Drivers, knelpunten en kansen voor 'Virtual Power Plants' in het Belgische elektriciteitssysteem

Drivers, Bottlenecks and Opportunities for Virtual Power Plants in the Belgian Electricity System

Brecht Zwaenepoel

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Gent, Juli 2016
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Glossary

ARP Access Responsible Party first. 7, 17

ATC Available Transfer Capacity first. 45

BRP Balance Responsible Partner. 16, 124

CAPEX Capital Expenditures. 24

CCGT Combined Cycle Gas Turbine. 121–124

CHP Combined Heat and Power. 107

CIM Continuous Intraday Market. 15

COP Coefficient Of Performance. 107

CREG Commissie voor de Regulering van de Elektriciteit en het Gas. 9

CVPP Commercial Virtual Power Plant. 15, 43

DAM Day Ahead Market. 15, 122

DER Distributed Energy Resource. 1, 16, 52, 124

DG Distributed Generation. 1

DSO Distribution System Operator. 23

FCR Frequency Containment Reserve. 51

FRR Frequency Restoration Reserve. 124

HVDC High Voltage Direct Current. 2

MTTR Mean Time To Repair. 130

NZEB Near Zero Energy Building. 118

OPEX Operational Expenditures. 24

ORC Organic Rankine Cycle. 101

RES Renewable Energy Source. 3, 7, 51

SCADA Supervisory Control And Data Acquisition. 129

TSO Transmission System Operator. 1, 16, 23, 47, 52, 122

TVPP Technical Virtual Power Plant. 43

VPP Virtual Power Plant. 8, 43, 123

ZEB Zero Energy Building. 118

Nederlandse samenvatting –Summary in Dutch–

Overal ter wereld stijgt het energiebewustzijn. Twee belangrijke factoren zijn hiervoor verantwoordelijk: de vaak bediscuteerde klimaatopwarming en de stijgende energieprijzen door de toenemende druk op olieproducten [1]. Dit moedigt beleidsmakers en de publieke opinie aan om de consumptie van primaire energiebronnen te beperken en om de energie-efficiëntie te verhogen. Een groot deel van de nieuwe en energie-efficiëntere technologieën maakt echter gebruik van elektriciteit. Gastoestellen worden bijvoorbeeld vervangen door warmtepompen en voertuigen worden elektrisch aangedreven. Het resultaat is dat de primaire energieconsumptie daalt, maar het elektrisch verbruik toeneemt.

Productie van elektriciteit staat onder wereldwijde druk. Meer dan de helft van de wereldwijde elektriciteitsproductie is afkomstig van fossiele brandstoffen [2]. Hierdoor komt er op deze vorm van energieproductie meer economische en omgevingsdruk. Europa is door een gebrek aan voldoende eigen fossiele brandstoffen [3] aangewezen op de import ervan. Ook het gebrek aan de andere grote bron voor elektriciteitsproductie, met name kernenergie, zorgt voor politieke en sociale druk. Deze drijfveren zorgen voor de ontwikkeling en installatie van grote hoeveelheden nieuwe elektriciteitsproducenten zoals windturbines, zonneparken en warmtekrachtkoppelingen. Ondanks dat deze bronnen meestal met het laag- en middenspanningsnet verbonden zijn, zorgen hun grote aantallen toch voor een significante impact op het hoogspanningsnet. Door het gebrek aan regelbaarheid van vele van deze eenheden komt de stabiliteit van het elektrische net in het gedrang.

Om het milieu te sparen en om de afhankelijkheid van externe bronnen te beperken heeft Europa zich ambitieuze doelstellingen gesteld voor hernieuwbare energiebronnen. Dit heeft echter belangrijke gevolgen voor de operationele stabiliteit van het elektrische net door het gebrek aan regelbaarheid van vele van deze bronnen. Virtual Power Plants vormen een strategie om grote hoeveelheden van relatief kleine bronnen te beheren en bedienen. Hierdoor kunnen ze bijdragen aan de werking van het net.

In dit werk worden eerst de verschillende elektriciteitsmarkten besproken. Dit schept een kader voor de werking van een commerciële VPP. CVPPs zijn nodig om decentrale bronnen op te schalen naar het niveau van de bestaande elektricteitsmarkten. Op deze manier vormen ze een tool om de liberalisering van de energiemarkt verder door te zetten en creëren ze gelijke kansen. Kleinere bronnen hebben immers geen gelijkwaardige toegang tot de energiemarkt daar deze niet ontworpen is voor dergelijke kleine vermogens en energiehoeveelheden. Vervolgens werd onderzocht of een grootschalige fotovoltaïsche VPP voordelen zou kunnen halen uit clustering en het verhandelen van energie op de groothandelsmarkt. Bij de publicatie van dit proefschrift was bewezen dat het niet de moeite loonde omdat de beoogde winst te klein was. Dit was hoofdzakelijk te wijten aan de grote impact van de groenestroomcertificaten. Maar zelfs zonder de groenestroomcertificaten is het niet de moeite zonder dat ingegrepen kan worden in de energieproductie. Het risico van de groothandelsmarkt is daarna verder onderzocht. Dit resulteerde in de ontdekking van een kwetsbaarheid in het onbalanssysteem. Dit systeem is ontworpen om deelnemers aan te zetten om hun marktpositie correct te voorspellen. Deze voorspelling is belangrijk voor de netbeheerder om vroegtijdig problemen in het net te kunnen detecteren.

