanism: Privacy Protection, Openness and Scalability. The first two are ensured by the data protocol used in the communications between the agents. This protocol is uniform for all agents and solely based on market information. Local information specific to
DER devices is not included in the communications. Scalability is ensured through specific choices in the market design and agent topology.

Further, this chapter provides a classification of DER controllability and a Proof of Principle simulation study. The latter focusses on an island microgrid having a wind-diesel generation system as the primary electricity supply source. Using PowerMatcher to unleash the flexibility potential present in the island’s households, the available wind power is utilised better and the use of the diesel generator reduced. The peak power requested from the diesel genset was reduced by 45%, while the total amount of diesel-produced electricity reduced by 40%. This result shows that the distributed system of the PowerMatcher is able to perform demand and supply coordination, while at the same time it contributes to a greener energy supply (more wind utilisation) and a more efficient system operation (peak power reduction).

8.5.1 What’s next?

All previous chapters in this thesis converge into the design of the PowerMatcher as described in this chapter. The three non-functional requirements have been leading in the process towards this design. Now, it is time to converge again, while focussing on the functional requirements. How can DER device agents best be designed? How does the PowerMatcher perform in relevant real-world use cases when field deployed? In the next two chapters in Part III, we will look into bidding strategies for DER device agents (in Chapter 9) and we take a closer look into the complex business of electricity trade & supply (in Chapter 10). After that, in Part IV, we will try to validate the PowerMatcher with the set of requirements in mind. In this, the topical focus will diverge into a wide variety of simulation studies and field experiments investigating PowerMatcher’s performance in different use cases and applications.
Chapter 9

Bidding Strategies of Device Agents

SYNOPSIS: The PowerMatcher does its coordination on timescales close to the real-time. To do so, the PowerMatcher maintains a dynamic merit-order list of all DER participating in the cluster. In order to make optimal coordination decisions involving individual DR units, having this list in the right order is of utmost importance. To achieve this, the merit order needs to be based on the true marginal cost of the individual DER units. However, the marginal electricity cost of most types of DER is highly dependent on local context and, hence, change over time. In the context of the research question regarding Bidding Strategies of DER Device Agents (Q4), strategies of different types of DER have been assessed. This assessment revealed a bid strategy spectrum of short-term bid strategies of various DER units. At one extreme of the spectrum, strategies are based entirely on true marginal cost. At the other, strategies are completely dependent on price dynamics in the electronic market. Further, we introduce decision diagrams as a graphical way to analyse and design device strategies. These results provide guidelines for the design of Local Device Agents for DER. Following these guidelines results in agent societies that find an optimal division of work in given DER clusters under all circumstances.

NOW THAT THE system’s design is known, one needs to know how DER devices can best be involved in the coordination task. Here, the notion of a dominant strategy as used in game theory and micro-economics is important. A dominant strategy is defined as the best strategy an agent can follow regardless of the strategies of the other agents in the market. Are DER devices participating in a PowerMatcher cluster subject to such a strategy? If so, that would provide a basis for clear and straightforward guidelines for the design of these agents. A further question would be how this strategy is influenced by the device’s primary process. To participate in the electronic market, the device agent must formulate a market bid that reflects the momentary available flexibility within the constraints set by this primary process. Hence, we formulate a research question as:
In this chapter, we investigate the mechanisms that determine the momentary marginal costs of distributed generators and the momentary marginal benefits of demand response resources. Section 9.1 takes a closer look at the functional task of DER agents in relation to the notion of a dominant strategy. In Section 9.2, we analyse the strategy of three specific DER devices. The findings of this analysis are generalised in Section 9.3, where the existence of a bid strategy spectrum is shown and the position of particular real-world DER configurations in this spectrum is determined. The resulting insights have led to a set of practical guidelines for device agent strategy design presented in Section 9.4. The design method uses decision diagrams, the graphical way of visualising strategy choices as introduced in subsection 9.2.3. Section 9.5 concludes the chapter.

9.1 The Dominant Strategy of DER Devices

PowerMatcher’s coordination is based on the aggregated bid, or aggregated demand function, as held and kept up to date by the Auctioneer agent. This demand function can be seen as a dynamic merit-order list of the agent society of connected DER units. Micro-economic theory learns that, to make optimal decisions based on this list, the merit order needs to be based on the true marginal cost (or marginal benefit in the case of demand response) of the individual DER units.

So, we need to reason about the marginal electricity cost of DER. This isn’t straightforward, however, as the marginal electricity cost of most types of DER are highly dependent on local context and, hence, change over time. For example, the marginal electricity production cost for a CHP is highly dependent on the amount of heat demanded from the unit at a particular time. Thus, when the heat demand is high, the marginal cost for the electricity production is low and vice versa. The dynamic marginal cost levels of the units in the cluster result in the dynamic nature of the merit order list. As we will show later on, there exists a class of DER units for which, under circumstances, the marginal cost level cannot be determined unambiguously.

From a micro-economic viewpoint, the DER units are assumed to participate in a competitive market. This assumption holds when the number of DER units in the agent society is relatively high and their traded volumes are of the same order
of magnitude. A competitive market leaves no room for speculation or gaming, and all market players are so-called **price takers**: a change in one individual bid has a negligible influence on the price at the market level. The dominant strategy for players in a competitive market is to optimise its own utility by truly bidding its marginal cost [49]. These locally-optimal strategies lead to a merit order list that results in an globally-optimal allocation, as those DER which are best fit to respond to a certain event are the first to be selected to do so.

### 9.2 Agent Strategies Based on Short-term Economics

As described in the previous section, the optimal strategy of an agent active on a competitive market is to bid according to its momentary marginal cost. For a PowerMatcher device agent, the bidding strategy is a mapping from its context history to a market bid. This context includes:

- The process controlled by the agent, including the current state of the process and economical parameters such as marginal operating cost.
- The market environment in which this agent is situated, including the market mechanism and market prices.

In the extremes, there are two agent types that are forced to base their bid on either of the two context elements described above:

1. Those agents operating a DER unit that has clear and unambiguous levels of marginal costs. In a competitive market, the dominant strategy of these agents is to bid entirely according to their marginal operating costs.
2. Those agents operating a DER unit that does not have unambiguous marginal costs at all. In these cases, the bidding strategy can only be based on market parameters, i.e. the market price (history).

As said, these cases are the extremes of a spectrum and hence, there is a group of agents whose bidding strategy is somewhere in the middle of this spectrum. In the next subsections, we will give examples of these extreme and intermediate cases.

#### 9.2.1 A Strategy Fully Based on Marginal Cost

An example of a bidding strategy entirely based on the marginal cost level is that of a fuelled electricity generator set, for instance a gas generator set. The marginal cost for a given period of operation depends on the fuel price, the efficiency of the
generator and the running-history dependent maintenance costs. Furthermore, each startup of such a generator causes additional costs for maintenance and fuel. The dominant strategy in this case is bidding a price equal to the marginal operation cost.

The bidding strategy is a function of the following parameters:

- $p_f$ [ct/m$^3$] Fuel price
- $r_g$ [Wh/m$^3$] Generator fuel rate
- $P_g$ [W] Generator electrical power
- $m_r$ [ct/h] Maintenance cost rate
- $c_s$ [ct] Additional start-up maintenance costs
- $f_s$ [m$^3$] Additional start-up fuel use

The marginal cost for operating the generator for a time period of $\Delta t$ is:

\[
\begin{align*}
    c_{m,r}(\Delta t) &= \left( \frac{P_g p_f}{r_g} + m_r \right) \Delta t \\
    c_{m,s}(\Delta t) &= c_{m,r}(\Delta t) + c_s + f_s p_f
\end{align*}
\]  

(9.1) (9.2)

where $c_{m,r}$ is the marginal cost when the generator is already running at the start of the $\Delta t$ time period, and $c_{m,s}$ when it has to be started up.

Therefore, the optimal bidding function is given by:

\[
d(p) = \begin{cases} 
0 & \text{if } p < c_m \\
-P_g & \text{Otherwise}
\end{cases}
\]  

(9.3)

where $c_m$ equals either $c_{m,r}$ or $c_{m,s}$ depending on the running state of the generator.

Note that, by definition, $d(p)$ is negative in case of supply, hence the minus sign before the $P_g$ term. It is clear that this bidding strategy depends entirely on the cost parameters of the generator. The market price history does not play a role in this strategy.

### 9.2.2 A Strategy Fully Based on Price History

At the other extreme is the bidding strategy of an electricity storage facility. Systems such as batteries, flywheels and pumped storage, charging from the electricity grid at one time and discharging to it at another. The aim of the agent is to buy electricity in periods of low prices, store it and resell in periods of high prices. Hence, the notion of what defines a “high price” or a “low price” is crucial in the agent’s bidding strategy. Maximising the agent utility comes down to determining
9.2 Agent Strategies Based on Short-term Economics

the charge/discharge price that yields the best profit. This optimal price set is entirely dependent on the dynamic price characteristics of the market environment plus the time needed for a full charge or discharge.

Charging and discharging a storage device is subject to round-trip energy losses. Note that, for the operation of a storage system to be profitable in the long run, the margin between the buy price and the resell price must exceed the costs for these losses. However, these costs do not influence the optimal price levels themselves.

Therefore, the agent requires some sort of function $E$ that yields estimates of the optimal charge and discharge prices given the current price history and the charging/discharging time:

$$\langle \overline{p}_c, \overline{p}_d \rangle = E(H_p, T_s)$$  \hspace{1cm} (9.4)

$$T_s = \frac{C_s}{P_s}$$  \hspace{1cm} (9.5)

where:

$P_s$ [W] Storage charging/discharging power
$C_s$ [Wh] Storage capacity
$T_s$ [h] Storage charging/discharging time
$H_p$ [ct] Price history vector

Based on these estimated price levels the bidding function can be defined by:

$$d(p) = \begin{cases} 
P_s & \text{if } p < \overline{p}_c \\
-P_s & \text{if } p > \overline{p}_d \\
0 & \text{Otherwise}
\end{cases}$$  \hspace{1cm} (9.6)

The long-run profit is highly dependent on the quality of the estimator $E$, which must operate in dynamic market environments whose characteristics, in most cases, will be unknown at design time.

9.2.3 An Intermediate Strategy

This case is based on configurations found in installations supplying heat to residential areas: a CHP/Gas heater combination. A typical configuration combines a CHP, a more traditional gas heater and a heat storage buffer. An installation of this type was part of the field test cluster used in the commercial portfolio balancing field trial we will describe in section 12.1.
The marginal cost levels depend on the following parameters.

\[ \eta_{chp} \] Thermal efficiency of the CHP
\[ \eta_{chp} \] Electrical efficiency of the CHP
\[ \eta_{htr} \] Thermal efficiency of the heater
\[ p_g \] [ct/m³] Gas price
\[ H_c \] [kJ/m³] Gas combustion heat
\[ T_{max} \] [°C] Upper limit inner temperature heat buffer
\[ T_{min} \] [°C] Lower limit inner temperature heat buffer

Typically, the thermal efficiency of the heater will be higher than that of the CHP:
\[ \eta_{chp} < \eta_{htr}. \]

The heat demanded by the residential area is subtracted directly from the heat buffer. The local control goal of the CHP/heater combination is to keep the inner temperature of the buffer, \( T \), between thermal limits \( T_{max} \) and \( T_{min} \). Hence, the buffer level is defined as:

\[
L_B = \frac{T - T_{min}}{T_{max} - T_{min}}
\]  

(9.7)

To prevent the buffer from over or under heating, three levels are defined at which special control actions are to be taken:

- \( L_H \): High buffer level: just below the fill level of 100%. Above this level both the CHP and the heater must be switched off to prevent overheating. CHP operation is only possible in combination with heat dump, if that is technically possible (and ethically acceptable).

- \( L_L \): Low buffer level: the level under which either the heater or the CHP must be switched on to prevent under heating.

- \( L_{LE} \): Low emergency level: just above 0%. Below this level both heater and CHP must be switched on.

These levels define four different operational modes (see figure 9.1):

1. Below \( L_{LE} \), the high heat demand is the dominant factor in the operation of the installation. This is a must-run situation for both CHP and heater, regardless of the electricity price.

2. Between \( L_{LE} \) and \( L_L \), there is a heat demand that could be met by either the heater or the CHP. Hence, there is a choice of producing this heat using the
9.2. Agent Strategies Based on Short-term Economics

Figure 9.1: Bid strategy of a Heater/CHP combination as found in heat network systems delivering heat to residential areas. The strategy is well-defined in two areas: (i) below $c_1$, which is the marginal cost for CHP-produced electricity when heat demand is high, and (ii) above $c_2$, the CHP’s marginal electricity cost when there is no heat demand at all.

heater or the CHP. In the latter case, the operating costs will be higher (as $\eta_{chp} < \eta_{htr}$) with additional electricity production in return. While the heat demand is covered by the CHP, the marginal cost of the additional electricity production is equal to:

$$c_1 = c_{chp} - c_{htr}$$

(9.8)

where $c_{chp}$ is the marginal cost for heat produced by the CHP regardless the value of the co-produced electricity, and $c_{htr}$ is the marginal cost for the heater-produced heat. With:

$$c_{chp} = \frac{p_g \eta_{chp}}{H_c}$$

(9.9)

$$c_{htr} = \frac{p_g \eta_{htr}}{H_c}$$

(9.10)
equation (9.8) can be expanded to:

\[ c_1 = \frac{p_g}{H_e} (\eta_{chp} - \eta_{htr}) \]  

(9.11)

Accordingly, the CHP is operated when the market price for electricity exceeds \( c_1 \), otherwise the heater is operated.

3. Above buffer level \( L_H \), there is no heat demand. Hence, there is a choice to run the CHP and dump the produced heat. Even if the installation is not technically capable to discard CHP-produced heat, the marginal cost level of this option is of interest as it provides one of the strategy boundaries of the forth operation mode, described below.

During CHP operation just for electricity production, the marginal cost for the electricity equals to:

\[ c_2 = \frac{p_g}{H_e} \eta_{chp} \]  

(9.12)

If the market price is above \( c_2 \), it is profitable to run the CHP, even when the produced heat is discarded.

4. In the region between \( L_L \) and \( L_H \), there is a high level of freedom to let the CHP operation be dependent on the electricity price. At both boundaries of this region, the bidding strategy is well defined: at level \( L_L \) it is profitable to produce whenever \( p > c_1 \), while at level \( L_H \) it is profitable to produce whenever \( p > c_2 \). The ‘naive’ or ‘ignorant’ strategy would be to connect these two points linearly. However, dependent on both the dynamic price characteristics of the market and the used risk profile different trajectories are possible. In figure 9.1, two alternative strategies are shown. The risk-averse strategy tries to avoid must-run situations for both CHP and heater by taking the chance to fill the buffer whenever it is profitable to run the CHP. The other alternative strategy waits for higher prices to operate the CHP, with a higher risk of missing profit opportunities and ending in the must-run regions for heater and CHP.

9.3 The Existence of a Bid Strategy Spectrum

As becomes apparent, there exists a spectrum of DER bidding strategies. On one end of the spectrum, bidding strategies are based directly on true marginal cost or benefit. Along the spectrum, optimal bidding strategies become less dependent on marginal cost levels and more on the price dynamics in the (VPP) market context.
9.3. The Existence of a Bid Strategy Spectrum

As may be clear from the description of the CHP/Gas Heater combination, price-dynamics based strategies are not unambiguously defined but are dependent on a desired risk level.

In figure 9.2, the relative positions of a number of DER units are shown. Below, we discuss briefly the spectrum position of units not described previously.

- Generators of renewable power, such as wind turbines and photo-voltaic solar systems, typically have low marginal costs associated with them, as these consist mainly of maintenance costs. Fuel costs, the main marginal cost component for most other generation types, are essentially absent here. Therefore, the dominant strategy of renewables is to generate at any going electricity price. This positions them at the marginal-cost based extreme of the spectrum.

- CHP with heat buffer: In high-price situations, the bidding strategy of a solitaire CHP is similar to that of the CHP/Heater combination. The marginal cost for CHP produced electricity in the (theoretical) heat-dump case ($c_2$ in figure 9.1) is applicable here as well. However, the low-price behaviour is dependent on the value attached (by the user) to a reliable heat supply and the risk level one allows for occasionally not being able to cover the heat demand entirely. Minimising this risk is highly dependent on the prevailing price-dynamic characteristics. Hence, the position of CHPs on the right-hand side of the spectrum.

- Direct Electrical Space Heating or Cooling: Modern building constructions show relatively high degrees of thermal inertness. This can give some degree of freedom in the operation of systems for space heating and cooling, but is dependent on the current temperature and the temperature desired by the user.
As learnt in field experiences, it is possible to shift cooling or heating periods forward or backward in time without infringing user comfort [59, 77]. Here, the agent strategy goal is to provide the desired comfort level against minimal electricity costs, shifting cooling/heating actions towards low-priced periods as much as possible. Comparable to the strategy for storage units, the notion of what 'low prices' actually are is crucial for a successful strategy. This locates this DER type directly in the price-history based end of the spectrum. However, as learnt from experiences with demand response programs aiming at influencing user behaviour, most users are willing to offer some comfort in order to avoid periods of high tariffs. Due to this, we position Direct Electrical Space Heating or Cooling just left of the spectrum end.

Freezer: The case of a freezer is similar to that of space heating/cooling described above, hence the position near the price-history based end of the spectrum. As a minor difference, for this instance, the cost of 'lost service' is known as this equals the total value of the stored food items.

9.4 Guidelines for Device Agent Design

Based on these findings, the following design guidelines for DER agent strategies can be formulated:

1. Analyse the marginal cost for producing and/or the marginal benefit for consuming electricity under different system states of the DER at hand. Search for system states where the marginal cost or benefit can be unambiguously defined. If any, formulate the marginal cost benefit in terms of the device’s parameters and system variables.

2. Determine the position of the DER device in the bid strategy spectrum.

3. If the device is located in the marginal-cost based extreme, the agent strategy must be based on the marginal cost formulation of step 1.

4. If the device is located in the price-history-based extreme of the spectrum, the agent must implement an automatic analysis of the market-price history. This analysis must provide the agent with a notion of ‘high’ and ‘low’ prices in the market context in relation to the device capabilities. The agent’s bidding strategy must be based entirely on these.

5. If the device is located somewhere between the two extremes, a decision diagram as introduced in Figure 9.1 has to be created. First, plot the unambiguous
cost points, as found in step 1, into the diagram. Determine the price segments in which the strategy isn’t well-defined, in Figure 9.1 this is the space between prices $c_1$ and $c_2$. Define the state-price trajectory according to the desired risk profile.

9.5 Conclusion

The main practical result of the work presented in this chapter is a set of practical guidelines for DER device agent design. These guidelines make use of decision diagrams to analyse the relation between the observed market price and the state of the DER device as introduced in this chapter. In the validation part of this thesis we shall come back to these topics when we describe the strategy design of particular devices present in field experiments.

The main theoretical finding of the chapter is the existence of a bid strategy spectrum for DER units participating in a market-based control cluster delivering (near-) real-time balancing services. On one end of the spectrum, bidding strategies are based straightforwardly on true marginal cost or benefit. On the other spectrum end, optimal bidding strategies are dependent on the price dynamics in the electronic market context and the desired risk level.

Relevance to Power Systems Engineering

The technical challenge is to design agent societies that find an optimal division of work in a given cluster of distributed generators and demand response resources under all circumstances. As has been shown, the merit order in such a society is highly dependent on the local context of the DER units in the cluster. In turn, the location of the DER device in the strategy spectrum determines how this local context, condensed into the device state and device parameters, is mapped into a market bid. Insight in these dependencies is necessary to design optimal market-based coordination and control systems. Based on these, guidelines for the design of Local Device Agents for DER have been provided. Further, the decision diagrams that have been introduced in subsection 9.2.3 provide a graphical way to analyse and design device strategies.

Relevance from an Electricity Business Perspective

These results contribute to the understanding of the business economics of Virtual Power Plants and active distribution networks. A good understanding of marginal
cost mechanisms of DER units participating in a VPP or active network can be used when analysing the profitability of these measures.

**Relevance to Computer Science**

This result does not directly add to the scientific knowledge base in CS as the results are formulated from a electrical engineering and control engineering point of view. However, to our knowledge this kind of analysis of the micro-economic considerations of control agents is non-existent in MAS literature. This might give an opportunity to generalise and reformulate these findings and introduce them in Computer Science as part of future work.

**9.5.1 What’s Next?**

The yield at this point is a distributed coordination mechanism, PowerMatcher, based on Market-based Control, and a good insight into the way Distributed Energy Resources are able to participate in it. By design, the PowerMatcher meets the three non-functional requirements: Openness, Privacy Protection and Scalability. Now, it is time to look at the application side of the coin and investigate whether this system meets the functional requirements and endures field deployment. The latter may provide additional empirical backing for the non-functionals as well.

However, before we dive into the validation, we make a stop over to look into the rather complex business of electricity trade and supply. A good understanding of the day-to-day market operations of a trade & supply business is a prerequisite to comprehend how DER flexibility can be put to value in the electricity wholesale markets. The next chapter takes you into this world.
UNLEASHING THE INHERENT flexibility of smaller electricity producing and consuming units is of interest for energy suppliers as well as distribution network operators. For the former, the actual value creation takes place in the wholesale markets for electricity. To understand this process, it is important to understand the workings of, and the relationships between, the different electricity markets and the trading position of a supplying company in it. Because of the complexity of this subject, we give a thorough description of trade & supply operations in the wholesale markets and the way DER flexibility can be turned into value on these markets.