Na de economische analyse werden de technische mogelijkheden onderzocht. Ten eerste zijn de benodigde netondersteunende diensten in kaart gebracht. Dit creëerde een framework voor de verdere uitwerking van een technische VPP. Vervolgens werden verschillende soorten energieopslag en hun potentieel voor het Belgische elektriciteitssysteem onderzocht.

Daarna werd de case onderzocht die de aanleiding vormde voor dit doctoraat: congestiebeheer. Omdat er geen vergoeding bestaat voor congestiebeheer, werd onderzocht als een VPP meerdere services kon combineren en daarbij gebruik kon maken van de mogelijkheden van dynamische herconfiguratie om congestie aan te pakken. Hierbij werd bewezen dat het activeren van neerwaartse reserves in het gecongesteerde gebied de congestie kan verminderen. Tegelijk biedt dit de mogelijkheid een vergoeding te bieden voor de afgeregelde windenergie. Dit zou kunnen leiden tot een systeem waarbij neerwaartse reserves geactiveerd worden in gecongesteerde gebieden in plaats van gelijkmatig over de gehele regelzone. Dit resulteert in een vermindering van onbetaalde afschakelingen.

Vervolgens werd bewezen dat het economisch niet interessant is om PV-energie te reserveren voor snelle opwaartse reserves. PV leek een goede bron voor primaire reserve door het gebrek aan inertie. Voortijdige afregeling om opregelcapaciteit te voorzien bleek economisch niet haalbaar, hoewel er een technisch potentieel lijkt.

Het laatste deel onderzoek op technische VPPs toonde aan dat er een enorm potentieel aanwezig is bij residentiele vraagsturing. Verminderen van het vermogen van residentiële aansluitingen kan in noodgevallen enorme besparingen opleveren.

Als volgende topic werd het potentieel van thermische bronnen in combinatie met het elektrische net onderzocht. Dit eigen onderzoek toont aan dat thermische bronnen een grote hoeveelheid flexibiliteit kunnen leveren aan het elektrische net. Warmtenetten in combinatie met elektriciteitsopwekking kunnen het verschil in voorspelde en reële opbrengst van hernieuwbare bronnen wegregelen.

Tot slot worden alle voorgaande technologieën gecombineerd om door middel van een cluster van verschillende bronnen de taken van een gascentrale over te nemen. Hierbij wordt aangetoond dat de energie-output en het dynamisch gedrag van een klassieke thermische centrale nagebootst kan worden door het combineren van verschillende bronnen en lasten. Het vervangen van de energie geproduceerd door een gasgestookte centrale door hernieuwbare bronnen is eenvoudig indien dit op jaarbasis berekend wordt. Op een dag per dag tijdsschaal wordt dit echter veel moeilijker. Een eerste resultaat is dat zonder te investeren in grootschalige elektrische opslag een dergelijke vervanging onmogelijk is.

Een tweede gevolg van het vervangen van een gascentrale door hernieuwbare bronnen is dat er regelmatig overproductie zal zijn. Er kan op vier manieren met dit overschot omgegaan worden: afregelen, exporteren, vraagsturing of opslaan. Exporteren naar de buurlanden lijkt de gemakkelijkste oplossing: er moeten immers geen bijkomende maatregelen genomen worden. In het verleden is echter al aangetoond dat de kans dat onze buurlanden samen met ons land een productieoverschot hebben, reëel is. Dit resulteert in negatieve prijzen zoals in het verleden reeds meerdere malen aangetoond is. Dit is niet wenselijk op lange termijn. Daarom zullen opslag en afregeling noodzakelijk zijn. Daar grootschalige opslag van elektrische energie momenteel financieel onhaalbaar is, is op korte termijn afregelen de enige realistische optie. Opslagtechnologie evolueert echter razend snel, waardoor dit binnen enkele jaren competitief zou kunnen worden. De groeidoelstellingen voor hernieuwbare energie laten het echter niet toe daar op te wachten ...

Virtual Power Plants zijn een methode om kleine actieve bronnen en lasten te integreren in een systeem ontworpen voor grootschalige centrale energieproductie. Virtual Power Plants bieden de mogelijkheid om deze gedistribueerde bronnen efficiënt te beheren. Daarbij wordt rekening gehouden met de eigenschappen van het bestaande net. Door Virtual Power Plants kan de overgang geleidelijk plaatsvinden, zonder abrupte veranderingen in het bestaande systeem.

English summary

All over the world, energy awareness is increasing. Two important factors are accountable for this raise in attention: the much debated climate change and increasing energy prices due to increasing pressure on oil products [1]. This encourages policy makers as well as the public opinion to aim for reducing the primary energy consumption and increasing the energy efficiency. A large portion of the new and more energy efficient technologies shift towards the use of electricity. For example: gas boilers are replaced by heat pumps and vehicles switch from combustion engines to an electrical drive train. As a result, although primary energy consumption becomes more efficient, more electrical energy is required.

Generation of electricity is also under pressure. As more than half of the electricity production worldwide is based on fossil fuels [2], this results in environmental and economic pressure. In Europe [3], the lack of large own (fossil) energy reserves enforces dependence on fuel imports. Also, the other large primary energy resource for electricity production, i.e. nuclear power, is causing much political and social concern. The aforementioned circumstances are the drivers for the development and installation of a large amount of new electricity producing devices like wind turbines, solar parks and combined heat and power units. Although these devices are mostly connected to the low and medium voltage grid, due to their large numbers they have a significant impact on the high voltage grid as well. The lack of controllability of many of these units can cause significant pressure on the stability of the electrical power system.

To preserve the environment and to decrease dependence of external energy sources, Europe has set ambitious goals for the electricity production from Renewable Energy Sources (RES). However, this encompasses large stress on the operational stability of the electricity grid due to a lack of controllability of many of these sources. Virtual Power Plants (VPPs) are a concept to manage and control large amounts of relatively small energy resources and integrate them in the operation of the grid.

In this work, first the different electricity markets are discussed. This provides an introduction to the operational environment of a commercial VPP. Commercial VPPs are required to adapt the scale of distributed resources to the scale of the existing electricity markets. As such, they provide a tool to further implement the energy market liberalisation as they enable a level playing field. Smaller resources have no reasonable access to the energy markets as the market is not designed for such small power and energy levels. Next, it was investigated if a large scale solar power VPP could benefit from clustering and trading its energy in the market. At the time of publication, it was shown that the effort was not up to the potential gain

due to the large impact of the green power certificates. But also without the GPCs, the risk is quite high as no corrective means are possible. The risks of trading on wholesale markets were also further investigated. This resulted in the discovery of a vulnerability of the imbalance system, which is designed to encourage grid participants to correctly predict their position in the energy market. This prediction is important to the system operator, as it is used to detect potential problems in the system before they become troublesome.

After the economic analysis, technical opportunities and challenges were investigated. First, the required ancillary services of the grid are investigated. This set a framework for further research of technical services provided by a VPP. First, several storage technologies and their applicability to the Belgian electricity system were investigated.

Next, the research returned to the original case providing the initiation to this PhD: congestion management. As no remuneration exists for congestion management services, it was investigated if a VPP could combine services and use its dynamic character to relieve congestion problems. It was shown that activating downward reserve within the congested area could reduce the congestion while providing remuneration for the curtailed wind energy. This could lead to a system where downwards activations are allocated to congested areas instead of evenly all over the regulation zone, reducing unpaid curtailment.

Next, it was proven that reserving part of the predicted solar power to activate as quick upward reserve capacity is not economically viable. PV power seemed to be a good resource of primary reserve as there is no inertia involved. Pre-emptive curtailment to reserve upward regulation capacity is shown to be currently not economically viable, although potentially technically sound.

The last research conducted on technical VPPs showed the enormous potential of residential curtailment. Reducing the capacity of residential connections in case of scarcity can save significant power.

Next, the potential of thermal energy resources in relation to the electrical grid was investigated. This original research proves that thermal resources can provide a large amount of flexibility to the electrical grid. Combining thermal grids with power production can alleviate the prediction errors made on large scale renewable sources by buffering thermal energy.

Finally, a combination is made of the earlier investigated technologies in order to propose a cluster of different resources to fullfill the tasks of a gas fired power plant. It is shown that by combining several resources together, energy output and dynamic behaviour of a classic thermal plant can be emulated. Replacing the amount of energy generated by a gas fired power plant by renewable energy can be simply met based on yearly energy production. However, on a day by day basis, this becomes much harder. Without investing in large scale storage, it is almost impossible.

A second consequence of replacing a gas fired plant with renewable resources is that there will be a lot of days with overproduction or shortage. There are four ways of dealing with this: curtailment, export, demand side management or storage. Export to neighbouring countries seems to be the easiest solution: no special measures need to be taken. However, as history has already shown, the possibil-

ity of neighbouring countries also having an energy surplus at the same time as Belgium is real. This will result in negative prices as happened several times before. In the long term, this is not desirable. Therefore storage and curtailment will be necessary. As large scale electrical energy storage in the near future is still inevitably expensive, curtailment is the only realistic option in the short term. Storage technology is changing rapidly, so it can be expected to be competitive within a few years. The renewable energy growth targets however do not allow us to wait.

Virtual Power Plants are a way to integrate small active resources in a system designed for large central power production. By combining and controlling these dispersed resources, Virtual Power Plants offer a method to help managing the electrical grid with a lot of small resources in an efficient way, without changing existing structures in a disruptive way.