We focus here on parties that are active on the wholesale markets with the purpose of supplying electricity to end-customers. The high-level interactions of such an ‘energy supplier’ were discussed in section 3.2 in the context of figure 3.4. Here we further detail the trading actions of an electricity supplier on the different wholesale markets for electricity.
10.1 Wholesale Market Timescales and Electricity Profiles

The contract portfolio of an energy supplier consists of end-customers of different types: industries and households in various customer segments. The aggregate of these customers follows a certain profile of electricity exchanged with the electricity grid. It is in the suppliers commercial interest to buy this load profile on the wholesale market in advance and as precise as possible. Any remaining difference between the traded profile and the actual profile is automatically traded on the bal-
10.1. Wholesale Market Timescales and Electricity Profiles

Figure 10.2: Market price data of the Endex futures market in the Netherlands. The Endex matches buyer and sellers of electricity for three different products: base load, peak load (from 8am to 8am) and 16-hours peak load, from 7am to 11pm. Period lengths vary from 1 month for the next 6 months to complete calendar years up to 5 years ahead. This screen shot is dated May 5th, 2009.

The ‘Electricity Wholesale Market’ consists of a collection of markets working in different time scales, as shown in figure 10.1 (a). An energy supplier, trades on these different markets in order to minimise both its procurement costs and its price risk level.

More than 1 year ahead  An energy supplier buys part of the load profile he expects to deliver in a certain time period already years ahead on the futures market. The amount of energy he buys depends on the expected contract portfolio for that future time period, the average load profile of that portfolio and his estimation of the price risk of the different wholesale markets. At the futures market, common products are base load blocks and peak load blocks (e.g. 8am to 8pm) for complete calendar years or year quarters. These power blocks are either bought via an over the counter bilateral trade, for instance with a production plant owner, or via a futures market operator. An example of the latter is Endex, see Figure 10.2.
Suppose an electricity supplier has an expected daily load profile for a certain period as depicted by the solid line in Figure 10.3. Suppose further that this supplier does not own generation assets of its own, so all energy supplied to its customers must be bought on the markets. One to five years in advance, this supplier is able to buy the power blocks, indicated in gray, on the futures market. Note that this is an iterative process in which year blocks are bought first, which are adjusted for seasonal influences when the year-quarter products become available, etcetera.

**1 year to few days ahead** Uncertainty in the expected load profile decreases over this period for a number of reasons. Firstly, the exact composition of the contract portfolio becomes clear, with new customers acquired and old ones leaving as client. Secondly, the uncertainty in the weather forecast reduces over this period. By buying and selling base load and peak load blocks for specific months the supplier is able to detail its profile to the level of individual months. In bi-lateral trades with power producers or middle-man traders, the supplier can do the same for individual weeks or days.

**1 day ahead** On the day-ahead market, the supplier buys and sells power, again, in order to get closer to the current expectation of the profile. Weather forecast uncertainty has decreased further and special events (the national team plays the World Cup Final) have become known. Virtually all day-ahead trading takes place via the Power Exchange operated by a market operator that pools all demand and supply for each of the 24 hours of the next day. Trading in hourly blocks allows the supplier to detail its coarse profile of base and peak
Figure 10.4: Power exchange (day-ahead market) trades to cover an expected load. (a): Power exchange adjustments made to the profile bought on the futures market. Power is bought for those hours where the expected load is higher than the power bought on the futures market. Likewise, power is sold for the hours where the expected load is lower. (b): The resulting profile in hourly power blocks.

Load blocks bought on the futures market into a profile of hourly blocks. From Figure 10.4 it can be seen that this may involve both buying and selling.

Few hours ahead Market parties are allowed to trade until a certain gate closure
time, which is typically a few hours before real time, i.e. the time of actual delivery. The gate closure is further discussed in section 10.2. Until gate closure, intraday-trades are possible either via a market operator (intra-day market) or via bi-lateral trades with individual market parties.

At the time of delivery, all customers in a supplier’s contract portfolio exchange a certain amount of electrical energy with the electricity network. When the supplier’s forecasts were right, there is little discrepancy between the net volume actually exchanged with the network and the traded energy volume. However, all remaining discrepancy is automatically traded on the balancing market. We will look at this in greater detail in the next section.

10.2 The Balancing Market Revisited

The Balancing Market Mechanism is used by Transmission System Operators (TSOs) throughout the world. The balancing market has been described from a bird-eyes view in subsection 3.2.4. Here, we zoom in on some of the implementation details of the balancing mechanism relevant to balancing services delivered by virtual power plants. The European variant of this mechanism is part of the ETSO Scheduling System (ESS) and is widely implemented by European TSOs. In this context, an actor that is responsible for a balanced energy volume position is called Balance Responsible Party (BRP). The Balancing Mechanism consists roughly of three parts:

1. **Balancing responsibility**: the obligation of BRPs to plan or forecast the production and consumption in their portfolio and to notify this plan to the TSO. The granularity of notified plan is given by the settlement period length, typically 15 or 30 minutes. The notification is done before some gate-closure time, a predefined period ahead of the start of the settlement period.

2. **Reserves for frequency response**: the TSO contracts generation capacity for primary, secondary and emergency reserve. Production sites of a certain capacity are obliged to make available a predefined portion of their capacity to the TSO. Market parties signal the availability of reserve capacity by sending a bid to the TSO. In case of (smaller or bigger) system-wide imbalance, the TSO calls off the reserves available, in the order of their bid prices, to restore the instantaneous system balance.

3. **Settlement of imbalance costs with the balancing responsible parties**: in a later stage, the TSO charges the actual costs for the used reserve and emergency capacity to those BRPs that had deviations from their energy programs. These charges are referred to as imbalance costs.
This system gives wholesale trading parties incentives to maintain their own portfolio balance, while it provides means to charge the costs made by the TSO when maintaining the real-time system balance to those parties responsible of the unbalance.

Depending on the nation or state specific regulations, the plan notified to the TSO is valid for a certain grid area, referred to as a control zone. The BRP is obliged to provide a plan for each control zone it has contracted generation or load in, and needs to follow the plan for each zone individually. So, a BRP is allowed to compensate for imbalance occurring in one part of a control zone using units in another part of the same zone. Typically, control zones cover a large geographical area: The Netherlands, for instance, is a single control zone, while the United Kingdom is divided in 14 of such zones. In real time, deviations between the planned electricity production and consumption in a specific control zone become visible to the TSO through deviations in the planned import to or export from the zone. In real time, the TSO monitors the zonal balance and maintains the real-time zonal balance by adjusting generation up and down using the contracted reserve capacity. By doing this, the TSO compensates the net imbalance of the group of BRPs having a deviation from their notification. Afterwards, the TSO compares the real, measured, energy profile of the full portfolio of each BRP, with its notification. For every settlement period, the costs made for the usage of reserve and emergency capacity made by the TSO are spread over all BRPs that caused imbalance in that particular period. Although the TSO balances the over-all system on a seconds basis, settlement of imbalance caused by BRPs is done on a longer timescale, typically 15 or 30 minutes.

In the remainder of this chapter, we consider the situation in one single control zone. Consequently, if we refer to a BRP having a contract portfolio and taking measures to influence the imbalance position of this portfolio, we assume this to take place in one control zone.

10.3 Portfolio Imbalance: Wind Energy

As imbalance prices are generally more volatile and on average higher than day-ahead prices, the system of balancing responsibility imposes imbalance risks to market parties. Among BRPs, this risk will vary with the predictability of the total portfolio of the BRP. BRPs with low portfolio predictability are faced with higher imbalance risks.

Typically, wind power production suffers from low predictability. This gives higher imbalance costs resulting in a lower market value for electricity produced by wind turbines. In general, any market disadvantage due to high imbalance costs can
be reduced by increasing either the predictability or the controllability. Using specialised forecasting techniques as post-processors to high-resolution meteorological models, the day-ahead predictability of wind energy production has been improved substantially over the last decade [23, 10]. However, a substantial error margin remains.

Figure 10.5 shows a typical remaining forecasting error profile of such a system. The figure shows three main sources of wind energy forecasting errors in three consecutive windy periods. In the first windy period in the figure, around March 8th, the forecast is relatively good, but the turbine is out of operation for a certain period of time, supposedly for some technical reason. For the next windy period, both the complex shape and wind magnitude of a passing weather system were forecasted fairly well, but the timing was wrongly forecasted. Finally, around March 11th, the forecasting system gives a good forecast for both shape and timing of the passing weather system. Unfortunately, the magnitude of the electricity output is seriously
10.4 Virtual Power Plant Balancing

10.4.1 Balancing Actions by BRPs

As described above, the system of balancing responsibility imposes imbalance risks to market parties. In practice, there is virtually always a smaller or bigger discrepancy between the traded energy volume, as notified to the TSO, and the real measured profile. Figure 10.6 shows such a discrepancy. To reduce this risk, market participants undertake balancing activities. These activities can both take place before gate closure as well as in the settlement period itself:

- **Pre Gate Closure:** Typically, balancing activities before gate closure occur in the power exchanges. Market parties fine tune their positions close to real time by contracting with generators or suppliers in order to adapt their position according to short-term load forecasts. This is the day-ahead and intra-day trade as described in subsection 10.1.

- **Within the Settlement Period:** After gate closure, each BRP is on its own: each trade with other market parties cannot be notified to the TSO and, thus, will contribute to the BRP’s imbalance. The BRP can only influence the producing and consuming units in its own portfolio to achieve in real-time the desired net physical energy exchange with the network for each control zone.

The exact meaning of the word ‘desired’ depends on the information the BRP has in real-time regarding the system-wide balance and/or the momentary imbalance...
prices. Here, three different information levels can be distinguished:

1. **No Information** on the system-wide imbalance or on the expected imbalance prices for the current moment in time is available to the BRP. This is the case when the TSO does not publish imbalance (price) information in real-time. Further, the BRP has no means to estimate the sign and magnitude of the current imbalance. In this case, the best strategy of a BRP is minimising its portfolio imbalance in each settlement period.

2. **Information on the system-wide balance magnitude** is available to the BRP. This is the case in regions where the TSO publishes in (near-)real-time the current imbalance volumes, see Figure 10.7 (a). With this information, a BRP can determine whether its current imbalance position will result in imbalance costs (when the imbalance directions of both the BRP and the system are the same) or in imbalance revenues (when the portfolio imbalance is opposite to the system imbalance). A semi-passive strategy of a BRP is minimising its portfolio imbalance only in cost situations. An active strategy is to counteract the system imbalance when it is relatively high and, thus, imbalance prices are expected to be high.

3. **Information on the actual imbalance prices** is available to the BRP. This is the case when the TSO publishes the imbalance prices in real-time (see Figure 10.7 (b)) or, alternatively, when the BRP has means to estimate the current imbalance price level. In some regions, the TSO publishes the momentary imbalance prices in (near-)real-time. When prices are not published in real-time, those BRPs actively offering frequency regulating reserve capacity to the TSO bid ladder are able to make an estimate of the going imbalance prices. For it is known to these parties which of their own reserve capacity bids are called off by the TSO. By strategically placing their reserve capacity bids spread over the bid ladder price range, a BRP is able to make a good estimate of the going imbalance price. In this case active strategies will be used predominantly. Regardless of the imbalance in its own portfolio, the BRP will use its operational flexibility to counteract the system imbalance when imbalance prices are high.

In all three cases, the BRP has to react to any risk or opportunity occurring in a settlement period within the same (15 or 30 minutes) period. Thus, any useful operation has to take effect within a few minutes in order to sort effect before the settlement period ends.
10.4. Virtual Power Plant Balancing

Figure 10.7: Two instances of the ‘balance delta’ table of the Dutch TSO Ten-net showing the momentary system-wide imbalance, for the most recent half hour [68]. The web page with the table is updated every minute with a 2 to 3 minute delay. (a): The table as available from 2004 until September 2009. (b): The table as available since September 2009 when info on the prices of the price setting bids was added. Tennet publishes this information in order to make the energy market more transparent [70].

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</tr>
<tr>
<td>9</td>
<td>1301</td>
<td>21:40</td>
<td>0</td>
<td>158</td>
</tr>
<tr>
<td>10</td>
<td>1300</td>
<td>21:39</td>
<td>0</td>
<td>184</td>
</tr>
<tr>
<td>11</td>
<td>1309</td>
<td>21:38</td>
<td>0</td>
<td>151</td>
</tr>
<tr>
<td>12</td>
<td>1308</td>
<td>21:37</td>
<td>0</td>
<td>144</td>
</tr>
<tr>
<td>13</td>
<td>1307</td>
<td>21:36</td>
<td>0</td>
<td>142</td>
</tr>
<tr>
<td>14</td>
<td>1306</td>
<td>21:35</td>
<td>0</td>
<td>139</td>
</tr>
<tr>
<td>15</td>
<td>1305</td>
<td>21:34</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>16</td>
<td>1304</td>
<td>21:33</td>
<td>0</td>
<td>134</td>
</tr>
<tr>
<td>17</td>
<td>1303</td>
<td>21:32</td>
<td>0</td>
<td>131</td>
</tr>
<tr>
<td>18</td>
<td>1302</td>
<td>21:31</td>
<td>0</td>
<td>128</td>
</tr>
<tr>
<td>19</td>
<td>1301</td>
<td>21:30</td>
<td>0</td>
<td>125</td>
</tr>
<tr>
<td>20</td>
<td>1300</td>
<td>21:29</td>
<td>0</td>
<td>122</td>
</tr>
</tbody>
</table>

(a) The table as available from 2004 until September 2009. (b) The table as available since September 2009 when info on the prices of the price setting bids was added. Tennet publishes this information in order to make the energy market more transparent [70].
10.4.2 Reducing Ramping Steepness

The ramp rate of a generator is the speed at which the power output of the generator can be regulated upwards (ramp-up rate) or downwards (ramp-down rate). For every generation unit these rates are limited to a certain level which is defined by the technical capabilities of the unit. For thermal power plants, especially the ramp-up rate is limited.

As Figure 10.8 shows, load profiles of bigger groups of consumers may exhibit rising flanks that cannot be matched by the ramp rate of any of the generation units in the set of units collectively following the load. In these cases, a number of units need to be ramped up simultaneously in order to follow the ramping rate of the load pool. A VPP gives the opportunity to reduce the number of traditional power plants needed in such a situation. A VPP would be able to manage the demand in such a way that the overall steepness of the load pickup becomes lower. At the same time, the VPP would be able to ramp up the distributed generators in the VPP cluster. As the number of generating units in a typical VPP will be high, a VPP will be able to reach a high ramp rate.

On the level of a BRP, reducing ramping steepness of the contracted load pool has a number of potential benefits. Firstly, wear of thermal power plants is reduced by avoiding fast thermal fluctuations in the plants’ construction. Secondly, the number of traditional power plants needed to follow the cumulated load ramp of the BRP’s

![Figure 10.8: Reducing the ramping speed of a customer pool’s daily profile. Traditionally, the rising flanks of a daily profile are matched by ramping a number of power plants simultaneously. Reducing the profile’s flank steepness decreases the number of power plants needed to follow the ramping. Figure adapted from [54], courtesy of Essent.](image-url)
clients may be lower. Thirdly, it makes ramping power available to deliver to the TSO as regulating power.

10.5 Conclusion

In this chapter, we have seen how trade and supply companies operate on the wholesale markets for electricity in a liberalised market setting. Ahead of the time of delivery, energy profiles of different granularity are traded on different timescales, first on the futures markets, then on the day-ahead market followed by the intra-day market. The latter two are known as the power exchange. At the moment of delivery, any discrepancies between the actual realisation and the traded volume are automatically traded on the balancing market.

Using flexibility in demand, value can be created on these markets in different ways. On the power exchange, this can be done by shifting demand away from high-priced time periods. In which manner value can be created on the balancing market depends on the level of market information the trading party has at his disposal. When information on the actual situation on the balancing market is available, an active approach can be followed by responding to the situation on the imbalance market. If such information is lacking, the party can create value by balancing its own commercial portfolio by minimising the real-time imbalance over the own customer base.

10.5.1 What’s Next?

At this point we completed the theory and the systems design. The proof of the pudding is in the eating. So, we are going to investigate how the designed system behaves in practice. Part IV of this thesis validates the PowerMatcher using field experiments and simulation studies. Chapter 11 explains how.
Part IV

Field Deployment and Validation
Chapter 11

Validation Approach

SYNOPSIS: With the design of the PowerMatcher, we have a coordination system design based on the answers to the first three research subquestions and practical design guidelines for DER agents based on the answer to the last subquestion. This covers a good deal of the main question of this research: how to design a coordination mechanism that integrates distributed energy resources in the operation of the electricity system and meets the six requirements? It is claimed that the PowerMatcher meets these requirements. So, in order show this claim holds, we need to validate the designed system against all its requirements. This validation has been done in a series of Field Experiments and Simulation Studies.

These field experiments and simulations integrate a wide variety of DER devices into PowerMatcher operations. Both distributed generators as demand response devices have been covered. Devices include home appliances, industrial installations and an electrical vehicle. This gives strong empirical support to the earlier conclusion that PowerMatcher is open by design for a wide variety of DER devices. This validates requirement R1.

POWERMATCHER IS DESIGNED to be a general-applicable energy management technology able to utilise the flexibility of Distributed Energy Resources (DER) in a scalable way. The design of the PowerMatcher provides the first step in our search for a coordination mechanism that integrates distributed energy resources in the operation of the electricity system and meets the six requirements defined. The second and final step is the validation of the design against the system requirements formulated. As argued in section 8.3, the requirement regarding Privacy Protection has been met by design. For the five remaining requirements we formulate five corresponding claims. The PowerMatcher is:

1. able to operate a wide variety of DER devices,
2. able to improve the wholesale market position of an energy trade & supply business,

3. able to contribute to active management of electricity distribution networks.

4. able to raise the electricity system’s accommodation ceiling for renewable power generation, and

5. scalable to mass-application levels.

In this part, we validate the innovation concept for these five important claims. In this chapter, we will start with a brief look into the five claims to define the corresponding validation criteria. Then, we give an overview of the field experiments and simulation studies performed to do the validation (Section 11.2). The final section in this chapter focusses on the first claim, openness. As the technical integration of DER devices runs as a red thread though all field experiments, we give an overview of how the validation work as a whole validates this claim. Each of the subsequent four chapters in Part IV describe the validation for one of the remaining claims.

11.1 Validation Criteria

11.1.1 DER devices to address

In order to prove that the PowerMatcher is capable of interaction with a wide variety of DER devices, one needs to show that such an interaction is actually possible for each main class of DER devices in operation today.

As defined earlier on in this text, we let DER encompass distributed generation, demand response and distributed storage. However, operational DER can be found in the former two classes. Currently, the number of storage devices exchanging power with the grid bi-directionally is negligible. Note that, in this respect, we treat a smart-charging electric vehicle as demand response. Apart from the distributed generation/demand response division, another dichotomy can be made according to the environment in which DER devices can be found: in homes or in industries. This separation makes sense from the perspective of nominal power which is in the order of 100 W to 1 kW for DER in homes and of 10 kW to 10 MW in an industrial environment. Further, there is a large difference in the type of control systems used. These two separations result in four quadrants, as shown in table 11.1.

In order to prove the claim that the PowerMatcher is able to operate a wide variety of DER devices, we need to show that for DER types in all four of the quadrants:
11.1. Validation Criteria

Table 11.1: DER types in four quadrants.

<table>
<thead>
<tr>
<th>Smart Homes</th>
<th>Demand Response</th>
<th>Distributed Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heat Pumps</td>
<td>Micro CHP</td>
</tr>
<tr>
<td></td>
<td>Electrical Vehicles</td>
<td>Photovoltaic Panels</td>
</tr>
<tr>
<td></td>
<td>White Good Appliances</td>
<td></td>
</tr>
<tr>
<td>Smart Industries</td>
<td>Cold Store</td>
<td>Industrial CHP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Emergency Generator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind Turbine</td>
</tr>
</tbody>
</table>

1. it is technically possible to interface the device with a device agent, and

2. the smart device is able to participate in a relevant smart grids application in a field or simulation environment.

So, we need to show the possibility of making DER units PowerMatcher-ready for each of the quadrants, and we need to show that these units are able to participate in a real-world smart grid application. In the next section, Section 11.2, five field experiments and three simulation studies covering specific smart grid applications involving DER are described. The validation of the openness claim is done through the total set of these experiments and simulations. In Section 11.3 is detailed how the experiments and simulations validate this specific claim.

11.1.2 Application Fields: Market & Networks

Claim 2 and 3 address the two main application fields of the PowerMatcher technology: involving DER flexibility in market operations and active distribution management. In order to prove that the PowerMatcher can provide considerable benefit in these application fields, one needs to show the effects of the technology in a real-world setting, preferably in field experiments and, where needed, supported by realistic simulation studies. Table 11.2 shows the validation items we want to address regarding these two application fields.