1

Introduction

1.1 Introduction of the work

This research started in 2011 as a reaction to the problematic congestion of a high voltage line in Ostend, Belgium. Due to the planning of many offshore wind farms, the onshore grid became congested. The planned wind farms had grid capacity reserved with the grid operator. Altough these farms were not yet build, the grid operator had to take these future projects into account before allowing new connections. Although there was no technical congestion, further development of offshore wind and onshore Distributed Energy Resources (DER) were halted. As a result, the grid operators faced congestion in this region, which is connected in antenna 1.1. Due to this virtually congested line, no large DER projects could be connected from September 2011 onwards.

Altough the potential congestion was fairly minimal, estimated to only a few hours a year, the impact on the economy was large. Many companies that wanted to invest in renewable energy, faced a stand-off with the grid operators. No Distributed Generation (DG) projects larger than 400 MW were granted since. This was a major concern for Ostend, which is the 'energy port' of Flanders and Belgium.

It should be noted that the Transmission System Operator (TSO) Elia, responsible for the congested line, had foreseen this problem for years before. The plans for the necessary grid reinforcement (Stevin) project were already made. However, political tinkering prevented Elia from starting the project. The procedures for large infrastructure projects were to be adapted several times. Different political levels, next to individual stakeholders and lobby groups, filed opposition to

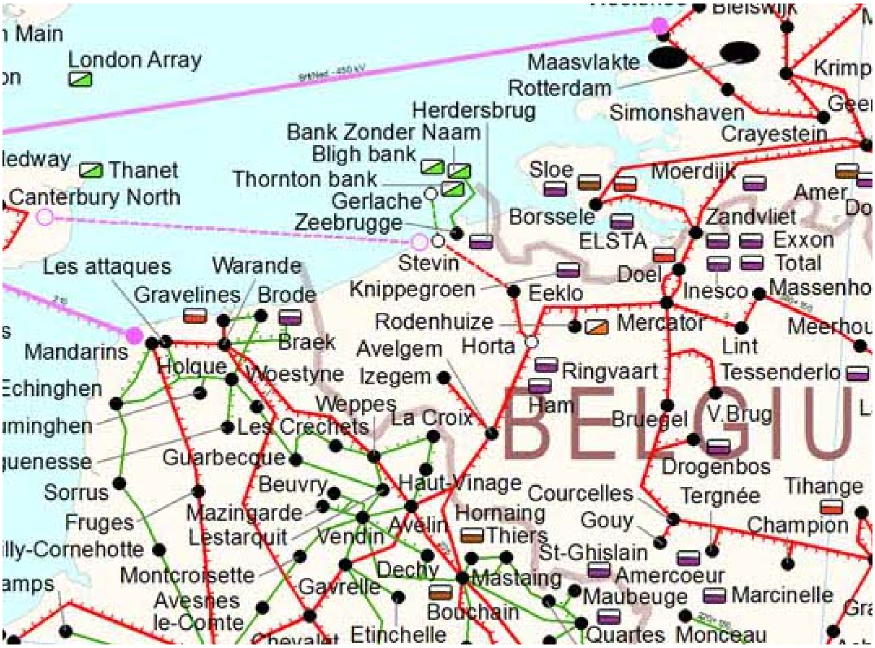

Figure 1.1: The high voltage grid in North-West Belgium and surroundings

the high voltage lines. The lack of high voltage interconnection prevented half of the granted offshore wind capacity, the necessary High Voltage Direct Current (HVDC) connection to the United Kingdom and many medium to large onshore (renewable) energy investments. The political bungling ended only in 2015, and Elia started the construction of the 43 km, 6 GW high voltage line.

1.2 Motivation and goals

A Virtual Power Plant is a method to group distributed resources to cooperate and work together in a system designed to deal only with large energy production units. These distributed resources can be either energy production, consumption or storage. The electricity grid originates from individual power plants, delivering electricity to their neighbourhoods. During decades, these regional grids merged to become larger and larger systems. Today, Europe is interconnected in one single grid. Although physically this grid is connected for decades, electricity markets are still in the merging process. This results in a rapidly changing environment in which grid users need to operate.

Next to this still developing structure, the nature of power production is also changing. Former production plants were large central units, reliably delivering power to the grid. Most of these production plants adapt their power output according to the demand. However, this production park is quickly changing under environmental and political pressure. Large central power plants with their own primary energy source are replaced with small dispersed production units powered by sun, wind or other primary sources. These sources are not always available, posing new challenges to maintain the power balance.

Although Renewable Energy Sources (RES) are less dependant on external resources like fossil fuel or uranium, they are often still dependant on the weather, time of the day, tide etc. As long as the renewable energy share in the total electrical energy production was small, this posed no big problem. To encourage their installation, wind and solar energy got priority access to the grid. Renewable energy production should be used first, before nuclear and fossil power. This resulted in a massive adoption of RES during the last decade. However, not much care has been taken to actively incorporate these new resources into the grid. RES were installed as ‘fit and forget’.

As the share of these resources increases, so do their problems. Today, sometimes half of our electricity comes from these renewable sources. This poses new challenges. Traditionally, the generators adapted their output to the varying demand. However, as wind and solar were granted priority dispatch rights, the fluctuations should be taken care of by an increasing smaller amount of traditional power plants. Given the European political goal of reaching 20% renewable electricity by 2020, some major changes should be made.