In electricity trade and supply we intent to show that PowerMatcher is applicable for running virtual power plants (VPPs). As explained in the previous chapter, VPP operations include commercial portfolio balancing and operations on the balancing market. Both target the Imbalance Market position of an electricity supplier. The first application minimises the real-time imbalance within a supplier’s contract portfolio, while the latter takes a more active approach by actively responding to the situation on the imbalance market. The active approach is possible when the right information on the market situation is available, as elaborated in the previous
11. Validation Approach

Table 11.2: PowerMatcher Application Validation Items

<table>
<thead>
<tr>
<th>Activity</th>
<th>Who*</th>
<th>Time frame</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portfolio Balancing</td>
<td>T</td>
<td>5 - 15 min</td>
<td>Diminish portfolio imbalance</td>
</tr>
<tr>
<td>Market Operations</td>
<td>T</td>
<td>5 - 15 min</td>
<td>React to bal. market situation</td>
</tr>
<tr>
<td>Congestion Management</td>
<td>D</td>
<td>5 min - 2 hour</td>
<td>Avoid network overload</td>
</tr>
<tr>
<td>Black-Start Support</td>
<td>D</td>
<td>5 min - 2 hour</td>
<td>Avoid network overload</td>
</tr>
</tbody>
</table>

*T = Trade & Supply, D = Distribution Network Operator.

chapter. Both applications require a performance on a scale of minutes. Chapter 12 describes the validation activities performed for these applications.

In distribution management, the validation focusses on congestion management and black-start support. Both applications aim at avoiding network overload situations. The first in a normal operational mode, the latter during a system restoration after a black-out. These applications, as described in Chapter 13, involve timescales of minutes to hours.

11.1.3 Integration of Renewables

Integration of renewables is an important driver for smart grid developments. An important validation item for any smart grid energy management technology is the ability to raise the accommodation ceiling for renewables in the electricity system. Synchronising DER units with large-scale generation of sustainable electricity is key in raising this ceiling. In order to prove that the PowerMatcher is able to raise this ceiling, one needs to show that the technology is able to improve the utilisation of large-scale generation of renewable electricity by a cluster of responsive end-user systems. As the accommodation ceiling is reached in future scenarios of high renewables penetration, a simulation study following a future energy scenario seems to be the most suitable way to provide this proof. In Chapter 14 we describe such a study and its results.

11.1.4 Scalability

The PowerMatcher has solid theoretical scalability properties, as argued in Chapter 4 and in Section 8.3.2. However, the proof of the pudding is in the eating. The PowerMatcher should still perform well under mass-application circumstances, even in the most time-critical applications. So, this theoretical evidence should be
11.2 Validation Means

The validation has been performed in a series of field experiments and simulation studies. This section gives a short introduction of each of these, with an overview of the key partners and persons involved. For each experiment or simulation study, the role of the author in the research activity is indicated.

11.2.1 Crisp Field Experiment

The first version of the PowerMatcher has been developed in 2004 within the CRISP project [64]. This project, partially funded by the EU under the 5th Framework Program, investigated how Information and Communication Technologies (ICT) could bring further benefits for sustainable development and growth of the power grid. In this sense, CRISP was a smart grid project avant la lettre and has been a pivot project in the European smart grid research. Project partners were: ECN (lead), IDEA, EnerSearch, E.on, Blekinge University of Technology and ABB. Three different field experiments have been performed within the project: in Sweden, France and The Netherlands. The latter tested the PowerMatcher technology in a commercial portfolio balancing setting. The Dutch energy supplier ENECO supported the experiment as assistant contractor. The field deployment targeted a portfolio balancing activity of an energy supplier using industrial and residential DER at different locations in The Netherlands. The experiment involved wind energy, a CHP supplying heat to a residential area, an industrial cold store, an emergency generator and an experimental home equipped with a heatpump system. The experiment contributes to the validation against requirements R1: “Openness”, and R4: “Trade & Supply Functionality”. A detailed description of the experiment and its results can be found in section 12.1. The team at ECN responsible for the field experiment included Maarten Hommelberg, Cor Warmer, René Kamphuis, Fred Kuijper, Sjaak Kaandorp and Gerrit Jan Schaeffer. The author was involved as lead architect.
11. Validation Approach

11.2.2 Micro-CHP Field Experiment

The Micro-CHP Field Experiment included 10 homes equipped with micro-CHP units all located in the northern part of The Netherlands. PowerMatcher was used to cluster these devices to deliver congestion management services collectively.

Shortly after the successful completion of the field experiment in the CRISP project in 2006 the PowerMatcher team at ECN was approached by the Dutch gas trading and transporting company Gasunie. At that time, Gasunie was developing micro-CHP systems for the Dutch market and was confronted with concerns from the Dutch distribution network operators. These concerns regarded network stability and power quality in case of a massive roll-out of micro-CHPs in their networks. In order to show that distributed generation can be an opportunity for optimised network operations, Gasunie initiated a field experimental project in which micro-CHP systems were clustered together in a virtual power plant to deliver congestion management services to the DNO. The PowerMatcher team was hired in an 100% payed assignment to build the VPP in cooperation with people from the Gasunie laboratories in Groningen (which are now part of KEMA). The gas trade department of Gasunie (now separated from Gasunie and called GasTerra) was the main funding source with co-financing from the Energy Valley Foundation and the three largest Dutch DNOs: Continuon (now Alliander), Essent Netbeheer (now Enexis) and ENECO Netbeheer (now Stedin).

Within the project, 10 micro-CHPs were equipped with a hardware node interfacing the CHPs with a PowerMatcher Device Agent. The cluster successfully reduced the peak loading on the distribution network as is detailed further in section 13.1. The experiment contributed to the validation against requirements Openness (R1) and Active Distribution Functionality (R5). The core team at ECN working on this project was the same as that of the Crisp Experiment. At the side of Gasunie, Jan Willem Turkstra and Pierre Bartholomeus played an important role. The author led the ECN part of the team during the design and roll-out phase and the initial experiments. Later on, Maarten Hommelberg took over this role. Bart Roossien played an important role in the data analysis. A more detailed description and the results of the experiment can be found in section 13.1.

11.2.3 PowerMatching City Field Experiment

PowerMatching City is located in the Hoogkerk suburb of the city of Groningen in the north-east of The Netherlands. This living smart grid community was officially opened in April 2010 and is still operational at the time of writing. PowerMatching City is claimed to be Europe’s first fully developed Smart Grid [57]. Current activities take place in the sequel project PowerMatching City II.
Activities in PowerMatching City I were conducted under the auspices of the European FP6 supported project INTEGRAL, which was initiated and led by the PowerMatcher team at ECN. The Dutch field experiment in that project was performed together with partners KEMA (field trial lead), Humiq and Essent. 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. The core of PowerMatching City is formed by 22 common Dutch households, located in the suburb of Hoogkerk near the city of Groningen, the Netherlands. These households have been equipped with different PowerMatcher-ready devices ranging from heating systems to smart appliances. 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 system operator (DSO) and the commercial aggregator (CA) (i.e. the utility or energy service company carrying balancing responsibility for a group of prosumers).

The experiment contributed to the validation of the PowerMatcher in three different aspects. Firstly, the experiment extensively tested virtual power plant use cases, run from the viewpoint of energy supplier Essent. The outcomes of these experiments contribute to the validation of the Trade & Supply Functionality requirement (R4). A description of the results of this part of the experiment can be found in Section 12.2. Secondly, the experiment implemented congestion management using the Fast LMP algorithm, as described in Chapter 7. Due to this algorithm it became possible to combine VPP operations by the energy supplier with congestion management in the network. This work is described in Section 13.4 and contributes to the validation against the Active Distribution Functionality requirement (R5). Finally, this field experiment contributed to R1: Openness, as different types of DER devices have been integrated in the experiment.

At ECN, colleagues René Kamphuis, Pamela MacDougall, Bart Roossien, Gerben Venekamp and Sjaak Kaandorp played an important role in the realisation of the experiment. Key persons at the project partners involved in the experiment were: Frits Bliek and Albert van den Noort of KEMA, Jörgen van der Velde, Eric Baker and Oscar Brouwer of Humiq (now named ICT Automatisering) and Marcel Eijgelaar of Essent. The author was directly involved in the initiation and initial outlining of the field experiment. During the realisation phase of the experiment, he played an advisory role to the design and implementation team bringing in results of Chapter 9 on agent strategies and of Chapter 7 on the Fast LMP algorithm. In a later stage, the project became under the author’s supervision when the author was appointed research coordinator of the Energy Management priority area within ECN’s Intelligent Energy Networks multi-annual research programme.
11. Validation Approach

11.2.4 Plug-in Hybrid Car Field Experiment

The Plug-in Hybrid Car Field Experiment ran in 2009 and 2010 in and around the village of Petten, The Netherlands. In an ECN-internal project, the PowerMatcher team bought a plug-in hybrid vehicle and made it \textit{PowerMatcher Ready}. The car is a Toyota Prius converted into a plug-in vehicle. The PowerMatcher team enhanced the car with an on-board computer running a device agent and a user interface. The car was included in a cluster of simulated electric vehicles operated to intelligently charge whenever the local network capacity allows for it. The experiment contributed to the validation against requirements \textbf{R1} (Openness) and \textbf{R5} (Active Distribution Functionality). Further details are given in subsection 13.2.3. Key contributors to the technical realisation of the project were: Peter van der Laag, Bart Roossien and Sjaak Kaandorp. The team reported to the author as the research coordinator of ECN’s Energy Management research priority area.

11.2.5 SmartHouse/SmartGrid Scalability Field Experiment

SmartHouse/SmartGrid Scalability Field Experiment ran in 2010 spread out over the PowerMatching City location in Hoogkerk, The Netherlands and data centers at SAP Research in Karlsruhe, Germany and ECN in Petten, The Netherlands. The SmartHouse/SmartGrid project focussed on Smart Houses interacting with Smart Grids to achieve next generation energy efficiency and sustainability. The EU FP7 co-funded project consisted of SAP Research (project lead), Fraunhofer IWES, MVV Energie, TNO, ICCS, and PPC. Originally, ECN was project partner, however, TNO took over their responsibilities when the smart grid group at ECN moved to TNO. Within this project, the PowerMatcher team performed a scalability test in close corporation with SAP Research. In this field experiment, the PowerMatcher architecture was operated at mass-application data traffic levels. We did this by implementing a full top-to-bottom slice of the architecture needed to cluster one million smart responsive households. Side-branches cut away from the architecture were replaced by data mimicking agents generating the data traffic volume of the pruned branch. The base of the slice was formed by the field cluster of 22 households in PowerMatching City. The experiment, described in detail in chapter 15, provided insight in the scalability of the PowerMatcher (requirement \textbf{R3}).

At ECN/TNO, the project was led by the author, who was also the leader of the project’s field trials workpackage encompassing three different field experiments spread over Europe. The scalability experiment has been set up and run in close corporation with the team at SAP Research (notably Anke Weidlich and Stamatios Karnouskos), and with colleagues Cor Warmer, Pamela MacDougall, Gerben Venekamp and Sjaak Kaandorp.
11.2.6 PowerMatcher Simulation Environment

A simulation tool has been developed around the version 3 implementation of the PowerMatcher. See Figure 11.1. Using the tool, one is able to simulate clusters of DER devices both in Business-as-Usual scenarios, where devices are controlled by standard local controllers, and in PowerMatcher scenarios, where devices interact through PowerMatcher agents.

The tool comes with a libraries of models of and agents for the most commonly used DER devices. The author was part of the design team for the simulation environment.

11.2.7 SmartProofs Smart Heat Pumps Simulation

Using the simulation capabilities of the PowerMatcher v3 implementation, it has been assessed whether the PowerMatcher is able to let distribution networks ride through extreme-load situations. In cooperation with the distribution system operators in the SmartProofs project consortium (Alliander, Enexis and Stedin), critical (overloading) scenarios have been formulated for a distribution network of which
the loading is dominated by heat-pump heating. The study has been performed by Olaf van Pruissen with design input from René Kamphuis, Cor Warmer and the author, under auspices of ECN’s Energy Management research priority area which was supervised by the author. The simulation study contributes to the validation of R5: Active Distribution Functionality.

11.2.8 Grid4Vehicles Electric Vehicles Simulation

Within the Grid4Vehicles project, a thorough 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. The study has been performed Bart Roossien with design input from Joost Laarakkers. The research felt within ECN’s Energy Management research priority area which was supervised by the author. The simulation contributes to the validation of R5: Active Distribution Functionality.

11.2.9 SH/SG Large-scale Wind Integration Simulation

To date, the most extensive simulation performed using the simulation tool has been performed within the SH/SG project. In a simulation study PowerMatcher’s potential contribution to the integration of large-scale wind power generation has been assessed. The study simulates 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. The study investigates the PowerMatcher’s ability to raise the accommodation ceiling for renewable energy and, thus, validates the corresponding requirement R6. The simulation has been designed, performed and analysed in close cooperation with Pamela MacDougall and Cor Warmer.

11.2.10 Overview

Thus, our validation activities encompass four different field experiments and three simulation studies each targeting a subset of the system requirements as defined at the beginning of this study. Table 11.3 summarises which requirement is targeted by which experiment or simulation study.
11.3 Openness Validation: Integration of DER Devices

The field experiments described integrate a wide variety of DER devices into the operations of the smart electricity grid. Apart from the individual claims that are validated by the work described in next few chapters, the work as a whole provides the validation of the first claim as described in Chapter 11:

*The PowerMatcher is able to operate a wide variety of DER devices.*

As stated in section 11.1.1, in order to prove that claim it needs to be shown that (i) it is technically possible to interface to a device (type) and (ii) the smart device is able to participate in a relevant smart grid application. Table 11.4 sums up the DER devices used in the field experiments and simulations performed. From the results summarised in the table, we conclude that the PowerMatcher is able to operate a wide variety of DER devices. The field experiments and simulation provide strong empirical support to the earlier conclusion, as drawn in Chapter 8, that PowerMatcher is open by design for a wide variety of DER devices (requirement R1).

### Table 11.3: Requirements tested per field experiment or simulation study.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>R1</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crisp Field Experiment</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micro-CHP Field Experiment</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PowerMatching City Field Experiment</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plug-in Hybrid Car Field Experiment</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SmartHouse/SmartGrid Scalability Field Experiment</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SmartProofs Smart Heat Pumps Simulation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grid4Vehicles Electric Vehicles Simulation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SH/SG Large-scale Wind Integration Simulation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* R1: Openness; R3: Scalability; R4: Trade & Supply Functionality; R5: Active Distribution Functionality; R6: RES Integration.
Table 11.4: DER Devices covered in the Field Experiments and Simulation Studies performed with the PowerMatcher Smart Grid Technology.

<table>
<thead>
<tr>
<th>DER Type</th>
<th>DR*</th>
<th>DG*</th>
<th>Interface</th>
<th>Participate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Smart Homes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Pump</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Micro-CHP</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Electrical Vehicles</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Industrial Installations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold Store</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Emergency Generator</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CHP</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Wind Turbine</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

*DR = Demand Response; DG = Distributed Generation.
Chapter 12

Optimisation in Electricity Trade & Supply

SYNOPSIS: The requirement that the PowerMatcher is applicable in the electricity trade and supply business (requirement R4) has been addressed in two field experiments. In the Crisp Field Experiment, commercial portfolio balancing (i.e. avoidance of imbalance costs) has been tested successfully using industrial and domestic DER units. An imbalance reduction of 40 to 43% was achieved in a real-life DER cluster having an imbalance characteristic dominated by wind electricity production. In the PowerMatching City field experiment, a more active approach has been taken by actively responding to the situation on the imbalance market. During the experiment, the VPP successfully followed its optimised energy profile as traded on the day-ahead market (peak shaving) as well as provided regulatory power via a near-real-time response to the momentary imbalance market situation (i.e. actively creating value on the imbalance market). The outcomes of these field experiments validate the claim that the PowerMatcher is able to improve the wholesale market position of an energy trade & supply business.

FLEXIBLE OPERATION OF Distributed Energy Resources creates value for a trade and supply business, as we detailed in Chapter 10. In this chapter, we validate the claim that the PowerMatcher is able to improve the wholesale market position of an energy trade & supply business. We do that on the basis of the results of two field experiments. In the Crisp Field Experiment, a group of industrial and residential DER, including wind power generation, is treated as the portfolio of a trade & supply business. PowerMatcher aimed to balance this portfolio in order to avoid imbalance costs. In the PowerMatching City field experiment, a more active approach has been taken by actively responding to the situation on the imbalance market.

Section 12.1 describes the Crisp field experiment and its results. Section 12.2 presents the relevant validation work done in PowerMatching City. Section 12.3
concludes the validation work regarding PowerMatcher’s applicability in trade & supply operation.

12.1 Commercial Portfolio Balancing

The PowerMatcher was first deployed in a field situation in the EU-funded CRISP project [64]. As part of this project three field experiments were carried out. The field test described here was one of them. The key-idea of this deployment is the utilisation of real-time flexibility of end-user costumers to balance a BRP portfolio. For each control zone, the BRP aggregates all its contracted flexible distributed generation and responsive loads in a virtual power plant (VPP). The BRP uses the VPP for its real-time balancing actions, the process described in Section 10.4.1.

It may be clear to the reader that high predictability and/or high controllability of the total BRP portfolio pays off in the form of lower imbalance costs. The business idea at hand focusses on the controllability side of the coin: the actions a BRP can perform in the post gate closure stage to let its DER portfolio follow the forecasted profile as notified to the TSO. The field experiment ran in a context where there is no information available of the system-wide imbalance (i.e. the situation as described in bullet point 1 on page 184). The TSO does not publish imbalance (price) information in real-time, nor has the BRP any means to estimate this. In this case, the best strategy of a BRP is minimising its portfolio imbalance in each settlement period.

12.1.1 The CRISP Field Test

For the purpose of the field test, five different installations were brought together in the portfolio of a virtual BRP. In reality, the installations represent a small part of the portfolios of two different BRPs, but for the sake of the experiment they were assumed to represent the full portfolio of one single BRP. Note that the number of five DER entities is rather small regarding the business rationale behind the field test. However, the main aim of this first field test was to get field experience with market-based control using different types of DER and to assess the impact of certing the DER flexibility on the portfolio imbalance.

Figure 12.1 gives the configuration of the field test. Each of the five DER installations was equipped with a so-called “Local CRISP Node”, processing hardware hosting the PowerMatcher local device agent. These agents interacted with the existing local measurement and control system. Table 12.1 gives an overview of the capacities of the individual installations included in the test. In order to give the smaller sized installations a good influential balance compared to the bigger ones, two of the sites were scaled up by an on-line simulation.
12.1. Commercial Portfolio Balancing

Figure 12.1: Configuration of the DBS field test.

Table 12.1: Production (P) and Consumption (C) Capacities of the Field Test Installations

<table>
<thead>
<tr>
<th>Site</th>
<th>P/C</th>
<th>Capacity</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Turbine</td>
<td>P</td>
<td>2.5 MW</td>
<td>-</td>
</tr>
<tr>
<td>CHP</td>
<td>P</td>
<td>6 MW</td>
<td>-</td>
</tr>
<tr>
<td>Cold Store</td>
<td>C</td>
<td>15 kW</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Emergency Generator</td>
<td>P</td>
<td>200 kW</td>
<td>-</td>
</tr>
<tr>
<td>Heat Pump</td>
<td>C</td>
<td>0.8 kW</td>
<td>80 kW</td>
</tr>
</tbody>
</table>

* P = Production; C = Consumption.

The local agents communicated with the electronic market system using a virtual private network running over a standard ADSL internet connection or (in one case) a UMTS wireless data connection. Due to the small size of the cluster, all local agents could be connected to one Auctioneer Agent running on a server, the “Central CRISP node” in the figure.
The cluster consisted of the following DER units:

- **Wind Turbine.** The wind turbine is located in Kreileroord, in the north-west of The Netherlands. The day-ahead forecast of the turbine’s output is made using the dedicated wind energy output forecasting method described in [10]. The turbine is the largest source of imbalance in the cluster (see also subsection 10.3). Note that the marginal operating costs of a wind turbine are virtually zero, as it does not include fuel expenses. Thus, it will not be economically attractive to curtail the output power of wind turbines for purposes of imbalance cost reduction. Accordingly, the turbine’s control agent always states inflexible—or inelastic—production bids of a magnitude equal to the current power output.

- **CHP.** The combined heat and power production unit is located in the vicinity of a residential area in Houten, a town in the center of The Netherlands. Its produced heat is fed into the heat network of the residential area. The complete CHP plant consists of a CHP/Gas heater combination as described in subsection 9.2.3 of the chapter on local agent strategies. This particular installation has three separate CHP installations, three gas heaters and a heat storage buffer. When running, the power production of each of the CHPs equals to 2 MW electrical and 20 MW thermal. The electricity is fed into the electricity network, i.e. delivered to the BRP. The heat is fed into the heat buffer, from which the heat demand of the residential area is supplied. The control agent’s local control objective is to keep the storage level of this buffer within a predefined temperature band. Since the operation of the CHP-system is crucial for the heat supply to a large number of dwellings, participation in the field test system imposed a high operational risk. For this reason, the field test system did not control the physical system itself, but a validated software model of the system. However, the local control agent system was implemented completely, only the local control signals were fed into the software model instead.

- **Cold Store.** The cold store is a large industrial freezing storage of a meat processing factory in Gouda. The control agent’s local control objective is to keep the temperature level of the cell within a predefined temperature band. The precautionary measures described for the CHP apply here as well: to minimise the operational risk the local control system signals were fed into a validated thermal model of the cold store.

- **Emergency Generator.** The emergency generator is a diesel-fuelled generator located in a multistory car park in Scheveningen, The Netherlands. In case of an interruption of the electricity supplied from the grid, the generator supplies
electricity to the buildings’s electrical system. The control agent will switch
the generator on when the price level on the clusters’s electronic market ex-
ceeds the marginal cooperating costs of the generator. These include fuel and
maintenance costs as well as an additional cost penalty for every system start.

**Heat Pump.** The heat pump system is for domestic space heating and hot tap
water heating. When the device is switched on, it consumes 0.8 kW electrical
power and delivers 8 kW to either the space heating radiators or the hot tap
water buffer. The control agent’s local objective is to keep the temperatures in
the living room and in the water buffer within a predefined temperature band
around their respective set points. The heat pump is installed in a research
dwelling at ECN, a real house having virtual inhabitants. The heat-demand
behaviour is simulated by a computer system that opens and closes hot water
taps and showers and adjusts room thermostat settings automatically accord-
ing to the behavioural pattern of an average Dutch household with 4 persons.
This site was included in the cluster in order to gain insight into the software
agent’s performance on a real-life thermal process.

### 12.1.2 Imbalance Reduction Results

The field test ran for a number of months in 2006. As is the case with almost any
research prototype of comparable size and complexity field-deployed for the first
time ever, the resulting data set is dominated by ‘teething troubles’. However, the
field test resulted in a number of periods of good data quality, enough to draw well-
founded conclusions. One of these periods is depicted in Figure 12.2. This figure
shows the imbalance as caused by the wind turbine together with the imbalance of
the cluster as a whole. In this figure, the wind imbalance serves as the reference
case. As the other installations were altering their operations in order to reduce
the cluster imbalance, there is no insight in the reference figure of the whole cluster
imbalance (i.e. when all installations would be running freely). However, the wind
turbine is the main source of imbalance in the cluster, so it gives a good, ‘on the save
side’, estimate, as the total imbalance will likely be higher.

The total imbalance reduction over the 11-day period in the figure is 40%. As is
clear from the figure this reduction is mainly achieved by compensating for the over-
production of the wind turbine. Apparently, there is enough flexibility in the cluster
to increase consumption and decrease production in these periods. Most of the un-
derproduction of the turbine is not compensated at all. As it seems, the flexibility to
increase production or to decrease consumption is much lower. Closer analysis of
the individual agents’ behaviour suggested a reason for this. As the weather was
quite cold during this particular period early May, the CHP’s residential area de-
manded high volumes of heat. Consequently, the CHP was in a ‘must-run’ situation with no room to shift production towards the periods of wind underproduction.

### 12.1.3 Individual DER unit behaviour

The test dwelling on the ECN research site was added to the field test cluster in order to have one DER unit available where the research team would have complete freedom to experiment. As described above, the dwelling’s heat demand for tap water and space heating is covered by a 0.8 kWe heat pump system. The local control agent’s objective is to keep the temperatures in the living room and in the water buffer within a predefined temperature band around their respective set points.

Figure 12.3 shows the temperature of the water in the hot tap water buffer (top) and the internal price on the electronic market (bottom). The temperature plot shows two types of spikes, corresponding to two different types of warm water usage. The numerous smaller spikes are caused by the usage of small amounts of hot water.
12.1. Commercial Portfolio Balancing

Figure 12.3: Top: Domestic Heat Pump – Tap water Buffer Temperature. Bottom: Electronic Market Electricity Price.

someone filling a dishpan or bucket, washing their hands using warm water, etc. This causes the temperature inside the buffer vessel to drop by a few degrees. The larger spikes are caused by a family member taking a shower. These occur less frequently, but take more heat, letting the temperature drop by more than 5 degrees Celsius. The allowed temperature band was set to the range between 43 and 53°C.

The bottom plot in figure 12.3 shows the prices on the electronic market. For this test, all agents were programmed to place bids in a price range between 5 and 10 price units. It is clear from the two plots that the agent heats the buffer to the maximum temperature only when the market prices are low. When the price on the electronic market is high, such as during the second half of the first day in the plot, the agent allows the temperature to drop towards the minimum temperature. Then, in the late evening of November 8th when someone is taking a shower, the temperature drops below the minimum. The agent is forced to accept the high electricity price, but only to heat the buffer to 45°C. After that, the agent waits until the price drops before heating the buffer to the maximum again.
Note that this behaviour of the agent helps balance the wind power production. When the wind turbine is overproducing, the electronic market price is low and the heat pump agent is eager to fill its buffer. Note further that nothing in the implementation of the heat pump agent was predesigned for a reaction to this particular global control goal. The agent only reacts to the electronic market price. Consequently, when the global control goal should change to something completely different, this local agent would remain unchanged and still react appropriately to the new situation.

### 12.2 Virtual Power Plant Market Operations

When information of the actual situation on the balancing market is available to a BRP in real time, the BRP would be able to counteract the system-wide imbalance and earn balancing revenues. Such a virtual power plant operation is opposed to balancing just the BRP’s own portfolio, as was done in the Crisp experiment. In this section, we will focus on the BRP as commercial aggregator and its interaction with the prosumer’s responsive demand and supply units in direct reaction on the wholesale market situation.

#### 12.2.1 PowerMatching City Field Test

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 is fitted with 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 is 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.

Twelve houses have been fitted with the heat-pump configuration. This configuration consist of an air–to-water heat pump, used for base load heating throughout the season, plus an high-efficiency gas-fired heater providing additional heat during peak loads and for domestic hot water. The nominal electrical power of the heat-pump used is 1 kW, while the thermal output lies around 3 kW. This is dependent on circumstances such as the outside temperature which influence the coefficient of performance (CoP). The gas heater has a thermal power of around 24 kW. The ten
12.2. Virtual Power Plant Market Operations

Figure 12.4: Heating systems used for demand supply matching in the Power-Matching City field experiment. Left: domestic CHP system with 210 liter heat storage tank. Right: Air-to-water heat pump with gas-fired heater and 210 liter heat store.

Micro-CHPs have an electric capacity of 1 kW and an heat output capacity of 6 kW providing heat for both base and peak load heating. Each CHP has an additional internal gas fired heater capable of boosting up the thermal power output with another 6 kW. This auxiliary gas heater can run independently from the micro-CHP. Each of the CHPs and heat pumps are connected to a 210 liter 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 [56].

12.2.2 Agent Strategy Heating Systems

The implementation of the local device agent’s strategies for the heating systems has been described by Roossien et al. [56]. The implementation closely follows the general micro-economic approach described in chapter 9 and in [42]. Figure 12.5
reproduces the decision graph used by the CHP agent. The buffer fill level $L$ is defined as:

$$ L = \frac{T - T_{\text{min}}}{T_{\text{max}} - T_{\text{min}}} $$

(12.1)

Similarly, to the strategy described in section 9.2.3, maximum and minimum buffer levels $L_{\text{max}}, L_{\text{min}}$ have been defined. Due to delays in the thermal response of the device these levels are not chosen to be 0% and 100% respectively. The CHP needs 5 to 10 minutes of operation before the heat delivery reaches its nominal value. Similarly, the system still delivers heat after switching off its stirling engine for some minutes due to the high thermal mass of the device.

The break-even point between producing heat with the CHP or the auxiliary gas heater is given by:

$$ c_a = c_y \left[ \frac{1}{\eta_a} - \frac{1}{\eta_{th}} \right] \left[ \frac{G_s}{P_{th}t_{\text{min}}} - \frac{E_s}{P_{th}t_{\text{min}}} \right]^{-1} \eta_{el} $$

(12.2)

where $\eta_a$ is the efficiency of the gas burner, $\eta_{th}$ and $\eta_{el}$ are the CHP’s thermal and electrical efficiencies, $G_s$ and $E_s$ are the gas and electricity consumed by the CHP during start-up, $P_{th}$ is the average thermal power output in normal operation, and $t_{\text{min}}$ is the minimum running time of the CHP excluding the start-up and cool-
down time. The gas price was assumed constant. Further, it was assumed that the start-up costs would be paid-back during the minimum running time.

In the agent strategy, this break-even point is used in a slightly different manner than in the strategy for the CHP heater combination as described in section 9.2.3. In that set-up the auxiliary heater was solely used as an emergency heater used when the buffer level dropped below its minimum level. Here, the aux heater is used in the normal operation of the heating system as well. It is clear from the graph that the break-even cost level $c_a$ is used to decide whether to use the CHP or the heater. However, it plays no role in the decision on whether to produce heat in the first place. This decision is based on a linear mapping from buffer level $L$ to the bid price. The cost levels $c_{\text{min}}$ and $c_{\text{max}}$ are the lowest and highest expected prices in the context of the electronic market.

A similar strategy was used for the heat pump systems, however with a curve moving from $(c_{\text{min}}, L_{\text{max}})$ to $(c_{\text{max}}, L_{\text{min}})$ in order to represent demand response instead of supply response. The price level at which using the gas burner is more favourable is:

$$c_a = \frac{\text{cop}}{\eta_a} c_g$$

where cop is the coefficient of performance of the heat pump.

12.2.3 VPP Operation

VPP operation within the portfolio of a commercial aggregator (CA) has been studied as one of the use cases. 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 12.6. It was concluded that the VPP successfully followed its optimised energy profile as well as provided the required regulatory power [44]. Thus, the PowerMatcher enabled the aggregator to improve its position on both the day-ahead and balancing market using the flexibility of its contracted prosumers.

Figure 12.7 visualises the flexibility available within the virtual power plant cluster over a period of 3.5 days. In this particular time period, the heating systems were the only devices providing flexibility. Just like a regular power plant, the VPP can be ramped up to output more power or ramped down to reduce the power output. However, where for a regular plant the minimum and maximum power output levels are fixed, for a VPP these levels change overtime. The highest and lowest line
Figure 12.6: VPP cluster in a real market environment, trading on the spot market (forecast) and regulatory market.

in the figure represent these control limits for this particular period. While, over time, individual devices move between “Must Run”, “May Run” and “Must Off” states (see section 8.1.2, notably figure 8.3), the VPP’s momentary minimum and maximum power output levels change with them. Naturally, the space between the two control limits represents the total momentary cluster flexibility, the control space available for power plant operations. The red line depicts the actual control curve resulting from operations on the day-ahead and balancing markets as described above. Note that, unlike a regular plant, a virtual plant can be controlled to consume electricity.

The PowerMatching City cluster has been used to reduce the imbalance caused by the wind turbine in a use case comparable to that described in section 12.1. It was demonstrated that the households were able to accommodate up to 60% of the imbalance generated by the wind turbine [57].
12.3. Conclusion

The main aim of the work presented in this chapter is to ascertain the second claim as described in chapter 11:

*The PowerMatcher is able to improve the wholesale market position of an energy trade & supply business.*

In Section 11.1.2, we stated that in order to validate this claim, one needs to show the effects of the technology in a real-world setting, preferably in field experiments and, where needed, supported by realistic simulation studies. Two types of virtual power plant operations were described as validation items in the trade & supply application area: Portfolio Balancing and Market Operations (see table 11.2). Table 12.2 gives an overview of the findings of the field experiments and simulation studies performed to validate this claim.

In two separate field experiments, we showed that PowerMatcher is applicable as a virtual power plant technology. In both experiments, the VPP was successfully applied for commercial portfolio balancing. In the first experiment described, an
Table 12.2: Validation Results in the Trade & Supply Application Area

<table>
<thead>
<tr>
<th>Validation Item</th>
<th>Result</th>
<th>Obtained in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portfolio Balancing</td>
<td>Wind imbal. reduction: 40 to 60%</td>
<td>Field</td>
</tr>
<tr>
<td>Balancing Market Reaction</td>
<td>Realisation of desired reaction</td>
<td>Field</td>
</tr>
</tbody>
</table>

An imbalance reduction of 40 to 43% was achieved in a real-life DER cluster having an imbalance characteristic dominated by wind electricity production. Using the field cluster of the PowerMatching City field experiment, a similar experiment reached an imbalance reduction of 60%.

Further, the PowerMatching City cluster was used for an experiment targeting the balancing market operations of an electricity supplier. Here, an active approach was taken by actively responding to the situation on the imbalance market. During the experiment, the VPP successfully followed its optimised energy profile, as traded on the day-ahead market, as well as provided regulatory power via a near-real-time response to the momentary imbalance market situation.

This validates the claim that the PowerMatcher is able to improve the wholesale market position of an energy trade & supply business.
Chapter 13

Active Distribution Management

SYNOPSIS: Electricity network operators form another class of parties having a potential benefit from utilising DER flexibility. Important smart grid applications for distribution network operators are related to the avoidance of network overload situations. When peak-loading of networks can be avoided, reinforcements of existing networks can be deferred and capital investments in new networks reduced. Network overloading may be avoided during normal operations, e.g. through congestion management, or in critical situations, for instance, during a system restoration after a black out. In a number of projects, field experience has been gained using PowerMatcher for congestion management. These experiments show an ability of substantial peak load reductions. These field results are backed by those of two comprehensive simulation studies. One of these studies additionally demonstrates the ability of the PowerMatcher technology to keep transformer load within rated capacity limits in a black-start recovery situation. The outcomes of these field experiments and simulation studies validate the claim that the PowerMatcher is able to contribute to active management of electricity distribution networks, which corresponds to the requirement of Active Distribution Functionality (R5).

Eletricity distribution networks are predominantly being operated in a passive manner. At design time, all parameters of a network segment are chosen to meet the expected worst-case operational scenario. For instance, the capacities of network components are dimensioned according to the expected worst-case network loading over the full operational lifetime. An active approach, where Distribution System Operators (DSOs) use flexibility available at DER units connected to their network, is expected to be beneficial for DSOs. Important smart grid applications for DSOs are related to the avoidance of network overload situations. Overloading may be avoided during normal network operation, e.g. through congestion management, or in critical situations, for instance during a system restoration after a black out.
In this chapter we validate the claim that the PowerMatcher is able to contribute to active management of electricity distribution networks. We do that on the basis of field experiences and simulation studies. In Section 13.1 we present the results of a field experiment involving micro combined heat and power (micro-CHP) units providing congestion management services. The two subsequent sections report on simulation studies into the impact of the technology for distribution network management. Section 13.2 investigates congestion management services delivered by smart-charging electrical vehicles, while Section 13.3 focusses on peak-load avoidance in extreme circumstances such as after a system restoration. The simulation results using the electrical vehicles are supported by field experiences obtained using a smart plug-in vehicle. Section 13.4 validates the fast algorithm for locational marginal pricing as defined in Chapter 7. The over-all conclusions are given in Section 13.5.

13.1 Congestion Management by micro-CHP systems

In the Northwestern region of Europe, decentralised generation of heat and power by micro-CHP units in households is expected to penetrate the market at high speed in the coming years. When the number of micro-CHP units in a region exceeds a certain limit, added value can be gained by clustered coordination via common ICT systems. In a field test a cluster of five Stirling based micro-CHP units of 1kW electric each has been operated as a virtual power plant\(^1\). The main goal of the field test was to demonstrate the ability of such a VPP to reduce the local peak load on the single low-voltage grid segment the micro-CHP units were connected to. In this way the VPP supports the local distribution system operator (DSO) to defer reinforcements in the grid infrastructure (substations and cables) when local demand is rising. Although not all micro-CHP units included in the field test were connected to the same low-voltage cable, during the experiment a connection to a common substation (i.e., low-voltage to mid-voltage transformer) was assumed. A more comprehensive description of the test can be found in [59] or [77].

13.1.1 Field Test Set-up

The field test focused on the network utilisation factor of the local distribution grid in three different settings:

\* **Baseline:** domestic load profile of 5 households.

\(^1\)In total 10 micro-CHPs were equipped to be part of the VPP. The results presented are realised with 5 of these 10 participating.
13.1. Congestion Management by micro-CHP systems

- **Fit-and-Forget**: load profile of 5 households plus micro-CHPs controlled in standard heat-demand driven manner (thermostat).

- **VPP operation**: CHP operation coordinated by PowerMatcher intelligent control to reduce peak-load, without any intrusion on comfort for consumers.

In the third setting, the micro-CHPs were controlled by local PowerMatcher control agents. These agents were clustered together with an objective agent monitoring the load on the shared transformer and demanding CHP electricity production when it exceeded a safety level.

The households participating in the field test were equipped with a Whispergen micro-CHP for heating of living space and tap water. For the latter, these systems were equipped with a tap water buffer of 120 liter. During the field test, the systems were extended with a virtual power plant node or VPP-node. The local agents ran on these VPP-nodes, communicating with the local infrastructure (micro-CHP, thermostat, and electricity meter) through power line communications and with the auctioneer agent through a TCP/IP connection. The end users communicated with the system by means of the thermostat.

The local agents aimed at producing CHP electricity in high-priced periods with a hard constraint of not infringing the users' thermal comfort. When the transformer load exceeded the safety level, the objective agent issued a demand bid aiming at steering the load back to the safety level. This increase in demand caused a price rise on the electronic market, which, in turn, triggered those agents most fit to respond (i.e., the ones having the highest heat demand at that moment) to run their CHP. The micro-CHP units were only operated in case of local heat demand, either for space heating or for tap water heating. No heat was dumped. An additional simulation study was done to verify the findings in the field test and to investigate circumstances not engaged in the field experiment, such as winter conditions.

13.1.2 Field Test Results

The field test was conducted in May 2007, which was an exceptionally warm month for The Netherlands. Therefore there was no space heating demand in the households, only demand for tap water heating. Figure 2 shows a typical day pattern during the field test when five micro-CHPs were participating in the VPP. The PowerMatcher shifts the micro-CHP production so that electricity is produced when there is a high demand for electricity. This lowers the peak load on the substation.

The main findings of the field experiment and additional simulation studies were:
13. Active Distribution Management

Figure 13.1: Typical measured day patterns for 5 micro-CHPs with PowerMatcher coordination: synchronisation of CHP output (dashed line) with domestic peak-demand (dotted) leading to peak load reduction at the transformer (solid line).

- The Fit-and-Forget policy did not provide benefits to the DSO in comparison to the baseline case. The load-duration curve was lowered on average by adding the micro-CHPs. However, the peak load remained virtually unchanged.
- Adding VPP operation, based on PowerMatcher intelligent control, led to a load-peak reduction of 30% in summer (field test result) and 50% in winter (simulation outcome). The system caused no infringement of the comfort of the users.

13.2 Congestion Management by Electric Vehicles

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.

In this section we investigate how intelligent charging of electrical vehicles can contribute to active management of distribution networks. Both a simulation study and field experiences are presented. In both studies, we consider the electrical car as demand response. Hence, we focus on intelligent vehicle charging. The possibility to discharge power from the car’s battery into the grid, the so-called Vehicle to Grid (V2G) option, isn’t taken into account. In the transition path from fossil-fuelled cars to electrical ones delivering V2G services, we expect the first smart grid interactions of electrical vehicles will be through intelligent charging. Intelligent charging does not require an high investment in equipment at the side of the vehicle, and the benefit for grid operations is already substantial as we will see.

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. This work, performed and published by Roossien et al. [60, 44], is summarised in sections 13.2.1 and 13.2.2, following the text used in [44]. Further, additional field experience was gained using a smart-charging plug-in hybrid car with results supporting the simulation outcomes. These results are described in section 13.2.3.

### 13.2.1 Simulation Set-up

A stochastic driving behaviour model was developed, based on a German mobility survey [1], 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 [66]. 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.

13.2.2 Simulation Results

Figure 13.2 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

![Figure 13.2: 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.](image)
13.2. Congestion Management by Electric Vehicles

Figure 13.3: Substation peak load for an urban district in North-Europe and South-Europe with and without PowerMatcher coordination.

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 13.3 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. In the Northern Case, the peak load is reduced from 190 kVA in the reference case to 150 kVA in the PowerMatcher case both at an 100% EV penetration. As the peak load without the EVs is just below this 150 kVA, the claim is justified that by using PowerMatcher a network reinforcement of \( \frac{(190 - 150)}{150} \approx 25\% \) has been avoided. In the Southern Case, the peak loads are 300 kVA and 225 kVA, respectively, resulting in an avoided
13.2.3 Field Experience and Results

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. Figure 13.4 shows a picture of the car. 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 car’s device agent was programmed to charge the car battery against low prices on the electronic market with the constraint to have the battery fully charged at the expected departure time as given by the driver. Apart from the departure information coming from the driver, the agent needs to receive the current state of charge of the battery. This data could easily be read into the on-board computer through a digital interface to the car management system. The agent automatically operated a relay switching the battery charger.

The Prius was added to a cluster of simulated cars charging from a virtual (i.e. reinforcement of approx. 30%).
13.2. Congestion Management by Electric Vehicles

Figure 13.5: Load profiles from the combined field simulation experiment using the PowerMatcher-ready plug-in hybrid vehicle. The time base in the plot starts at 6pm and ends at 3am. The base load are 10 households and the ‘No control’ curve is the additional charging load of 10 cars without intelligent charging. The ‘PowerMatcher’ curve gives the charging load under coordinated charging profile added. Here, the goal was to keep the total load below the network capacity of 12.5 kW.

simulated) residential low-voltage network. The network has just enough capacity to serve the 12 kW peak load of the households. The simulated cars each followed an individualised model generating their connect and disconnect times and driving pattern. The Prius was used by one of the research team members for commuting. Figure 13.5 shows a part of the resulting load profiles. The plot starts at 6pm just before the peak load for the group of household. In the uncontrolled case, the peak load of the households coincide with that of the charging cars (see the plot to the left). The resulting peak load of 17 kW is way over the network capacity of 12.5 kW. In the intelligent charging case, the goal was to keep the total load below this network capacity. The resulting load profile is added in the right plot in the figure. As can be seen from the figure, the load stays below the maximum capacity of the network, thus avoiding a reinforcement of \((17 - 12.5)/12.5 \approx 35\%\). These results give empirical backing to the simulation outcomes as presented above. So, PowerMatcher is able to avoid grid congestion through coordination of the charging processes of plug-in vehicles.
13.3 Heat Pump Active Network Services

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 100 to 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 PowerMatcher is able to ride through these extreme situations with a lower network capacity. The simulation results in this section are based on work by Van Pruissen et al. [73]. The study was performed within the SmartProofs project.