Controlling and taming the output of renewable sources and generally making them an integral part of our electricity system form a major challenge for the coming years. Several technologies are being developed. Virtual Power Plants, the clustering and controlling of resources via networks and software is one of such technologies. It can bridge the gap between the traditional grid of large central production plants and the future grid with many small dispersed production units.

1.3 European framework

Since the introduction of the Energy Union early 2015, Europe has set a frame for making energy more secure, affordable and sustainable. Reliable energy supplies at reasonable prices for businesses is one pillar of the Juncker plan to help revive the competitiveness of the European industry. Indeed, measures to secure the electricity supply have an impact on competition in the internal electricity market [4].

Next to the energy security strategy, the 2020 and 2030 energy strategy with its tightening targets for renewable energy, greenhouse gas reduction and energy efficiency is a growing concern to industry. In particular the rise in capacity of renewable energy sources into the electricity system and the lack of market-ready storage technologies is feared to increase price volatility and thus the total cost of the electricity system [5].

In the new energy market design, “electricity generated from renewable sources has become one of the most important sources of electricity, heralding a transition towards a low-carbon energy system. The move away from generation in large central power plants towards decentral production from renewable energy sources requires an adaptation of the current rules of electricity trading and changes the existing market roles. The electricity market needs to adapt to this new reality; it needs to fully integrate all market players, including flexible demand, energy service providers and renewables. The new market design should ensure that energy markets can fully support this transition at minimum cost." [6].

1.4 Origin of research

1.4.1 Line congestion

As mentioned in §1.1, this PhD research started in 2011 as a reaction to the problematic congestion in Ostend, Belgium. Large investments in renewable energy offshore led to new problems onshore. The existing transmission grid in the coastal area was not strong enough connected to the loads in the rest of the country. Elia, the Belgian TSO detected already in an early stage of the offshore developments that there might be a transmission problem. If all wind farms would operate at maximum power and the consumption in the local coastal area would be low, the single transmission line to this area could be overloaded. Although the chances this situation would happen any time soon was fairly minimal, the risk of an overload could not be taken. The fact that at the time being only the first turbines were only being placed, had no influence on the results. Elia had to take into account all granted capacity, even if realisation of the offshore wind turbine parks would take several more years. In the meanwhile, no more onshore production capacity was allowed, effectively halting tens of renewable energy projects in the area.

A partial solution was presented in the form of a telecontrol box. The potential investors could proceed with their plans, but the grid operators could disconnect their installations remotely if congestion was immanent. Two problems arose with this solution. First, no guarantee could be given when, how often or how long the plants would be disconnected. This posed a major financial risk to the potential investors. Secondly, the connection allowance was considered as a favour, and hence no remuneration in case of disconnection was foreseen. Not many potential investors perceived this as a viable solution.

Although the congested line will be replaced with a higher capacity one, alleviating the congestion problem in West-Flanders, similar problems still exist and emerge on several other locations. The main challenge is still to balance production and consumption, even under increasing variability and decreasing predictability.

1.4.2 Virtual Power Plants and microgrids

Research towards smart grid technology was already present in the research group before this PhD research, e.g. Tine Vandoorn who was researching microgrids. Microgrids are a cluster of DER, operating on a common feeder. Due to the built-in intelligence, these microgrids are capable of working as a separate grids, even separate from a stable power grid. This existing research was used as an anchor point for this PhD.

Despite the tremendous benefits of distributed energy resources (DER), some challenges arise from their penetration in the network. For instance, the capacity limits in terms of maximum power or voltage are reached more frequently and the changed, even bidirectional, power flows impact the network operation. To deal with the intermittent nature of an increasing share of DER and the increasing electricity demand, the future electrical power system will need to become more intelligent. However, the advent of the smart electrical grid will not be through a revolution, this is only possible through a gradual evolutionary change of the electrical network [7].

Because of the flexibility and scalability, microgrids have often been pointed out as a main actor in the development of the smart grid. It is expected that smart microgrids will emerge in the electrical network and the smart grid will be constituted of integrated smart microgrids [8]. Smart microgrids and separate DER can be aggregated into a Virtual Power Plant (VPP) to behave like a conventional central generator and help to manage consumption. VPPs can contribute to the DER integration in the smart grid by fully benefiting from the two-way communication and control functionalities provided by the smart grid. According to [8], it seems likely that the best way to deal with the increasing complexity in the distribution level is a VPP or (smart) microgrid topology, or a hierarchical network structure with both topologies layered on top of each other. Both VPPs and microgrids are attractive to provide a coordinated integration of DER in the electricity network and have in common that they aggregate DER. Microgrids are an aggregation of DER that can operate both in grid-connected and islanded mode. An important benefit is that the microgrid presents itself to the electrical network as a controllable entity. VPPs form an aggregation of DER as well, but this aggregation can be virtual, thus, software-based. Hence, the geographical limits of microgrid systems are removed, but islanding of the whole VPP is often not possible. VPPs can also consist of an aggregation of microgrids as shown in Fig.1.2. Hence, the concepts of smart microgrids and VPPs are similar with respect to the DER control.