13.3.1 Two critical scenarios

In cooperation with employees from Alliander, Enexis and Stedin, 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.
13.3. Heat Pump Active Network Services

• **Cold winter morning scenario:** An early cold Monday morning (−10°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.

13.3.2 Simulation Set-up

The simulation model consists of 100 households represented by a building model and a combined model of the heat pump and auxiliary heater. The full model represents the additional electricity used when the houses are heated by the heat pumps, as opposed to gas boilers, the predominant way of heating in The Netherlands. 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 by accepting higher prices for the heat pump operation. The auxiliary heater is controlled in a modulated manner allowing the agent to operate at any power below the rated power of 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.

### 13.3.3 Simulation Results

The simulation run has been performed for both the reference case and the PowerMatcher control case. Figure 13.6 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 coordinated 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. In the morning scenario, slower heating can be compensated by a smart thermostat. Such a thermostat uses the heating curve of the last few days to determine the right starting time in order to reach its setpoint at the user’s desired time.

Let’s see what this means for the design capacity per household. In the black-start scenario, the load from the 100 HPs is just over 800 kW, resulting in a minimal
design capacity of 8kVA per heat pump. Adding an uncertainty margin results in 10 kVA per HP. Recall that the simulation includes the HP loads only. If we calculate with a design capacity of 1 kVA for the rest of the household load, the resulting design capacity of the complete household is 11 kVA. With the transformer capacity chosen to be 275 kW (only to serve the 100 HPs), the household design capacity for the controlled case becomes $2.75 + 1 = 3.75$. So, the network capacity can be roughly 3 times lower as compared to the business as usual.

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.

13.4 Congestion Management using Bid Propagation

As described in chapter 6, Locational Marginal Pricing (LMP) combines commodity trade and infrastructure management in one single optimisation algorithm. The Fast LMP Algorithm for acyclic networks, as introduced in chapter 7, is suitable to be used in distribution networks which are predominantly operated in a radial, acyclic, topology. To recall, the algorithm propagates demand functions from the leaves of the tree to the root (swing node) in the first phase and back-propagates the nodal prices to the leaves in the second phase. The propagation process ensures that a demand function associated to a specific location in the network is, so-called, network sound. For any price, a network-sound demand function yields a local flow that is (i) within the local line capacity constraint, and (ii) accounts for network losses.

13.4.1 Field Test Set-up

In the PowerMatching City field experiment, the FastLMP algorithm has been validated in a congestion management application. In this setting, the FastLMP variant as described in section 7.4.2 has been used. In this variant, the availability of network capacity is determined using a load measurement. This load measurement is used as input to the demand function propagation performed by the concentrator agent associated to the measured network node. Refer back to Figure 7.6 and its description in the text for more info on this procedure. The smart devices used in PowerMatching City —and in the LMP experiment described here— have been described in Section 12.2.1 and the strategies of the device agents in Section 12.2.2. (highlighted)

Locational Marginal Pricing makes it possible to perform a dual goal optimisation. While optimising commodity trade through a market mechanism, the market outcome is guaranteed to stay within the constraints set by the infrastructure. In
this way the goals of the energy trader and the network operator are attained. In this field experiment, the trader runs a virtual power plant, the one covered in 12.2, while the network operator manages network loading to avoid overloading. As the 22 households participating in the PowerMatching City field experiment were not connected to the same low-voltage network section, a virtual transformer was created. It was assumed that this transformer carried the load of all households involved. The load of each house was measured individually and added together to get the virtual measurement of the transformer. The load of this transformer was then managed by the concentrator agent to stay under the rated power of 25 kW. Refer back to section 12.2.1 for a description of the 22 households and the smart devices installed.

13.4.2 Field Test Results

Figure 13.7 gives a typical load profile for the transformer during a 24-hour period (noon to noon). The blue profile gives the load that would have been on the trans-
13.4. Congestion Management using Bid Propagation

Figure 13.8: Load-duration curve for the profiles depicted in Figure 13.7. It is clear that the peak-load has been lowered to stay below the rated transformer capacity of 15 kW.

former without the congestion management in place. When this load approaches the rated substation load, the demand function propagated through the concentrator associated to the transformer is altered to lower the load. The green profile is the expected transformer load according to the propagated demand function. Note that this profile differs from the blue profile only when the load approaches the rated power. The realised load profile (red) closely follows the desired load profile. Deviations between those two originate in small deviations between the device agent bids and their actual realisation. Here, discrepancies may occur, for instance, when a heating system is starting up. Then the agent bids for the rated power, while the device needs some time to start up and reach this power. However, it is clear from the graph that the congestion management goal is met: the realised power load does not exceed the rated transformer power of 25 kW. From the load-duration curve in Figure 13.8, this can be seen as well. In this instance, the peak-load was lowered from 28 to 25 kW. Over a longer period, a peak load reduction of 15% in the common substation of the households was achieved.
13.5 Conclusion

The main aim of the work presented in this chapter is to ascertain the third claim as described in chapter 11:

The PowerMatcher is able to contribute to active management of electricity distribution networks.

which corresponds with the Active Distribution Functionality requirement. In Section 11.1.2, we stated that in order to validate this claim, one needs to show the effects of the technology in a real-world setting, preferably in field experiments and, where needed, supported by realistic simulation studies. Both congestion management and black-start support were defined as validation items (see table 11.2). Table 13.1 gives an overview of the findings of the field experiments and simulation studies performed to validate this claim.

Table 13.1: Validation Results in the Active Distribution Application Area

<table>
<thead>
<tr>
<th>Validation Item</th>
<th>Result</th>
<th>Obtained in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congestion Management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordination of $\mu$-CHPs</td>
<td>Peak reduction: 30–50%</td>
<td>Field</td>
</tr>
<tr>
<td>Smart charging of EVs</td>
<td>Peak reduction: up to 30%</td>
<td>Simulation</td>
</tr>
<tr>
<td>Smart charging of EVs</td>
<td>Peak reduction: 35%</td>
<td>Field</td>
</tr>
<tr>
<td>VPP &amp; Congestion Mgmt</td>
<td>Proof of Principle of FastLMP</td>
<td>Field</td>
</tr>
<tr>
<td>Black-Start Support</td>
<td>Grid capacity can be $3 \times$ lower</td>
<td>Simulation</td>
</tr>
<tr>
<td>Coordination of HPs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be seen from the table, good results have been obtained from field experiences in three different settings. Firstly, market-based control of a cluster of micro-CHPs led to substantial peak load reductions of 30% in summer and 50% in winter at the level of the low to mid-voltage transformer. These results were obtained without any infringement of the comfort for the inhabitants of the homes involved. In a Fit-and-Forget scenario, in which the micro-CHPs were locally controlled by thermostats, the network’s peak loading wasn’t lowered at all. This shows the ability of the PowerMatcher to shift operation of devices to relieve network peak loading.

Secondly, experience with a smart charging plug-in vehicle shows the impact of electric vehicles on the peak load of substations in residential districts and how this peak load might be reduced through proper PowerMatcher coordination. This combined field/simulation study showed that PowerMatcher coordination of EV charging in an residential area reduces the maximum network load by 35%. This finding
13.5. Conclusion

has been confirmed by extensive simulation studies. These show that, with PowerMatcher coordination, peak loading can be kept almost constant while EV-penetration levels rise to 100%. In contrast, without coordination, low EV-penetration levels of 20 to 30% already cause a significant increase in peak load level. At a 100% penetration the peak loading would raise with 25 to 30% without coordination. In an older network where the household power intake is close to the network capacity, smart EV charging by PowerMatcher avoids a network reinforcement of up to 30% according to the simulation study. For the combined field/simulation study this figure is even higher: 35%.

Thirdly, dual goal optimisation using the Fast LMP Algorithm was tested in the PowerMatching City field experiment. The algorithm successfully managed the network load of the cluster of 22 smart homes while at the same time allowing them to participate in a virtual power plant operated by the energy supplier. A peak load reduction of 15% in the common substation of the households was achieved. These results provide a proof of principle for the algorithm.

These field experiments and simulations focus on the normal operational mode of the electricity network. The simulation study described in Section 13.3 looked at extreme circumstances during normal operation and during a system restoration to recover from a power outage. The findings regarding the normal operation confirm the findings as described above. The outage recovery case investigated a black start on a cold winter day in a residential district where homes are electrically heated. Without proper smart grid technology in place, this results in an extreme high load peak. The local network needs to be designed to carry such a load peak even if it occurs only once or twice during the lifetime of the asset. PowerMatcher coordination has shown to keep transformer load within rated capacity limits under such extreme conditions allowing for a lower design capacity of the network. In our case, homes heated by heatpumps, black-start support allows for design capacity that is 3 times lower than when black-start support is not in place.

The results above validate the claim that the PowerMatcher is able to contribute to active management of electricity distribution networks.
Chapter 14

Integration of Large-Scale Wind Power

SYNOPSIS: In order to assess the ability of the PowerMatcher to raise the electricity system’s accommodation ceiling for renewable power generation (requirement R6), one has to look into future scenarios of large-scale renewable generation. However, the scale of individual smart grid experiments does not reach mass-application levels at this moment. Accordingly, we have to turn to a simulation study to get answers about the reaction of larger clusters of responsive loads and distributed generators on the varying output of renewables. In the simulation study performed, the reaction of 3000 individual smart households to the fluctuating output of solar and wind energy systems was studied. The study uses a 2040 scenario of high wind energy penetration and ran under real-life circumstances. The smart grid offers a large potential in utilising flexibility of demand and supply in homes to accommodate high levels of wind power generation, as the study shows. Using the PowerMatcher for demand and supply coordination, the accommodation ceiling for renewables is raised and the amount of energy from fossil fuelled power plants reduced.

INTEGRATION OF RENEWABLES is one of the key drivers behind the development of smart electricity grids. As argued in Chapter 2, an efficient integration of large-scale renewable electricity generation will involve response of demand and distributed generation through smart grid coordination. As we have shown in previous chapters, the scale of the individual experiments 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 and their influence on the integration of renewables.

In this chapter, we present the results of such a study to validate the claim done in Chapter 11 that the PowerMatcher is able to raise the electricity system’s accommodation ceiling for renewable power generation. The study simulates 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 study is based on a 2040 scenario for the Netherlands and is run under real-life circumstances.

The chapter is structured as follows: Section 14.1 discusses the study’s assumptions, scenarios, models and the input data used. Section 14.2 describes the simulation performed and its results, while Section 14.3 draws conclusions out of the results.

14.1 Assumptions, Scenarios, Models and Input Data

14.1.1 Renewable Generation Capacity

The simulation study targets a possible 2040 energy scenario for The Netherlands. We base the chosen electricity generation mix, residential electricity demand and distributed generation on two different sources: the WLO-Strong Europe (WLO-SE) scenario for 2040 and wind energy growth projections from the wind power sector itself.

The Welfare, Prosperity and Quality of the Living Environment study (in Dutch: “Welvaart en Leapfrogging”, WLO), is a set of scenario studies into all aspects of the Dutch society up to 2040 (see [17] for an overview in English). The study was executed by the Dutch planning offices for economy and environmental assessment (CPB and PBL, respectively) and the energy chapter of the study has been developed in cooperation with the Energy research Center of the Netherlands (ECN). The WLO study uses four different scenarios for the future of Europe, for the simulation study we present here, the WLO Strong Europe (WLO-SE) scenario will be used as input. One of the characteristics of this scenario is an effective international environmental and climate policy. The WLO-SE study provides quantitative data on the energy supply mix and the energy demand per sector. In the scenario, new generation capacity will at first be gas based. On the longer term, also coal gasification with Carbon Capture and Storage (CCS) will be applied. Due to the strong climate policy also energy from wind, PV and biomass will grow, leading to a share of renewable electricity in 2040 of more than 30%.

In our study, we focus on smart homes only. Accordingly, the industry demand and corresponding supply have been removed from the scenario. The total envisioned electricity demand in WLO-SE 2040 is 582 PJ, the total household demand is 130 PJ. To adjust for leaving the industry-related demand and supply out, the renewable capacities were scaled down by 0.22 (130/582). The second column in Table 14.1 shows the projected installed capacity for renewables for 2040, while the
14.1. Assumptions, Scenarios, Models and Input Data

Table 14.1: Installed generation capacities in the full WLO-SE 2040 scenario, covering the residential sector only, and scaled down to 3000 households.

<table>
<thead>
<tr>
<th>Installed Capacity</th>
<th>Total</th>
<th>Residential</th>
<th>3000 Homes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Onshore</td>
<td>2 GW</td>
<td>0.44 GW</td>
<td>156 kW</td>
</tr>
<tr>
<td>Wind Offshore</td>
<td>10 GW</td>
<td>2.2 GW</td>
<td>750 kW</td>
</tr>
<tr>
<td>Photovoltaics 2M m²</td>
<td>3 GW</td>
<td>660 MW</td>
<td>231 kW</td>
</tr>
<tr>
<td>Fossil Fuels</td>
<td>⋮</td>
<td>15 GW</td>
<td>5.25 MW</td>
</tr>
</tbody>
</table>

second column shows the adjustment. In the last column these figures have been scaled down from 8.6 million to 3000 households, which is the number we consider for our simulations. 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.

In the WLO-SE scenario, the offshore wind generation capacity will increase significantly over time. The wind energy sector, however, foresees an even faster growth of off-shore wind power. 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.

14.1.2 Household Prosumption and Flexibility

The models and input data used in the simulations were chosen such that the simulations ran under real-life circumstances. Household electricity demand profiles used in the simulations are randomly generated using a pattern generator validated with real household data. The patterns were individualised per household based on configurable parameters: total annual electricity consumption, number of persons in household and lifestyle. Additional to these settings, it was assumed that half of the households were equipped with a micro-CHP and the other half with a heat pump. The demand and supply flexibility in the households was realised solely by these heating systems. Both devices are used for space heating as well as tap water heating and have heat buffers of 120 liters (space heating) and 90 liters (tap water) allowing for flexibility in their operations. The devices were modelled according to those used in the PowerMatching City field experiment (see Sections 12.2.1 and 12.2.2).

The household heat demand profiles for space heating originated from a pattern generator based on a linear regression model. It uses 10-minute based ambient temperature and (horizontal) solar irradiation data. Per household, the total annual
heat demand in GJ was set according to the number of persons in the household and their lifestyle. Accuracy of the heat demand pattern generator has been validated against a detailed TRNSYS-based transient simulation of homes and their thermal systems.

All device models were developed to run with two types of controller, a traditional thermostat controller and a PowerMatcher controller which has added intelligence to respond to price incentives. In this way PowerMatcher control could be compared to the business-as- usual case.

14.1.3 Renewable Power Generation Patterns

The renewable generation supply patterns were generated using measured time series for wind speed and solar insolation. The wind data originated from the Dutch meteorological office KNMI. For the offshore wind power, a number of offshore sites were averaged to make an estimate of total offshore wind power. The solar irradiation data originated from a measurement program done at ECN. The weather time series were fed to a PV-solar system model and a wind turbine model to generate the power supply patterns.

14.2 Simulation & Results

As detailed above, the simulation involves renewable generation (PV-solar, on- and off-shore wind) and a cluster of 3000 households having responsive heating systems. The simulations investigate how much of the generation in this cluster is used within the cluster itself, both under business-as-usual control systems and under PowerMatcher coordination. Therefore, this cluster is treated as a closed system and we observe the total import and export to and from it. Lower import and export levels indicate a better utilisation of the power generated inside the cluster. A number of ten simulation runs have been done: a BaU and a PowerMatcher run for each of the five offshore wind capacity scenarios (750, 800, 850, 900, and 1000 kW). All other energy factors have been left unchanged over the scenarios. The simulations covered a period of 2 weeks in the month of November.

The main findings of the simulation study can be found in Figure 14.1 which depicts the difference in import and export to and from the cluster for each off-shore wind scenario. From the figure, it is clear that for each simulated case more wind was utilised within the cluster using the PowerMatcher technology as compared to business as usual. Table 14.2 gives the reductions in percentages. The second column the table shows 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
14.2. Simulation & Results

Figure 14.1: Sum of Wind Potential Utilised for Each use case in Business as Usual and PowerMatcher Modes.

Table 14.2: Percentage of Total Import and Export for Each Case.

<table>
<thead>
<tr>
<th>Offshore Wind</th>
<th>Export Reduction</th>
<th>Import Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>750 kW</td>
<td>90%</td>
<td>14%</td>
</tr>
<tr>
<td>800 kW</td>
<td>85%</td>
<td>16%</td>
</tr>
<tr>
<td>850 kW</td>
<td>79%</td>
<td>17%</td>
</tr>
<tr>
<td>900 kW</td>
<td>74%</td>
<td>18%</td>
</tr>
<tr>
<td>1000 kW</td>
<td>65%</td>
<td>21%</td>
</tr>
</tbody>
</table>

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 in 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.

### 14.3 Conclusions

This simulation study shows that the smart grid offers a large potential in utilising flexibility of demand and supply in homes to accommodate high levels of renewable energy sources. In the simulation study performed, the reaction of 3000 individual smart households to the fluctuating output of solar and wind energy systems was studied. The configuration of this mixed residential and RES cluster is based on a 2040 scenario of high wind energy penetration for The Netherlands. The simulation ran under real-life circumstances due to the use of validated models and measured time series. The simulation study shows that matching demand and supply in the cluster leads to an increase in RES utilisation: 65 to 90% of the green electricity, which would remain unused by the households, is actually used now. This leads to a decrease in total electrical energy exported from the cluster and, at the same time, a decrease in electrical energy needed from other sources in the range of 14 to 21%. For the Dutch case, this would mean avoided use of fossil-based electricity.

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 would be improved, thus increasing the utilisation of the renewable generation even further.

<table>
<thead>
<tr>
<th>Validation Item</th>
<th>Result</th>
<th>Obtained in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased RES utilisation</td>
<td>Uncommitted RE used: 65–90%</td>
<td>Simulation</td>
</tr>
<tr>
<td>Avoided gray energy usage</td>
<td>Reduced use of gray: 14–21%</td>
<td>Simulation</td>
</tr>
</tbody>
</table>

Table 14.3 gives an overview of the findings. These findings clearly show that electricity produced from renewable sources is much better accommodated when the PowerMatcher as coordination measure is in place. Consequently, it can be concluded that demand and supply matching by the PowerMatcher raises the accommodation ceiling for renewables and reduces the amount of energy needed from non-renewable sources.
Chapter 15

Demonstration of Scalability

SYNOPSIS: Hitherto, field experiences and simulation studies have shown the potential of the PowerMatcher technology for network operations, market operations, and integration of large-scale wind power generation. However, as the current field experiences do not yet approach mass-application scales, there is no empirical backing for the theoretical scalability properties of the technology. To overcome this, we performed a field experiment in which we could test the PowerMatcher architecture at mass-application data traffic levels. We did this by implementing a full top-to-bottom slice of the architecture needed to cluster one million smart responsive households. Side-branches cut away from the architecture were replaced by data mimicking agents generating the data traffic volume of the pruned branch. The base of the slice was formed by the field cluster of 22 households in PowerMatching City. Timing experiments done with this set-up show that a cluster of one million smart homes is able to react to outside stimuli within one minute. This is fast enough to be active on the wholesale markets for balancing, the most volatile electricity markets. This further demonstrates PowerMatcher’s scalability to mass-application levels, validating requirement R3.

SCALABILITY IS KEY in smart grid coordination as the number of responsive units involved in coordination will be huge in the future electricity grid. As described in subsection 8.3.2, the PowerMatcher has been designed with scalability as the key quality attribute. Unfortunately, none of the field experiments performed at the time of writing approaches a mass-application scale. Therefore, these experiments provide no empirical backing for the theoretical scalability properties of the technology.

To overcome this, we performed a field experiment in which we could test the PowerMatcher architecture at mass-application data traffic levels. We did this by implementing a full top-to-bottom slice of the architecture needed to cluster one million smart responsive households. 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 are 25 smart homes in the PowerMatching City field demonstration as described in section 12.2. Using this set-up we aim to validate the claim that the PowerMatcher is scalable to mass-application levels.

15.1 Performance Metric and Desired Value

The aim of the experiment is to assess the scalability of the PowerMatcher by testing it’s architecture under mass application circumstances. Therefore, 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.

15.1.1 Mass Scale

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.

15.1.2 Performance Metric

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 and, thus, the most attractive for VPP operations. 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. Note that the speed of the upwards communications in the PowerMatcher, i.e. the stream of bid updates towards the Auctioneer Agent, is irrelevant for the reaction speed of a PowerMatcher VPP.
15.1.3 Success Value

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 (dependent of the information available, see sec 10.4.1), 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.

15.2 Architecture Under Test

At the top of the architecture is the so-called Enterprise System, the conglomerate of all relevant sub-systems running at the level of the utility company operating 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. In the remainder of the text we refer to this architecture as the 1M architecture.

Note that the number of customers connected to such an infrastructure in field demonstrations is still a few orders of magnitudes lower than our target of one million. At the time of writing, the largest cluster of PowerMatcher-coordinated end-customers is the group of 25 households participating in the PowerMatching City field experiment. As described in the previous section, for the scalability test, we need to measure the update time $t_u$ needed to communicate a price change due to an operational action by the VPP operator down to the device agents in the homes. For obvious practical reasons we decided to implement a full top-to-bottom slice of the 1M architecture, from the Enterprise down to the PowerMatching City cluster. In order to keep the test realistic, we install data mimicking agents generating the data traffic of the pruned branch at the points where we cut off side-branches of the architecture. In this way, the data traffic through the slice is at the same level it would have been in a full implementation of the 1M architecture.
Figure 15.1 gives the configuration of the system under test. The configuration consists of a number of clusters of (mimicked) households:

1. **Field-deployed Smart Homes**: This sub-cluster is the group of real smart households in PowerMatching City aggregated by a concentrator agent. Each house has a household concentrator with one or more agents (heat pump, micro-CHP, etc.) connected. The household bid functions are sent to concentrator 1.1. Each house has a smart meter. The level 1.1 concentrator collects meter data from each household. The sub-cluster counts 25 smart houses in the field.

2. **Smart meter sub-cluster**: 100 real smart meters (see figure 15.2) running in parallel to a simulated cluster of 100 houses. The PowerMatcher control is a simulation of a cluster of 100 individual household models connected to a the PowerMatcher Concentrator Agent running on the level 1.2 concentrator hardware. This concentrator also collects the metering data from each meter. So, the sub-cluster counts 100 meters plus 100 simulated households.
3. **Mimicked level 1 clusters**: 98 dummy data providers each mimicking a cluster of 100 households. Each data provider is connected to a concentrator (1.3 to 1.100) and mimics the communications for both the VPP process and the metering data collection process. Accordingly, the 1.3 to 1.100 concentrators each carry the data traffic of 100 households, while the 2.1 concentrator carries the traffic of just under 10,000 households (25 + 100 + 98x100 = 9,925).

4. **Mimicked level 2 clusters**: Similarly to the level 1 mimicked clusters, level 2 has 99 concentrators fed by data providers. Here the data providers mimic 10k households: PowerMatcher communications and metering data. Accordingly, each level 2 concentrator carries the data traffic of 10k households.

5. **Enterprise level**: The level 2 concentrators handle the data traffic to the enterprise system. Each level 2 concentrator communicates its aggregated VPP bids as well as the variable tariff metering data coming from its underlying households. With each of the 100 level 2 concentrators serving 10k house-
15. Demonstration of Scalability

holds, the enterprise level processes the data traffic of 1 million households. At the enterprise level, the PowerMatcher auctioneer agent is running. It receives incoming bids from the level 2 concentrator agents and is connected to an objective agent providing a VPP front-end interface to the operator of the virtual plant. This objective agent receives an operational setpoint from the dispatch operator of the utility and sends a corresponding bid to the auctioneer. In a real-world roll-out, it is the enterprise that sends each participant in the VPP a bill settling the electricity exchanged with the grid against the then-current real-time price. The rating and billing process that yields those bills takes two major inputs: (1) the metering data as received from the level 2 concentrators, and (2) the real-time prices as set by the auctioneer.

15.3 Latency Measurements

As defined in subsection 15.1.2, the metric for the reaction speed of the VPP is the time it takes to communicate a price update from the top of the architecture to the device agents. The PowerMatcher software does not have the ability to trace an event through the system as the system wasn’t designed to have this feature. To be able to trace price information, the VPP-front-end objective agent was replaced by a so-called controlled price objective agent which allows for setting the price as a parameter. Note that this only replaced the objective agent while the rest of agent topology remained untouched. By setting predefined prices, the price level itself can be used as a label. The label prices could then be traced through the system, using the event log file of individual agents. This resulted in a labour-intensive data collection process as each price event had to be located in the log file of each agent along the communication chain.

In order to relate the measured time events, the local machine time of each system involved was synchronised with a reference clock.

15.3.1 Raw Results

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 15.1, 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.
15.3. Artificial Latencies

From the results described above, 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. Therefore, we analyse these artificial latencies in this subsection, and correct the raw measurements accordingly in the next.

- **Passing of fire walls:** The Enterprise system and the objective agent at the top of the architecture are not running at a server at the same location. The first runs at SAP Research in Germany and the latter runs at a server located in The Netherlands. To reach the web service between the two a fire wall needs to be crossed on either side. To cross each fire wall a polling mechanism is used with an interval of 1 minute. On average, the polling introduces a 30 second latency on either side of the web service. Note that, in a real setting of a VPP operation, the Objective Agent and Auctioneer will run on a server at the Enterprise system and, thus, the polling can be avoided.

- **Connection of the field cluster:** The cluster of field-deployed smart homes was already in operation before the architecture for the scalability test was set-up. The ICT system of the field cluster included home-gateway hardware running an PowerMatcher Concentrator Agent communicating with an Auctioneer Agent serving the whole cluster. Ideally, to include this cluster to the larger cluster of the scalability test, this Auctioneer should be replaced by a...
Concentrator Agent (i.e. concentrator 1.1 in Figure 15.1). However, the field cluster ran an earlier version of the Auctioneer software, including specific features for monitoring and data collection within the field cluster and the field cluster would not run without it. Therefore, a work-around was needed to connect the cluster while keeping the Auctioneer in place. The work-around is depicted in the left-hand-side of Figure 15.3. It involves two PowerMatcher Objective Agents interconnected by web services connecting the field cluster to concentrator 1.1. Through the web services, the aggregated bid curve of the field cluster is transferred to the 1.1 concentrator and fed into the electronic market. Price updates that are communicated towards the field cluster are forced on the field cluster by the Objective Agent at that side of the interface. In this way, the functional behaviour is equivalent to having just the 1.1 concentrator in place. As may be clear, the work-around results in an added latency in the communication chain. This latency is mainly caused by, again, two polling mechanisms at either side of a web service.

**Specific field cluster implementation:** The PowerMatching City field experiment was originally set up to take the technology further towards maturity and to demonstrate the ability of end-customer systems to deliver flexibility to both the energy supplier and the network operator. In order to visualise the workings of different subsystems, a separate data collection system has been build up along side the application. Every minute, the data collection system writes the current status of each agent into a database. Due to this, there is an extra latency at the end of the chain, i.e. at the device agent, as an incoming price update won’t be written into the database before the end of the running minute. This results in an average additional latency of 30 seconds.

### 15.3.3 Corrected Results

If we correct for the artificially introduced latencies, as described in the subsection above, the total latency reduces to 30 seconds, as listed in the last column of Table 15.1. Based on this figure, plus a worst case estimation of the total measurement, we can say that the reaction of the 1M households is below 1 minute. This is well below the success value of 5 minutes.

### 15.4 Conclusion & Discussion

The aim of the experiment described in this chapter is to assess the scalability of the PowerMatcher by testing it’s architecture under mass application circumstances.
15.4. Conclusion & Discussion

Here, we consider 1 million households as mass scale application and virtual power plant operation has been chosen as the context for the test. The performance metric used is the time needed to communicate a setpoint change at the top of the VPP down to all households. In the event-based communication structure of the PowerMatcher this determines the reaction speed of the VPP as a whole. If this reaction time is under 5 minutes, the VPP can be used for operations in the balancing market which is the most volatile wholesale market for electricity and, thus, the most attractive market for VPP operations.

The experiment shows that the reaction of a PowerMatcher architecture serving 1M households is below 1 minute. This is well below the success value of 5 minutes. This shows that under mass-application circumstances the flexibility potential of a PowerMatcher cluster can be accessed fast enough for operations in the balancing market. Thus, this demonstrates PowerMatcher’s scalability to mass-application levels.

<table>
<thead>
<tr>
<th>Table 15.1: Latency timing results.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Node</strong></td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Enterprise</td>
</tr>
<tr>
<td>Concentrator level 2</td>
</tr>
<tr>
<td>Concentrator level 1</td>
</tr>
<tr>
<td>Home gateway</td>
</tr>
<tr>
<td>Device</td>
</tr>
</tbody>
</table>

15.4.1 What’s Next?

Now, the question arises what will happen when the system is scaled-up further. What will be the latency when 100M households (or end-customers: residential, commercial or industrial) are connected? Let’s calculate further with the one minute mentioned above to reach $10^6$ end-customers, which is definitely on the safe side.

<table>
<thead>
<tr>
<th>Table 15.2: Validation Result for Scalability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Validation Item</strong></td>
</tr>
<tr>
<td>Scalability</td>
</tr>
</tbody>
</table>
We reached the flexible devices in that number of households in four communication steps: 15 seconds per step on average. Going from $10^6$ to $10^8$ end-customers would add one communication step, so, the safe estimation is that this can be done in less than 1 minute and 15 seconds. The process uses very narrow bandwidth messaging, especially if the messaging overhead is kept low by using a lightweight messaging protocol. Although the number of end-customers gets very large, the data volume is low as compared to the internet traffic this number of homes and businesses produce. Therefore, I do not see a reason why the communication time would not increase linearly with the height of the logical tree when another concentrator level is added. Then, we reach $10^{10}$ end-customers in one and a half minute. The world population approximates to $7 \times 10^9$ people. With an estimated average household size of four, and a quarter of the people in the world lacking an electricity connection, the total number of connected homes is around $1.3 \times 10^9$. Let’s assume that the world has an equal number of electricity connections for the commercial and small industrial sector. Then there are $3.6 \times 10^9$ for relatively small end-customers world-wide, which is still under the $10^{10}$ that can be reached in one minute and 30 seconds. Naturally, this is a purely theoretical exercise as including this number of customers in one virtual power plant will most likely never become a sensible thing to do. However, it is possible to include all residential end-customers in the world in a PowerMatcher cluster and still have a response time fast enough for balancing market operations!
Part V

Conclusion
Chapter 16

Conclusion

This thesis presents a novel coordination system for making the electricity grid smart. The way the demand/supply balance is maintained in the grid did not change in the first century of its existence. As we have seen, three major trends are forcing technological changes: (i) the Transition to Sustainability, (ii) the Electrification of Everything, and (iii) the Decentralisation of Generation. These trends call for a drastic change in the way electricity grids are operated. The end-customer side of the electricity system, currently mainly passive, needs to be actively involved in the system coordination. This will drastically change the end-customer’s view on the electricity grid and conversely the view of the sector on the end-customer, residential and industrial customers alike. One of the main challenges of the smart grid is to involve medium and small sized electricity consuming, producing and storage devices in coordination of the electricity system. This also is a huge change in the way coordination is done in the electricity system. Coordination changes from centrally managing a few power plants to coordination among a huge number of smaller generators and responsive loads. The two most important smart grid coordination tasks are balancing at a system level, to integrate large-scale renewable energy, and network management at a local level in the distribution networks, to cope with the overloading of our aging distribution networks.

16.1 Requirements and Research Questions

For this novel coordination mechanism, we formulated six main requirements, three non-functional and three functional ones:

- **R1: Openness.** The coordination mechanism must be open for a wide variety of DER device possible without hampering the device’s primary purpose.

- **R2: Privacy Protection.** The coordination mechanism must involve DER devices at the premises of electricity end-customers without infringing the privacy of the end-customer.
**R3: Scalability.** The coordination mechanism must be scalable to mass-application levels.

**R4: Trade & Supply Functionality.** The coordination mechanism must be able to improve the wholesale market position of an energy trade & supply business.

**R5: Active Distribution Functionality.** The coordination mechanism must be able to contribute to active management of electricity distribution networks.

**R6: RES Integration Functionality.** The coordination mechanism must be able to raise the electricity system’s accommodation ceiling for renewable power generation.

The main research question addressed in this thesis has been formulated as:

**Q0: Main Research Question.** How to design a coordination mechanism that integrates distributed energy resources in the operation of the electricity system and meets the defined requirements?

The three non-functional requirements defined – Openness (R1), Privacy Protection (R2) and Scalability (R3) – direct towards the technology of Multi-agent Systems (MAS). MAS theory provides a paradigm for designing open, flexible, scalable, and extensible ICT systems aimed to operate in highly-complex environments. Market-based Control is an approach where software agents in a Multi-agent System each control a physical process and compete on an electronic market for a scarce input resource needed to attain the control goal of each individual process (e.g. keep a temperature within limits). Then, the MAS research line resource allocation of flow commodities is highly relevant for our research question. This research line is primarily focussed on efficient algorithms for assigning flow resources (i.e. infinitely divisible streams) to different applicants under scarcity.

To provide theoretical underpinning for the coordination mechanism design, four subquestions have been formulated regarding the fundamentals of Multi-agent Systems, Market-based Control, algorithms for resource allocation of flow resources, and Locational Marginal Pricing:

**Q1: Optimality of Market-based Control.** Consider an interactive society of a large number of agents, each of which has an individual control task. Is it possible to provide mathematical proof of the optimality of the control strategy that interactively emerges from this agent society with respect to both local and global control performance criteria?
16.2 Main Results

16.2.1 The Answer to the Main Question

The design of the PowerMatcher is the answer to the first part of the main research question: how to design a coordination mechanism that integrates distributed energy resources in the operation of the electricity system. The desired coordination mechanism can be designed as a market-based control system having a distributed electronic market in a tree-shaped topology on which DER devices trade their momentary electricity production or consumption. Operational flexibility of the end-customer’s electricity consuming and producing devices has a value in the electricity system. PowerMatcher empowers the end-customer to sell this flexibility to the parties interested. This selling is completely automatic using a piece of intelligent software —an “Agent”— installed at the premises of, and running under the authority of, this end-customer.

The remaining part of the main question refers to the six requirements the coordination mechanism has to meet. By design, the PowerMatcher complies with three of the six requirements to the coordination mechanism: Privacy Protection, Openness and Scalability. The first two are ensured by the data protocol used in the communications between the agents. This protocol is uniform for all agents and solely based on market information. Local information specific to DER devices is not included in the communications. Scalability is ensured through specific choices in the market
Table 16.1: Validation of Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Design</th>
<th>Field</th>
<th>Sim.</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Openness</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>8.3.1, 11.3</td>
</tr>
<tr>
<td>R2: Privacy Protection</td>
<td>✓</td>
<td></td>
<td></td>
<td>8.3.1</td>
</tr>
<tr>
<td>R3: Scalability</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>8.3.2, Ch.15</td>
</tr>
<tr>
<td>R4: Trade &amp; Supply Functionality</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>Ch.12</td>
</tr>
<tr>
<td>R5: Active Distribution Functionality</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>Ch.13</td>
</tr>
<tr>
<td>R6: RES Integration Functionality</td>
<td></td>
<td>✓</td>
<td></td>
<td>Ch.14</td>
</tr>
</tbody>
</table>

design and agent topology. Regarding the three functional requirements, the PowerMatcher has been extensively validated in five field deployment experiments and three simulation studies. These empirical validation activities further confirmed the validity of two of the non-functional requirements. Table 16.1 summarises by what validation means each of the six requirements have been validated and gives references to the relevant chapters and sections per requirement. Table 16.2 gives an overview of all validation results, each of which we will elucidate in the next five subsections.

From the above, and two tables, we conclude that the PowerMatcher meets all six requirements. Therefore, the main research question of this thesis has been answered.

For the requirements that have been validated in the field and/or through simulation studies, the next five subsections state the main findings and conclusions. Thereafter, subsection 16.2.7 gives the theoretical findings of this thesis.

16.2.2 Openness

The field experiments performed integrate a wide variety of DER devices into the operations of the smart electricity grid. Home appliances, electrical vehicles and industrial installations have been made responsive and participated in highly relevant smart grid applications. This gives strong empirical support to the earlier conclusion that PowerMatcher is open by design for a wide variety of DER devices. This validates the Openness requirement R1.

16.2.3 Scalability

Field experiences and simulation studies have shown the potential of the PowerMatcher technology for network operations, market operations, and integration of
**Table 16.2: Summary of Validation Results for the PowerMatcher**

<table>
<thead>
<tr>
<th>Validation Item</th>
<th>Result</th>
<th>From</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trade &amp; Supply</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portfolio Balancing</td>
<td>Wind imbal. reduction: 40 to 60%</td>
<td>Field</td>
</tr>
<tr>
<td>Balancing Market Reaction</td>
<td>Realisation of desired reaction</td>
<td>Field</td>
</tr>
<tr>
<td><strong>Active Distribution Mgmt</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congestion Management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordination of $\mu$-CHPs</td>
<td>Peak reduction: 30–50%</td>
<td>Field</td>
</tr>
<tr>
<td>Smart charging of EVs</td>
<td>Peak reduction: up to 30%</td>
<td>Simulation</td>
</tr>
<tr>
<td>Smart charging of EVs</td>
<td>Peak reduction: 35%</td>
<td>Field</td>
</tr>
<tr>
<td>VPP &amp; Congestion Mgmt</td>
<td>Proof of Principle of FastLMP</td>
<td>Field</td>
</tr>
<tr>
<td>Black-Start Support</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordination of HPs</td>
<td>Grid capacity can be 3× lower</td>
<td>Simulation</td>
</tr>
<tr>
<td><strong>RES Integration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased RES utilisation</td>
<td>Uncommitted RE used: 65–90%</td>
<td>Simulation</td>
</tr>
<tr>
<td>Avoided gray energy usage</td>
<td>Reduced use of gray: 14–21%</td>
<td>Simulation</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large-scale VPP reaction</td>
<td>1M households in &lt; 1 min.</td>
<td>Field</td>
</tr>
</tbody>
</table>

large-scale wind power generation. However, as the current field experiences do not yet approach mass-application scales, there is no empirical backing for the theoretical scalability properties of the technology. To overcome this, we performed a field experiment in which we could test the PowerMatcher architecture at mass-application data traffic levels. We did this by implementing a full top-to-bottom slice of the architecture needed to cluster one million smart responsive households. Side-branches cut away from the architecture were replaced by data mimicking agents generating the data traffic volume of the pruned branch. The base of the slice was formed by the field cluster of 22 households in PowerMatching City. Timing experiments done with this set-up show that a cluster of one million smart homes is able to react to outside stimuli within one minute. This is fast enough to be active on the wholesale markets for balancing, the most volatile electricity markets. This further demonstrates PowerMatcher’s scalability to mass-application levels, validating the Scalability requirement R3.
16.2.4 Trade & Supply Functionality

The requirement that the PowerMatcher is applicable in the electricity trade and supply business (requirement R4) has been addressed in two field experiments. In the Crisp Field Experiment, commercial portfolio balancing (i.e. avoidance of imbalance costs) has been tested successfully using industrial and domestic DER units. An imbalance reduction of 40 to 43% was achieved in a real-life DER cluster having an imbalance characteristic dominated by wind electricity production. In the Power-Matching City field experiment, a more active approach has been taken by actively responding to the situation on the imbalance market. During the experiment, the VPP successfully followed its optimised energy profile as traded on the day-ahead market (peak shaving) as well as provided regulatory power via a near-real-time response to the momentary imbalance market situation (i.e. actively creating value on the imbalance market). The outcomes of these field experiments validate the claim that the PowerMatcher is able to improve the wholesale market position of an energy trade & supply business.

16.2.5 Active Distribution Management Functionality

Important smart grid applications for distribution network operators are related to the avoidance of network overload situations. When peak-loading of networks can be avoided, reinforcements of existing networks can be deferred and capital investments in new networks reduced. Network overloading may be avoided during normal operations, e.g. through congestion management, or in critical situations, for instance, during a system restoration after a black out.

In a number of projects, field experience has been gained using PowerMatcher for congestion management. Firstly, market-based control of a cluster of micro-CHPs led to substantial peak load reductions of 30% in summer and 50% in winter at the level of the low to mid-voltage transformer. These results were obtained without any infringement of the comfort for the inhabitants of the homes involved. Secondly, while coordinating electric vehicle (EV) charging, PowerMatcher has shown to reduce peak load levels of 30 to 35%, even when in a residential area the EV penetration grows to 100%. In an older network where the household power intake is close to the network capacity, smart EV charging by PowerMatcher has been shown to avoid a network reinforcement of up to 35%. Thirdly, dual goal optimisation using the Fast LMP Algorithm was tested in the PowerMatching City field experiment. The algorithm successfully managed the network load of the cluster of 22 smart homes while at the same time these households participated in a virtual power plan operated by the energy supplier. A peak load reduction of 15% in the common substation of the households was achieved. This result provides a proof
of principle for the Fast-LMP algorithm. Additional to the field experiments and simulations focusing on the normal operational mode of the electricity network, a simulation study has been done focusing on extreme situations e.g. during a system restoration to recover from a power outage. The outage recovery case investigated a black start on a cold winter day in a residential district where homes are electrically heated. Without proper smart grid technology in place, this results in an extreme high load peak. PowerMatcher coordination has shown to keep transformer load within rated capacity limits under such extreme conditions, resulting in a lower design capacity of the network. In our case, the capacity could be designed three times lower than when black-start support would be not in place.

The outcomes of these field experiments and simulation studies validate the claim that the PowerMatcher is able to contribute to active management of electricity distribution networks, which corresponds to the requirement of Active Distribution Functionality (R5).

16.2.6 Integration of Renewable Energy Sources

In order to assess the ability of the PowerMatcher to raise the electricity system’s accommodation ceiling for renewable power generation (requirement R6), one has to look into future scenarios of large-scale renewable generation. However, the scale of individual smart grid experiments does not reach mass-application levels at this moment. Accordingly, we have to turn to a simulation study to get answers about the reaction of larger clusters of responsive loads and distributed generators on the varying output of renewables. In the simulation study performed, the reaction of 3000 individual smart households to the fluctuating output of solar and wind energy systems was studied. The configuration of this mixed residential and RES cluster is based on a 2040 scenario of high wind energy penetration. The simulation ran under real-life circumstances due to the use of validated models and measured time series. The simulation study shows that matching demand and supply in the cluster leads to an increase in RES utilisation: 65 to 90% of the green electricity which would remain unused by the households is actually used now. This leads to a decrease in total electrical energy exported from the cluster and, at the same time, avoided use of fossil-based electricity in the range of 14 to 21%.