In microgrids, a distinction between primary and secondary control can be made. The microgrid primary control often avoids the usage of local communication as it is responsible for a robust stable operation of the network. The primary control of the distributed generation (DG) units is different in the grid-connected mode from the islanded mode. In the grid-connected mode, the DG units are current-controlled and deliver a pre-specified amount of power in the network. In

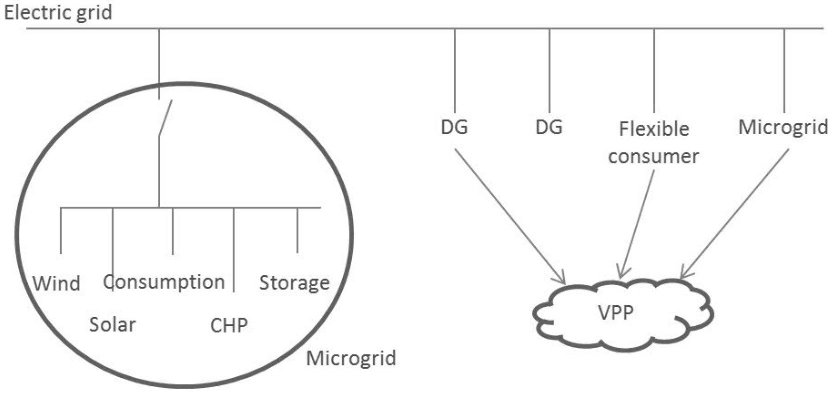

Figure 1.2: VPPs and microgrids

the islanded mode, no stable (voltage) reference is present. Therefore, the DG units are voltage-controlled and are responsible for both voltage and power control of the microgrid. The primary control is responsible for the reliability and stability of the system, and thus needs a fast control strategy. The secondary control operates on a slower time frame and deals with other aspects of the system, such as the power exchange between utility network and microgrid, resource allocation, voltage profile optimisation and frequency restoration. Hence, this control can benefit from using (wide area) communication. For the active loads, again a distinction between primary and secondary demand response (DR) can be made. Like the primary DG control, the primary DR is responsible for reliability issues such as stabilising the microgrid. It operates very fast, comparable with the time response of the DG units, and hence does not require inter-unit communication.

The primary DR can be combined with the more conventional secondary DR. This operates on a slower time frame, is responsible for issues such as economic optimization and resource allocation, and is part of the smart grid concept. From the utility perspective, the secondary control signals only need to be communicated to the Point of Common Coupling (PCC) instead of all the smart meters in the microgrid. This delivers important scaling advantages and mitigates the communication burden.

VPPs are not capable of islanding, hence, their primary control is similar to that of the DG units in the grid-connected mode. By aggregating DER, the VPP can participate in the electricity markets, deal with congestion problems and optimize voltage profiles in its feeders. As VPPs are software-based, like microgrid secondary control, they benefit from the communication functionalities delivered by the smart grid changes in the network.

In §3.5, a hierarchical structure is discussed with a VPP consisting of several microgrids. In this way, the communication and computational burden can be reduced and a more agent-based approach is taken. The VPP only communicates to the microgrid coordinator instead of to all microgrid elements. This will be further elaborated in §3.5. §1.4.2 and §3.5 have been published as an article [9].

1.5 Virtual Power Plants in a broader perspective

Virtual Power Plants and microgrids are not the only known solutions to integrate RES within the existing electricity grid. As has been described in §1.4.2, microgrids also a way to integrate DER in the grid. An other concept often used is an Energy Hub [10]. In an energy hub different energy resources meet and are transformed into each other.

As multiple definitions of these concepts exists, it is required to clarify the definitions used in this text. First, a microgrid is defined as a system where the different resources have a direct (electrical) impact on each other. In other words, a microgrid requires physical proximity in order to qualify as such. Most of the time, the microgrid will deal with reliability issues and local optimisation. A microgrid is a perfect tool to solve local, physical problems. As has been explained in §1.4.2, a microgrid can however receive its targets of a higher level, which could be a VPP or an other top level structure.

A VPP is in contradiction not physically bound. A VPP can collect resources from anywhere, as long as these can be useful for the business case. This implies the upper limit for VPPs: they need to lie within one market region. A VPP can not use a resource outside the target market region, as this is legally not possible and often not technically useful. Market integration is however an ongoing process, so the limits will change in the future. In the first place, VPPs will facilitate market access for units to small to access the market in an individual way. There are no hard limits, but depending on the market or service, the lower limit is merely decided by the economics. VPPs will require investments in a data platform, communication infrastructure and market access fees. In the case of a VPP selling technical services, also technical limitations will apply. Certain services have lower capacity limits, e.g. spinning reserve, while others are geographically limited, e.g. voltage management. Therefore, both upper and lower boundaries are case dependant. Also, a VPP will likely need to aggregate more than the minimal volume of resources in order to guarantee the required service level, especially in the case of ancillary services (ref. §3.3).

Determining the ideal operational conditions for VPPs will require a lot more discussion. Many candidates for the operation of VPPs exist: the TSO, the DSO, energy suppliers, Access Responsible Parties (ARPs), aggregators ...Some of these roles are already established while others are more recent or only available in Belgium. Aggregators are quite new to the energy system, but they are already operational since a few years. Although most of them do not call their system a VPP, they are conform to the above definition. All of them could use the concept of a VPP. However, conflicting goals can and will happen in the future. It could be possible the TSO requests an upward activation for frequency management, but the DSO requires downward regulation due to congestion and the ARP would like the resources to remain stable. A structure should be in place to decide upon these conflicting requests.

1.6 Overview of the work done

1.6.1 Research

As has been discussed in §1.4.2, the work originated in the existing microgrid research at the lab. Virtual Power Plants can be seen as a logical next step from microgrids. Altough the microgrid research focusses mainly on technical aspects, soon it was clear that for VPPs, the economical part is as important as the technical part. So in the beginning, the focus was on the energy markets and the possible benefits of clustering. This first research resulted in a paper presented on the IEEE Power and Energy Society General Meeting in 2013 [11]. In this paper it was investigated if solar energy can become more profitable if forces are joined in a Commercial Virtual Power Plant to sell the solar power on the wholesale market. The numbers are based on the Flemish region, however, the same procedure can be applied to other markets as well because the West European markets are coupled and share a common price for the majority of time. However, policy differs significantly between countries and regions, so this can have a major impact on support mechanisms. It turned out that for existing installations the potential benefits are marginal due to the small share of the energy revenue compared to the subsidy revenue in the total income of a solar plant. However, lower subsidies and coupling with other production resources and (flexible) consumers promise to be more profitable. This will be elaborated upon in §2.7.

Next, more technical aspects were investigated. Discussions with peers resulted in research on the possible interaction between thermal grids and VPPs. Waste heat valorisation in process industry is a common strategy today. The residual heat is converted to electricity by using steam turbines or organic Rankine cycles. As this energy conversion is likely constructed as an integral cooling capacity for the primary process, loss of electricity production will result in reduced process cooling and hence production capacity loss. These restrictions prevents these generators to deliver supporting services to the electrical grid. It is proven that coupling waste heat recovery with a district heating network provides flexibility to the electricity generation while ensuring cooling capacity to the process. This flexibility can be utilised by a Virtual Power Plant (VPP), e.g., to compensate for the variable output of renewable energy sources. Today, the power fluctuations are only compensated by traditional power plants (gas, coal,...) due to the scale and flexibility of these power plants. In chapter 4, a strategy is defined to balance variable (renewable) production with industrial waste heat. As such, some grid support tasks can be transferred from the central power plants to decentralised generation units. The backup of the variable sources is provided by utilising the local available capacity, while maintaining or improving energy efficiency of exothermal industrial processes. Operational boundaries are defined and new challenges identified. In this research, firstly, the heat sources available for this concept are identified. Secondly, the properties of the different conversion technologies are described. Thirdly, the benefits of a virtual power plant utilising waste heat are determined. Finally, this VPP concept is verified by means of a case study in Belgium, in casu Ostend Energy Port. Available heat from biomass, chemical processing and waste incineration is used as primary energy source to balance local renewable production. This work has been presented on the Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction conference [12]. This is further presented in §4.2.

Next, a small side step was made to storage technologies. This resulted in a joint publication with former colleague Mohammad Moradzadeh on different storage technologies applicable to the Belgian power system. The intermittent and fluctuating nature of output power of Renewable Energy Source (RES) can lead to serious security concerns such as congestion in the transmission system. Incorporating storage devices with RES is technically an effective means to mitigate this concern by allowing fluctuating RES to be as stable as traditional power plants. Storage is an even more consumer-friendly solution with greater control over electricity consumption time and price compared to e.g. demand-side management which offers limited control over the price for end users. It can also contribute to lower the electricity price, peak-shave the demand, defer upgrade investments, provide ride-through solution for (momentary) faults, contribute to voltage/frequency control, increase the share of green energy and thus reduce overall greenhouse gas emissions, improve power quality by reducing harmonic distortions and voltage sags/surges, facilitate utilisation of more efficient off-peak generation units, etc. This work assesses the technical applicability and economical viability of different storage devices to the Belgian power network, focusing on the structure of the Belgian electricity market. A high-level overview of widely-used storage technologies, their benefits and shortcomings are also provided. This work has been published in the proceedings of the 2013 IEEE Electrical Power & Energy Conference. This is further presented in §3.6.

Next, the focus shifted back towards the commercial aspects. Due to the threads of an energy shortage during the winter, the Belgian TSO, the government and the Commissie voor de Regulering van de Elektriciteit en het Gas, Electricity and Gas Regulations Commission (CREG) developed a plan to prevent a black out. Part of these plans was the installation of a strategic reserve. It was announced that if this strategic reserve had to be activated, the imbalance prices would skyrocket to more than ten times the normal peak values. This triggered the research of possible abuse of the imbalance system. In the resulting paper, presented at the IEEE Electrical Power & Energy Conference General Meeting 2014 [13], the risks and challenges of leaving the fixed rate system and trade directly on the more volatile day ahead markets while facing penalties resulting from wrong forecasts were investigated. It was proven that deliberately nominating to much or not enough energy can be financially positive, but also yield large risks. The results were discussed with Elia, the Belgian TSO. They were surprised by the discovered vulnerability and warned traders not to exploit it. This vulnerability was especially appealing to operators of (large) Combined Heat and Power (CHP). By nominating no production in sight of the activation of the strategic reserve yet producing at full power during the strategic reserve activation a large margin could be obtained. This is further presented in §2.8.