These findings clearly show that electricity produced from renewable sources is much better accommodated when the PowerMatcher as coordination measure is in place. Consequently, it can be concluded that demand and supply matching by the PowerMatcher raises the accommodation ceiling for renewables and reduces the amount of energy needed from non-renewable sources. This validates that the system meets the requirement for Integration of Renewable Energy (R6).
16.2.7 Theoretical Contributions

The theoretical contributions of this thesis give answer to the four research subquestions.

- **Q1. Optimality of Market-based Control:** Market-based distributed control and centralised ‘omniscient’ optimisation are equivalent, i.e. outcome identical. Chapter 5 of this thesis provides a formal proof for this finding.

- **Q2. Locational Pricing in Resource Allocation:** This thesis introduces the concept of locational marginal pricing in passive flow-commodity networks to the discipline of Computer Science (Chapter 6). Building forth on the Locational Marginal Pricing framework in power systems economics, a general-applicable Multi-agent Systems framework for finding network-feasible solutions in commodity flow networks has been formulated.

- **Q3. Locational Pricing for Radial Networks:** This thesis presents a novel fast algorithm for locational pricing in non-cyclic passive flow networks. (Chapter 7).

- **Q4. Bidding strategies of DER Device Agents:** The existence has been shown of a bid strategy spectrum for DER units participating in a market-based control cluster delivering (near-) real-time balancing services (Chapter 9). In the two extremes of the spectrum, bidding strategies are either based straightforwardly on true marginal cost or benefit or on observed price dynamics in the electronic market context combined with the desired maximum risk level.

The first three findings reinforce the theoretical foundation on which the general-purpose market-based control mechanism for large DER clusters has been built. The forth finding is the basis for a set of practical design guidelines for DER agents participating in a Market-based Control cluster.

For a discussion of the relevance of each of these findings, I refer to the conclusion section of the corresponding chapters.

16.3 What Makes Our Approach Special?

In Section 3.3, I introduced the Smart Energy Management Matrix as a means to reason about the properties of different smart grid energy management approaches. The matrix distinguishes if an approach takes decisions on local issues either locally or centrally, and whether the approach uses one-way or two-way communications.
Figure 16.1: The four main categories of smart grid energy management.

Figure 16.1, which reproduces Figure 3.6, depicts the classification of energy management approaches that thus arises. All these four approaches enable devices at the premises of end-customers to react to signals from the electricity system (grid or markets). The PowerMatcher is positioned in the top-right quadrant of the matrix.

As argued in detail in Section 3.3, there are a number of flaws associated with specific quadrants of the matrix. Approaches in the lower half of the matrix, for instance, have privacy and/or autonomy issues associated with the type of control performed. In the lower-left quadrant it is not possible to unleash the devices’ full response potential as no momentary device state information is used. Then, the approaches that provide certainty about the expected system reaction are found in the right-hand side of the matrix. Finally, approaches in the price reaction quadrant are not future proof, as a market inefficiency develops when a substantial number of customers is going to participate.

Accordingly, the market integration approach is the ‘hot spot’ of the matrix. Market integration (i) releases the full response potential of the devices participating, (ii) provides certainty about the system reaction, (iii) avoids market inefficiencies, (iv) protects the privacy of the end-customer and (v) has favourable scalability properties. The other three approach classes lack two or more of these features.
16.4 What’s Next?

So, the coordination mechanism to integrate end-customer flexibility into the smart grid has been developed and field tested with good results. What is next?

16.4.1 Field Demonstration Up-Scaling

At present, the electricity sector is making clear steps towards the introduction of the smart electricity grid. This is also reflected in the field experiments and demonstrations performed with the PowerMatcher. The first field experiments were carried out by technology parties. Since a few years, however, parties from the electricity chain have also become involved. Network operators and energy suppliers now play an important role. A sign that the market is ready for this technology and the technology is ready for the market. Another important development is the scale of the demonstration projects. The first two field trials, in 2006 and 2007, both involved less than ten flexible home appliances and industrial installations. From 2009 on, PowerMatching City in Hoogkerk ran with more than 20 households, while the total number of PowerMatcher-equipped homes will surpass 1000 before the end of 2013. These are 40 homes in Hoogkerk, nearly 300 in the Couperus Smart Grid project in The Hague and another 700 in the EcoGrid project in Denmark. More projects are in the preparatory phase.

16.4.2 Market Introduction

A broad uptake of this technology by energy suppliers and grid operators will boost the spreading of smart grids in the world, allowing higher levels of RES in our electricity system and an efficient operation of the distribution grids. Further, it enables a fast uptake of new, efficient technologies such as Electrical Vehicles and Heat Pumps. In principle, PowerMatcher is an interface technology as it defines how systems along the full electricity value chain need to interact to let the smart grid materialise.

A market barrier for the breakthrough of an interface technology is an interface deadlock, the chicken and egg problem that typically arises when equipment manufacturers on either side of a technical interface wait until the other side starts implementing first. For smart grid connectivity technologies, such as the PowerMatcher technology, the interface deadlock occurs on two levels:

- **Market Barrier 1**: the equipment manufacturer’s deadlock
- **Market Barrier 2**: the deadlock between utility companies and electricity network operators on the one hand and equipment manufacturers on the other.
16.4. What's Next?

The first deadlock occurs when manufacturers of DER devices wait for manufacturers of home/building automation systems to make their equipment communicate via smart grid protocols before developing smart-grid enabled products, and vice versa. The second deadlock occurs when the equipment manufacturing sector as a whole waits with implementing the right interfaces, as there is uncertainty if, and on what time scale, utility companies and electricity network operators are going to adopt smart grid technologies.

To overcome these market barriers, the smart grid team at TNO (which includes the research team that developed the PowerMatcher) and distribution system operator Alliander took the initiative to create the Flexiblepower Alliance Network (FAN). One of the aims of this alliance is to create and promote an open protocol based on the PowerMatcher’s protocol into a widely accepted & industrially adopted smart grids standard. This alliance is organised as a pre-competitive cooperation of stakeholders that is aimed to cover the entire smart grid value chain. The Alliance is open for all parties interested in adopting the technology in any way and will have a multi-tier membership comparable to what comparable alliances are using, such as the USB Alliance or the Bluetooth Alliance. More information can be found on the website of the alliance: www.flexiblepower.org.

Regarding the PowerMatcher technology the Alliance will provide:

- **Open Protocol Technical Specifications**: Protocol Definition, Device Classes, Programming Interfaces, etc.

- **Reference Implementation**: A full implementation of the PowerMatcher in Java and on the OSGi platform. This reference is based on an implementation by IBM which, in turn, has been based on the PowerMatcher v3 software code base as developed by the PowerMatcher research team. The software may commercially be used by alliance members and is expected to become open-source for non-commercial, educational and research purposes.


- **Simulation Tool**: Available for (market) research, such as assessment of use cases and business cases.

Industry Enabling will be a key activity of the alliance. This includes provision of the reference implementation serving as a concrete set of how-to-do-it examples to parties adopting the technology for product development. Organising interoperability testing events (also known as ‘plugfests’) where designers of products based on the standard test the interoperability of their products to those of other vendors may also be part of the alliance’s activities.
16.4.3 Towards a Smart Grid Market Model

In this thesis, we showed the necessity of introducing distributed control in the electricity infrastructure in order to cope with the interrelated trends of increasing sustainable electricity sources and distributed generation. We have shown how our coordination mechanism, the PowerMatcher technology, can be used for commercial trade and supply operations (in Chapter 12) as well as for active distribution management (Chapter 13). An important question is: how to combine the two? The beginning of the answer to that question lies in our theoretical work on network feasible solutions (Chapters 6 and 7), which provides a framework for combining virtual power plant operations with local network management. The proof of principle for this has been given by the PowerMatching City field experiment as described in Section 13.4. This approach may serve as a basis for a new market model that underlies the future smart grid. This market model is a set of engagement rules for all parties connecting to and interacting with the smart grid. This market model should then be supported by a generic smart grid middleware layer, a software layer that provides smart grid services to all connected parties. This layer acts as the ‘software glue’ between all actors and supports the multi-objective coordination that is needed in a smart grid.

Such a multi-objective coordination mechanism needs to be designed for a future electricity system characterised by:

- Distributed Generation and Demand Response are a substantial factor in the electricity system, having a substantial influence on the electricity markets as well as on network management.

- A substantial part of central generation is large-scale (off-shore) wind power generation and/or large-scale solar power plants.

- Market parties and network operators optimise their stakes using DER, owned by end-customers, in their commercial portfolio, or in their network area, respectively. End-customers optimise their own local energy stakes from economical, sustainability and energy efficiency viewpoints. Dependent on the situation, these stakes may be conflicting at one time and non-conflicting at another time.

- Incentives to market parties (generators, suppliers, network operators and end-users alike) reflect the true costs of both generation and infrastructure. On the one hand, this will increase efficient usage of the infrastructure (e.g. by network load factor optimisation) and on the other hand it gives the right market signals for investment decisions (Generation against Demand Response against Infrastructural investments, for instance).
Figure 16.2 shows an architecture that supports the market situation described above. It is a setting with multiple Market Parties (Balancing Responsible Parties, BRPs), each running a commercial virtual power plant (CVPP), and multiple Distribution System Operators (DSOs), each running a Technical Virtual Power Plant (TVPP). A TVPP performs active distribution management tasks for the DSO: congestion management, reduction of losses, etc. In the Figure the CVPPs are represented by the blocks labelled ‘Commercial Aggregation’ and the TVPPs by those labelled ‘Network Service Aggregation’.

A BRP has special interests:

- Desire to aggregate a high number of DER units, as this smoothens-out the stochastic behaviour of the individual DER.
- Aspiration to spread its DER portfolio over a big (national) area to increase spatial smoothing of weather influences on DG and on responsive loads.
- Has no locational aspects attached to the desired portfolio behaviour for most of its operational parameters.
- Avoids balancing costs when their portfolio as a whole is in balance.

As a result the commercial portfolio of a BRP is most likely located in the grid area of more than one DSO.

A DSO has special interests as well:

- Preference to address only the DER units in its grid area, sometimes even dependent on individual grid cells or segments.
- Desire to incentivise DER to deliver system management services.
- Has a locational aspect in the desired behaviour or the DER in its network.
- Avoids investments in infrastructural components by active management of the DER in their network.

In the orthogonal multi-objective architecture, the individual DER units at the premises of one customer, in the Figure represented by a house, receives incentives from both the BRP the end-customer has an energy contract with and the DSO that manages the grid segment the customer is connected to. In the figure, several BRPs are located in the bottom-right, each communicating with their customers. These customers are located in different network locations of the DSO(s) in the bottom-left. So, each end-customer provides commercial services directly to the CVPP of its supplier (BRP). At the same time, the end-customer provides local grid services to
Figure 16.2: Orthogonal multi-objective market-based architecture for the future electricity systems.
the DSO as well. Thus, each smart home responds automatically to incentives from both the BRP and from the DSO. The DSO sends equal signals to all smart homes in a particular grid area. The stakes of BRP and DSO come together at the smart home. When these stakes are non-counteracting, the smart home can deliver the services requested by the DSO for a lower price compared to the situation in which the stakes do counteract. Accordingly, those homes without an internal conflict will respond to both the CVPP and TVPP request first. In this way, flexibility services from DER will be used based on merit order and the stakes of the different parties will be balanced automatically against each other. The coordination mechanism proposed in this thesis forms the basis of this future smart grid market model.
Samenvatting

De meeste mensen gebruiken elektriciteit vrij ongemerkt. We merken pas echt hoe afhankelijk we ervan zijn als het een keer uitvalt, iets dat in Europa, en zeker in Nederland, gelukkig niet vaak gebeurt. Echter, voor de nabije toekomst verdient de betrouwbaarheid van onze elektriciteitsvoorziening extra aandacht wegens een drietal ontwikkelingen. Ten eerste vormt de snelle toename van duurzame energie een uitdaging voor het in balans houden van vraag en aanbod in het net. Deze balans is cruciaal voor het blijven branden van het licht. De tweede trend is het groeiende elektriciteitsgebruik, wat onze verouderende netten steeds verder richting overbelasting drijft. Verder wordt een deel van de opwek van elektriciteit gedistribueerd: grote aantallen relatief kleine opwekkers — zonnepanelen, kleine windturbines en micro-warmte-kracht (ook wel de ‘thuiscentrale’ genoemd)— leveren hun energie dicht bij de plaats waar het wordt gebruikt. Deze opwekkers opereren buiten het bereik van de centrale coördinatie in het elektriciteitsysteem.

Om de leveringszekerheid van elektriciteit in de toekomst te waarborgen is er een nieuwe manier van coördinatie nodig. De huidige opzet waarbij een handvol grote centrales de totale elektriciteitsvraag volgt zal niet meer voldoen. Doordat het aanbod van duurzame bronnen fluctueert, wordt het steeds moeilijker de balans tussen vraag en aanbod in het systeem te behouden. De vraag naar elektriciteit zal daarom waar mogelijk het aanbod moeten gaan volgen. Dat betekent dat bijvoorbeeld een vrieskist in een willekeurige keuken automatisch stroom gaat gebruiken als buiten op het dak de zon schijnt op de zonnepanelen, of als het kilometers verder hard waait op zee. Deze nieuwe manier van automatische coördinatie zou er tegelijkertijd voor moeten zorgen dat de netten niet worden overbelast, door slim gebruik te maken van de beschikbare capaciteit en extra belasting tijdens de piekvraag te vermijden. Er is, kortom, een nieuw slim coördinatie mechanisme nodig om het slimme elektriciteitsnet te verwezenlijken.
Door verschillende partijen in binnen en buitenland is in de afgelopen jaren gewerkt aan dit nieuwe coördinatiemechanisme voor het elektriciteitsnet. Het resultaat daarvan is de PowerMatcher. Dit proefschrift geeft een theoretische onderbouwing voor het ontwerp van de PowerMatcher en een uitgebreide validatie in simulatiestudies en veldexperimenten, waaronder “PowerMatching City”. Deze validatiestudies tonen onder meer aan dat de PowerMatcher de inpassing van duurzame energie verbetert en tegelijkertijd overbelastingen in het netwerk kan voorkomen. Het ontwerp van de PowerMatcher is gebaseerd op multi-agent technologie waardoor het systeem de privacy waarborgt en zeer goed schaalbaar is. Het theoretische werk brengt elementen uit elektrotechniek, informatica, economie en regeltechniek samen en geeft onder andere een wiskundig bewijs dat PowerMatcher onder alle omstandigheden de optimale oplossing vindt.


Het bedrijven van het elektriciteitssysteem verandert dus van het centraal regelen van een relatief klein aantal grote centrales naar coördinatie tussen een grote hoeveelheden (duurzame) opwekkers en flexibele gebruikers. Belangrijk randvoorwaarde hierbij is de schaalbaarheid van het gehele systeem. Het vanuit een centraal punt blijven sturen op systeembalans, waarbij straks een enorm aantal kleine en middelgrote energie-vragende apparaten en installaties betrokken zijn, loopt vast tegen de grenzen van communicatie en berekenbaarheid. Dit schaalbaarheidsprobleem is in werkelijkheid nog groter omdat ook de gedistribueerde opwekkers een rol zullen spelen in de coördinatietak.

Informatica, en met name het deelgebied van de multi-agent systemen, biedt hieruitkomst. Een multi-agent systeem is een gedistribueerd softwaresysteem, waar-
in zogenaamde intelligente agenten verantwoordelijk zijn voor lokale deeltaken en met elkaar communiceren om de hogere systeemdoelen te bereiken. Een goed ontworpen multi-agent systeem is een open, flexibel en makkelijk uitbreidbaarheid ICT-systeem dat goed kan opereren in een hoog-complexe en veranderende omgeving. Omdat de lokale software agenten zorgdragen voor lokale zaken, schermen zij lokale (en dus potentieel privacy gevoelige) informatie af voor de buitenwereld. De PowerMatcher is ontworpen en gebouwd op basis van deze multi-agent technologie. Het resultaat is een mechanisme dat op grote schaal kleinere consumerende en producerende apparaten kan betrekken in de systeemcoördinatie zonder de autonomie en privacy van de eigenaren van deze apparaten aan te tasten.

Door de inzet van de PowerMatcher kan er aantoonbaar meer duurzame energie in het elektriciteitsysteem worden gentregereerd. Doordat het systeem de match tussen vraag en aanbod verbetert, wordt er beter gebruik gemaakt van de beschikbare duurzame energie. Hierdoor vermindert de vraag naar energie uit andere bronnen, zoals fossiele brandstoffen. Een studie naar het energiegebruik van 3000 huishoudens in combinatie met een groot (offshore) windturbinepark, laat zien dat 65 tot 90% van de windstroom die zonder PowerMatcher niet zou worden gebruikt, met inzet van het systeem wel door de huishoudens gebruikt wordt. Dit vermindert op momenten dat er weinig groene stroom beschikbaar is het gebruik van grijze stroom met 14 tot 21%.

Door de energievraag en gedistribueerde opwekkers te laten reageren op de fluctuaties in het duurzame energieaanbod verbetert ook de marktwaarde van groene stroom. De lage voorspelbaarheid van bijvoorbeeld windenergieproductie levert in de groothandelsmarkt voor elektriciteit extra kosten op, de zogenaamde onbalanskosten. In twee van de veldtesten met PowerMatcher is een windpark aan een flexibel cluster gekoppeld om de afwijkingen in de windenergievoorspelling te compenseren. Dit verminderte de onbalans, veroorzaakt door het windpark, met 40 tot 60%. Wat een interessante business case vormt voor energieleveranciers.

Verder is in het veld aangetoond dat de PowerMatcher overbelastingen in het elektriciteitsnetwerk kan voorkomen. Door het slim aansturen van verwarmingsystemen (micro-warmtekracht en warmtepompen) en opladende elektrische auto’s kan de dagelijkse piekbelasting worden verminderd met typisch 30 tot 35%. In bestaande netwerken voorkomt dit voor de netwerkbeheerder een dure en omvangrijke verzwarings van het netwerk, terwijl in geval van nieuwe netwerken deze minder zwaar kunnen worden uitgevoerd. In één van de onderzochte gevallen zou door inzet van de PowerMatcher de netcapaciteit drie maal kleiner kunnen zijn.

Op dit moment is de elektriciteitssector duidelijke stappen aan het zetten richting de invoering van het slimme elektriciteitsnet. Dat is ook te zien aan de veldexperimenten en demonstraties met de PowerMatcher. Waar er bij de eerste veld-

Met een aantal industriepartners werkt TNO nu aan een open standaard op basis van de PowerMatcher. Via een industrie alliantie, het Flexiblepower Alliance Network (FAN), is de PowerMatcher voor de markt beschikbaar.
Most of us are not aware of the electricity we use. We only notice how we are dependent on electricity once it fails, which is fortunately something that does not happen often. In the near future, however, the reliability of our electricity supply will need special attention due to three developments. Firstly, the rapid increase in renewable energy creates a challenge for maintaining the balance of supply and demand in the network. This balance is crucial to keep our lighting on. The second trend is the growing use of electricity, which increasingly drives our aging networks towards overload. Furthermore, part of the electricity generated is becoming distributed: large numbers of relatively small generators — solar panels, small wind turbines and micro-combined heat and power— deliver their energy close to the place of consumption. These generators operate outside the reach of the central coordination within the electricity system.

In the future, to ensure the security of electricity supply a new coordination mechanism is required. The current structure, in which a few large plants follow the total electricity demand will no longer suffice. Due to fluctuations in the supply from renewable sources, it is becoming increasingly difficult to maintain the balance between supply and demand in the electricity system. Therefore, electricity demand will have to follow the supply where possible. That would mean that, for example, a consumer’s kitchen freezer would automatically start using electricity the moment the sun starts shining on their rooftop solar panel or when the wind increases at an offshore wind turbine park. At the same time, this new way of automatic coordination should prevent the networks from overloading. By shifting loads away from the moments of high peak demand, available capacity can be used in a smart way. There is, in short, a new smart coordination mechanism to achieve this smart grid.

A group of international partners, have worked in recent years to realise this new coordination mechanism for electricity. The result of that work is the PowerMatcher.
This thesis provides a theoretical basis for the design of the PowerMatcher and an extensive validation through simulation studies and field experiments, including "PowerMatching City". These validation studies show, among other things, that the PowerMatcher enables the integration of renewable energy while, at the same time, mitigates overload situations in the network. The design of the PowerMatcher is based on multi-agent systems which makes the system highly scalable and able to ensure user privacy. The theoretical work brings together elements from electrical engineering, computer science, economics and control. Further, it includes a mathematical proof of the optimal performance of the PowerMatcher.

The PowerMatcher moves the energy consumer to the center. Their role will change dramatically as a result of the above-mentioned developments. Firstly, consumers are also increasingly becoming producers of electricity. This is called a prosumer: sometimes a consumer and at other times a producer. More than a century, there were only one-directional electricity flows in the electricity networks, and now with the ‘consumer’ also providing power back to the network it’s becoming unidirectional. As a next step, the prosumer will also become a supplier of an electricity flexibility service. Household appliances and industrial installations will flexibly respond to the availability of cheap green electricity as well as to the availability of network capacity. Although not every device is able to shift its electricity use, many devices do have great potential for flexibility. Both in households and in industry, almost all devices having a thermal function can potentially be made flexible: heating, cooling and freezing. There are also many devices that need to complete their task within a certain time window, such as an electric car charging at night to be able to drive in the morning or a washing machine for which the user has set the completion time. Within the time allotted for their task, these devices are able to shift their electricity use.

Thus the operation of the electricity system changes from central control of a relatively small number of large power plants to coordination of large amounts of (sustainable) generators and flexible users. An important requirement for this coordination system is scalability. Maintaining the system’s demand and supply balance will involve a huge number of small and medium-sized energy-demanding equipment. Controlling this from a central point will soon reach the communication and computability limits. This scalability problem is even greater in reality as the distributed generators will also play a role in the coordination task.

Computer science, and in particular the area of multi-agent systems, can offer a solution. A multi-agent system is a distributed software system in which so-called intelligent agents are responsible for local sub-tasks, and communicate with each other in order to achieve the higher system goals. A well-designed multi-agent system is an open, flexible and easily expandable ICT system that can properly operate
in a highly complex and changing environment. As the local software agents take care of local business, it screens local (and potentially privacy-sensitive) information from the outside world. The PowerMatcher is designed and built based on this multi-agent technology. The result is a mechanism which allows for coordination of a large number of smaller consuming and producing devices without the autonomy and privacy of the owners of these devices becoming compromised.

By using the PowerMatcher, more renewable energy may be integrated in the electricity system. As the system improves the match between supply and demand, better use of available renewable energy can be achieved. This reduces the demand for energy from other sources, such as fossil fuels. A study of the energy consumption of 3000 households in combination with a large (off-shore) wind turbine park clearly shows this. When using the PowerMatcher, it was shown that approximately 65 to 90% of the wind power, which would normally not be used without coordination, could be locally utilised. As a result of this, the usage of power from fossil fuels is reduced by 14 to 21%.

A reaction from energy demand and distributed generators to fluctuations in the supply of renewable energy also improves the value of green power. The low day-ahead predictability of wind generation, for example, results in additional costs assigned through the electricity wholesale markets, the so-called imbalance costs. In two of the field tests performed with PowerMatcher, a wind farm was coupled to a flexible cluster in order to compensate for deviations from the wind power prediction. This reduced the imbalance caused by the wind farm 40 to 60%. This makes an interesting business case for energy suppliers.

Further, it has been shown in the field that the PowerMatcher is able to avoid overloading of electricity networks. By cleverly managing heating systems (micro-CHP and heat pumps) and/or charging electric cars, the daily peak loading could typically be reduced by 30 to 35%. In existing networks, this saves the network operator an expensive network reinforcement, while new networks can be less heavy designed. In one of the cases studied, the network capacity could be designed three times lower through application of the PowerMatcher.

At present, the electricity sector is making clear steps towards the introduction of the smart electricity grid. This is also reflected in the field experiments and demonstrations performed with the PowerMatcher. The first field experiments were carried out by technology parties. Since a few years, however, parties from the electricity chain have also become involved. Network operators and energy suppliers now play an important role. A sign that the market is ready for this technology and the technology is ready for the market. Another important development is the scale of the demonstration projects. The first two field trials, in 2006 and 2007, both involved less than ten flexible home appliances and industrial installations. From 2009
on, PowerMatching City in Hoogkerk ran with more than 20 households, while the total number of PowerMatcher-equipped homes will surpass 1000 before the end of 2013. These are 40 homes in Hoogkerk, nearly 300 in the Couperus Smart Grid project in The Hague and another 700 in the EcoGrid project in Denmark. More projects are in the preparatory phase.

With a number of industry partners, TNO is working on an open standard on the basis of the PowerMatcher. Through an industry alliance, the Flexible Power Alliance Network (FAN), the PowerMatcher will be made available for the market.
Over the course of the 20th century, the electrical power systems of industrialised economies have become one of the most complex systems created by mankind. On the other hand, the technology of electricity transmission and distribution did not change significantly in the first century of its existence. For instance, the way the demand/supply balance is maintained in the grid did not change in this first century. Now, three major trends are forcing technological changes: (i) the Transition to Sustainability, (ii) the Electrification of Everything, and (iii) the Decentralisation of Generation. These trends call for a drastic change in the way electricity grids are operated. The end-customer side of the electricity system, currently mainly passive, needs to be actively involved in the system coordination. Coordination changes from centrally managing a few power plants to coordination among a huge number of smaller generators and responsive loads. Centralised control of such a complex system will rapidly reach the limits of scalability. An intelligent electricity grid, generally referred to as ‘the smart grid’, is needed. In visions on the future electricity infrastructure, the internet is used as a metaphor for a smart electricity grid: the internet of energy. The internet has a number of desirable properties one would like to achieve in the smart grid, such as self-organisation and self-healing in a network-of-networks topology. Plus the user-centric design that allows active participation from and collaboration with the end-user and the smart systems that surround her. Thus, the internet is a useful metaphor for the future intelligent electricity network: the internet of energy. However, the analogy does not hold when one goes down to the technical characteristics below the general vision. As electricity is not information, electricity networks are fundamentally different from computer networks. Electricity is continuous matter, distributed using a passive infrastructure that lacks storage capacity. This is, for instance, reflected in the mathematics used to model the two kinds of networks, but also in the way electrical power systems...
are organised. The operation of the physical subsystem is separated from that of the commodity subsystem, in which the energy product is traded. Interactions between the two sub-systems are limited, yet crucial.

In order to integrate end-customer side of the electricity system, currently only passively connected, four main approaches can be followed: top-down switching, centralised optimisation, price reaction and market integration. We argue that the market integration approach take precedence over the other three, for a number of reasons, and implements a truly intelligent system.

Thus, one of the main challenges of the smart grid is to involve medium and small sized electricity consuming, producing and storage devices in coordination of the electricity system. We refer to these devices as Distributed Energy Resources (DER), encompassing Demand Response (DR), Distributed Generation (DG) and Distributed Storage. In the future electricity grid, DER devices deliver flexibility services to the system’s coordination task. In this respect, responsive electricity consumption is regarded as a resource as the main resource is flexibility in operation: the ability to shift electricity production or consumption in time. Here, the two most important tasks are balancing at a system level and network management at a local level in the distribution networks. For this novel coordination mechanism, we formulate six main requirements, three non-functional and three functional requirements:

- **R1: Openness.** The coordination mechanism must be open for a wide variety of DER device possible without hampering the device’s primary purpose.

- **R2: Privacy Protection.** The coordination mechanism must involve DER devices at the premises of electricity end-customers without infringing the privacy of the end-customer.

- **R3: Scalability.** The coordination mechanism must be scalable to mass-application levels.

- **R4: Trade & Supply Functionality.** The coordination mechanism must be able to improve the wholesale market position of an energy trade & supply business.

- **R5: Active Distribution Functionality.** The coordination mechanism must be able to contribute to active management of electricity distribution networks.

- **R6: RES Integration Functionality.** The coordination mechanism must be able to raise the electricity system’s accommodation ceiling for renewable power generation.
Based on the considerations above, and the defined requirements, the main research question addressed in this thesis is formulated as:

- **Q0: Main Research Question.** How to design a coordination mechanism that integrates distributed energy resources in the operation of the electricity system and meets the defined requirements?

The three non-functional requirements defined – Openness (R1), Privacy Protection (R2) and Scalability (R3) – direct towards the technology of Multi-agent Systems (MAS). MAS theory provides a paradigm for designing open, flexible, scalable, and extensible ICT systems aimed to operate in highly-complex environments. In a MAS, large numbers of software agents are able to interact. On the system level, intelligence of a well-designed MAS can be high, even while the complexity of individual agents remains low. Complex, intelligent, behaviour emerges as a result of a multiplicity of relatively simple agent interactions. This emergence of system-level intelligence can be achieved efficiently using electronic markets, which provide a framework for distributed decision making based on microeconomics. Using market mechanisms, agents collectively make decisions to allocate limited resources within the agent society. This process is known as resource allocation. Market-based Control comes into existence when the agents in a MAS each control a physical process and compete on an electronic market for a scarce input resource needed to attain the control goal of each individual process (e.g. keep a temperature within limits). As compared to centralised optimisation, the market-based approach has a number of advantages. Communications are uniformly based on market information. This results in an open system based on a communication protocol that is easily standardisable and doesn’t include specific local data. Further, due to its distributed nature, MBC has better scalability properties as well.

To provide theoretical underpinning for the coordination mechanism design, four subquestions have been formulated around MBC, Resource Allocation and the application thereof in the electricity field:

- **Q1: Optimality of Market-based Control.** Consider an interactive society of a large number of agents, each of which has an individual control task. Is it possible to provide mathematical proof of the optimality of the control strategy that interactively emerges from this agent society with respect to both local and global control performance criteria?

- **Q2: Network Feasible Solutions in Resource Allocation.** How can algorithms for allocation of flow resources be extended to yield network feasible allocation solutions obeying characteristics of passive flow networks? How can the mechanism of Locational Marginal Pricing (LMP) from the field of power systems economics be formulated in computer science terms?
Q3: Locational Pricing in Radial Networks. How can algorithms for Locational Marginal Pricing in non-cyclic passive flow networks take advantage of this topological property to find solutions against a lower computational burden?

Q4: Bidding strategies of DER Device Agents. Consider DER devices participating in an electronic market to coordinate their electricity production and/or consumption in (near-)real-time. How can the bidding strategies of these devices be formulated in micro-economic terms, e.g. marginal costs and market price dynamics? How does the nature of the physical process behind the DER device influence its dominant strategy?

When Market-based Control is going to be applied to a critical infrastructure such as the electricity network, it is desirable to have a good theoretical insight in the method. To address the research question regarding Optimality of Market-based Control (Q1), the theoretical foundations of distributed market-based control have been assessed. A novel theory has been developed which integrates multi-agent microeconomic market theory with control theory. The central result of this work is a general market theorem that proves two important properties of market-based control: (i) computational economies with dynamic pricing mechanisms are able to handle scarce resources for control adaptively in ways that are optimal locally as well as globally (‘societally’); and (ii) in the absence of resource constraints the total system acts as collection of local independent controllers that behave in accordance with conventional control engineering theory. This gives theoretical evidence that market-based control is ‘outcome equivalent’ to centralised optimisation as was perviously only empirically shown for a particular exemplar problem. This formal result provides the theoretical underpinnings for the market-based control system design we present further on.

The MAS research line resource allocation of flow commodities is highly relevant for our research question. This research line is primarily focussed on efficient algorithms for assigning flow resources (i.e. infinitely divisible streams) to different applicants under scarcity. The state-of-the-art in this research line does not provide algorithms that are able to consider the characteristics of the underlying transport network. In applying these, one implicitly assumes the network has virtually infinite capacity. It would be desirable if algorithms for allocation of flow resources would yield so-called network feasible solutions, i.e. allocation solutions that obey the characteristics of the underlying flow network. On the other hand, power systems economics provides a framework called Locational Marginal Pricing (LMP) which runs an electricity wholesale market while considering line capacity constraints and energy losses in the electricity transmission network. In answer to
the research question regarding Network Feasible Solutions in Resource Allocation (Q2), it has been investigated how LMP can be introduced in MAS. The contribution of this work is threefold. Firstly, the LMP framework is reformulated and expanded into a general applicable MAS framework. Secondly, it is shown that, under the common condition of demand and supply elasticity, the constrained optimisation problem posed by the framework has a unique solution and a search in the parameter space will converge to that solution. Thirdly, a distributed market algorithm that solves the constrained optimisation problem is provided.

Locational marginal pricing is an important mechanism for our research goal. LMP gives means to utilise DER flexibility for system-level balancing and for active management of the distribution networks simultaneously. However, LMP has been designed for the electricity transmission networks, where scalability is less of an issue. In electricity distribution, both the number of network nodes as well as the number of connected actors to be involved is much higher. This results in a heavier computational burden when applying LMP to these networks as the LMP algorithm scales badly with the number of network nodes. The work performed to answer the research question regarding Locational Pricing in Radial Networks (Q3) investigated how to reduce this computational complexity by making use of the differences in topology between distribution and transmission networks. In the distribution part of the electricity infrastructure, networks are predominantly operated in a radial, acyclic, topology. Flow calculations in radial networks are quite straightforward, as subtractions or injections at a certain node have a one-on-one influence on the flow through the lines between the root of the tree and that node. Making use of this property, a fast algorithm for locational marginal pricing (LMP) in radial networks has been developed. The algorithm makes only two passes through the network to come to a network feasible power flow at each network location. Accordingly, the method yields a local power flow that is (i) within the local line capacity constraint, and (ii) accounts for network losses.

Based on the theories in Part II, a general-purpose market-based control mechanism for large DER clusters has been designed and implemented. This multi-agent system, coined PowerMatcher, comprises four types of software agents. The first two types, named Auctioneer and Concentrator, implement a distributed electronic market. The third type is the Local Device Agent which trades on this market on behalf of a DER device. The last one, the Objective Agent, enables external control actions rooted in application-specific business logic. The system yields locational prices when Concentrator Agents perform bid transformations. By design, the PowerMatcher ensures three of the six requirements of the coordination mechanism: requirements R2 (Privacy Protection), R1 (Openness for DER) and R3 (Scalability). The first two are ensured by the data protocol used in the communications between
the agents. This protocol is uniform for all agents and solely based on market information. Local information specific to DER devices is not included in the communications. Scalability is ensured by design through choices in the market design and agent topology.

The PowerMatcher does its coordination on timescales close to the real-time. To do so, the PowerMatcher maintains a dynamic merit-order list of all DER participating in the cluster. In order to make optimal coordination decisions involving individual DR units, having this list in the right order is of utmost importance. To achieve this, the merit order needs to be based on the true marginal cost of the individual DER units. However, the marginal electricity cost of most types of DER is highly dependent on local context and, hence, change over time. In the context of the research question regarding Bidding Strategies of DER Device Agents (Q4), strategies of different types of DER have been assessed. This assessment revealed a bid strategy spectrum of short-term bid strategies of various DER units. At one extreme of the spectrum, strategies are based entirely on true marginal cost. At the other, strategies are completely dependent on price dynamics in the electronic market. Further, we introduce decision diagrams as a graphical way to analyse and design device strategies. These results provide guidelines for the design of Local Device Agents for DER. Following these guidelines results in agent societies that find an optimal division of work in given DER clusters under all circumstances.

Unleashing the inherent flexibility of smaller electricity producing and consuming units is of interest of energy suppliers as well as distribution network operators. For the former, the actual value creation takes place in the wholesale markets for electricity. Parties involved in energy trade and supply are having a competitive advantage when the electricity consuming and producing units under contract are either well predictable or controllable. Increasing the controllability in their customer pool can provide added value to the supplier’s wholesale electricity trade in a number of ways. Among these are reducing imbalance in the own trading portfolio, counteracting the total system imbalance and reducing the ramping speed of the aggregated customer’s profile.

With the design of the PowerMatcher, we have a coordination system design based on the answers to the first three research subquestions and practical design guidelines for DER agents based on the answer to the last subquestion. This covers a good deal of the main question of this research: how to design a coordination mechanism that integrates distributed energy resources in the operation of the electricity system and meets the six requirements? It is claimed that the PowerMatcher meets these requirements. So, in order show this claim holds, we need to validate the designed system against all its requirements. This validation has been done in a series of Field Experiments and Simulation Studies.
These field experiments and simulations integrate a wide variety of DER devices into PowerMatcher operations. Both distributed generators as demand response devices have been covered. Devices include home appliances, industrial installations and an electrical vehicle. This gives strong empirical support to the earlier conclusion that PowerMatcher is open by design for a wide variety of DER devices. This validates requirement R1.

The requirement that the PowerMatcher is applicable in the electricity trade and supply business (requirement R4) has been addressed in two field experiments. In the Crisp Field Experiment, commercial portfolio balancing (i.e. avoidance of imbalance costs) has been tested successfully using industrial and domestic DER units. An imbalance reduction of 40 to 43% was achieved in a real-life DER cluster having an imbalance characteristic dominated by wind electricity production. In the Power-Matching City field experiment, a more active approach has been taken by actively responding to the situation on the imbalance market. During the experiment, the VPP successfully followed its optimised energy profile as traded on the day-ahead market (peak shaving) as well as provided regulatory power via a near-real-time response to the momentary imbalance market situation (i.e. actively creating value on the imbalance market). The outcomes of these field experiments validate the claim that the PowerMatcher is able to improve the wholesale market position of an energy trade & supply business.

Electricity network operators form another class of parties having a potential benefit from utilising DER flexibility. Important smart grid applications for distribution network operators are related to the avoidance of network overload situations. When peak-loading of networks can be avoided, reinforcements of existing networks can be deferred and capital investments in new networks reduced. Network overloading may be avoided during normal operations, e.g. through congestion management, or in critical situations, for instance, during a system restoration after a black out. In a number of projects, field experience has been gained using PowerMatcher for congestion management. These experiments show an ability of substantial peak load reductions These field results are backed by those of two comprehensive simulation studies. One of these studies additionally demonstrates the ability of the PowerMatcher technology to keep transformer load within rated capacity limits in a black-start recovery situation. The outcomes of these field experiments and simulation studies validate the claim that the PowerMatcher is able to contribute to active management of electricity distribution networks, which corresponds to the requirement of Active Distribution Functionality (R5).

In order to assess the ability of the PowerMatcher to raise the electricity system’s accommodation ceiling for renewable power generation (requirement R6), one has to look into future scenarios of large-scale renewable generation. However, the scale
of individual smart grid experiments does not reach mass-application levels at this moment. Accordingly, we have to turn to a simulation study to get answers about the reaction of larger clusters of responsive loads and distributed generators on the varying output of renewables. In the simulation study performed, the reaction of 3000 individual smart households to the fluctuating output of solar and wind energy systems was studied. The study uses a 2040 scenario of high wind energy penetration and ran under real-life circumstances. The smart grid offers a large potential in utilising flexibility of demand and supply in homes to accommodate high levels of wind power generation, as the study shows. Using the PowerMatcher for demand and supply coordination, the accommodation ceiling for renewables is raised and the amount of energy from fossil fuelled power plants reduced.

Hitherto, field experiences and simulation studies have shown the potential of the PowerMatcher technology for network operations, market operations, and integration of large-scale wind power generation. However, as the current field experiences do not yet approach mass-application scales, there is no empirical backing for the theoretical scalability properties of the technology. To overcome this, we performed a field experiment in which we could test the PowerMatcher architecture at mass-application data traffic levels. We did this by implementing a full top-to-bottom slice of the architecture needed to cluster one million smart responsive households. Side-branches cut away from the architecture were replaced by data mimicking agents generating the data traffic volume of the pruned branch. The base of the slice was formed by the field cluster of 22 households in PowerMatching City. Timing experiments done with this set-up show that a cluster of one million smart homes is able to react to outside stimuli within one minute. This is fast enough to be active on the wholesale markets for balancing, the most volatile electricity markets. This further demonstrates PowerMatcher’s scalability to mass-application levels, validating requirement $R3$.

The validation work presented confirms that the DER coordination mechanism designed meets with requirements $R1$ to $R6$. This confirmation answers the second and remaining part of the main research question. To recall, the main question of this thesis read: “How to design a coordination mechanism that integrates distributed energy resources in the operation of the electricity system and meets requirements $R1$ to $R6$?” The theoretical work in this thesis, which answers the four research subquestions ($Q1$ to $Q4$), reinforces the theoretical foundation under the coordination mechanism design and its application. This design forms the answer to the first part of the research question at hand, while the validation makes the question fully answered. The desired coordination mechanism can be designed as a market-based control system having a tree-shaped distributed electronic market on which DER devices trade their momentary electricity production or consumption.
At present, the electricity sector is making clear steps towards the introduction of the smart electricity grid. This is also reflected in the field experiments and demonstrations performed with the PowerMatcher. The first field experiments were carried out by technology parties. Since a few years, however, parties from the electricity chain have also become involved. Network operators and energy suppliers now play an important role. A sign that the market is ready for this technology and the technology is ready for the market. Another important development is the scale of the demonstration projects. The first two field trials, in 2006 and 2007, both involved less than ten flexible home appliances and industrial installations. From 2009 on, PowerMatching City in Hoogkerk ran with more than 20 households, while the total number of PowerMatcher-equipped homes will surpass 1000 before the end of 2013. These are 40 homes in Hoogkerk, nearly 300 in the Couperus Smart Grid project in The Hague and another 700 in the EcoGrid project in Denmark. More projects are in the preparatory phase.

With a number of industry partners, TNO is working on an open standard on the basis of the PowerMatcher. Through an industry alliance, the Flexible Power Alliance Network (FAN), the PowerMatcher will be made available for the market.


[59] Bart Roossien, Maarten Hommelberg, Cor Warmer, Koen Kok, and Jan Willem Turkstra. Virtual power plant field experiment using 10 micro-CHP units at consumer premises. In SmartGrids for Distribution, CIRED Seminar, number 86. IET-CIRED, 2008.


One of the world’s most critical infrastructures, the electricity grid, is facing huge challenges in the near future. The rise in electricity generated from the wind and sun poses a challenge in balancing supply and demand in the grid. At the same time, the electrification of everything drives our ageing distribution networks to their capacity limits. The PowerMatcher, a novel coordination mechanism, was developed to address these challenges. This technology integrates large amounts of renewable energy in the electricity system and, at the same time, avoids overload situations in the electricity infrastructure. The technology was designed to be highly scalable and to protect the privacy of electricity consumers.

**The PowerMatcher: Smart Coordination for the Smart Electricity Grid** gives a thorough insight into this technology, its use and merits in specific application cases, as well as its performance in the field.

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