The research presented at the 2013 Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction conference was further deepened. The results have subsequently been published in the Applied Thermal Engineering journal. This resulted in a more detailed study of the opportunities of thermal grids in combination with VPPs. The publication proposes a method to provide ancillary services to the electrical grid with waste heat recovery. The thermal flexibility needed to provide variable electrical output is provided by connecting the thermal source to a thermal grid and a thermal storage unit. Large capacity low grade heat thermal storages are cheaper and more readily available than large capacity electrical storage solutions, and hence thermal storage is preferable.

In 4.4, the dimensions of a low temperature thermal storage buffer to balance the variability of a wind- or solar plant is determined. It is calculated that a spherical storage tank of 25 m diameter and 90-130 °C would be sufficient to balance the unpredictability of a 100 MW plant of either solar- or wind energy. The results are also presented in §4.

As two earlier publications already focussed on PV power, this was further investigated. This time, the focus was shifted to the technical aspects. In the time between the first publication of a Solar CVPP and this research, the price of green power certificates has dropped significantly and hence the balance between certificate and commodity revenue was restored. This provided the trigger to investigate if it could be viable to use solar energy as balancing provider. The resulting publication investigates the possibility of providing positive balancing services to the transmission system operator by aggregating solar power in a technical Virtual Power Plant.

Research concludes that it seems not interesting, neither economically nor energetically, to keep solar plants solely for positive balancing purposes. Combination of solar power with other sources or consumers can however be profitable, as solar power is quickly switched in case it is needed to react fast [14]. The results have been presented on the 2014 Young Researchers Symposium in Ghent and are further presented in §3.8.

In the above research, each time one aspect of a VPP was investigated. In [15], two services are combined. For this publication, the focus went back to the origin of this PhD, namely congestion management. As congestion is not a normal operational state of the grid, no market exists for congestion management. In case a new project could induce congestion, the traditional approach is either to reinforce the grid or reject the grid connection. Rejection of renewable resources due to congestion of the high voltage line in the north of West-Flanders was in 2013 politically no longer feasible. A temporary solution was designed to curtail renewable energy by the DSO and TSO in case of congestion. For the plant owners / investors, no compensation was foreseen. In this publication, it was investigated if the combination of an existing market, the secondary reserve market, could partially compensate the loss in case of curtailment. As a VPP can dynamically reconfigure its resources, it could allocate all downwards activations to the congested area, and all upward activations outside the affected area. The results are also presented in §3.7.

Returning to the combination of electricity and thermal energy, a contribution was made to the research of ing. Laveyne. In [16], it was investigated how the combination of a heat pump with a gas fired backup system could be economically optimised. It was demonstrated that the choice between gas and electricity as a primary source for heating could change depending on several parameters. This is also elaborated in §4.7. The resulting publication has been presented at the 2013 Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction conference.

The final research focused on the residential demand reduction potential. Between 2013 and 2015, plans were made for load shedding in the case of electricity production shortage. However, the load shedding would occur on the level of the transition between the TSO and DSO, resulting in a rolling blackout. In complete zones, all loads connected to a distribution feeder would be cut off. This final research focussed on an alternative, namely partial demand reduction of residential consumers. A significant power reduction would be possible by reducing the maximum load of individual homes, preventing the rolling blackout. This research is still in review for publication in a journal.

1.6.2 Publications

During the course of this PhD research, the author contributed to 14 publications, from which 7 as first author. A complete list can be found at the end of this chapter.

1.6.3 Media references

During the course of this PhD, the author submitted articles, opinions and interviews to the mainstream media. Not only the main topic of VPPs are used as a basis for discussion, but energy in general.

Several contributions to national newspapers in the form of opinion articles have been published. In these, reactions were given to policy changes or events of public concern regarding electrical energy. It started in a reaction to the ‘blackout prevention measures’ presented by the government preceding the first ‘blackout winter’. One of the measures presented to the public was to remove unused chargers from their outlet. Measurements in the lab showed this has no effect whatsoever. Our reaction to this list of measures even reached twice the national news. Several other opinion forming articles have been published.

1.7 Structure of this dissertation

In chapter 2, the economical aspects of a VPP are discussed. A Commercial VPP (CVPP) can get access to several energy markets. In essence, a CVPP does nothing more than a traditional supplier, except that a CVPP can use bidirectional communication to interact with its clients. As such, the CVPP can receive predicted and real time power profiles from its constituents. In return, the VPP can send control signals to the local units to alter their load to cope with real time deviations.

In chapter 3, more technical subjects are discussed. First, ancillary services and their role in the operation of the grid are discussed. A high level overview of ancillary services is provided, with their requirements on control level and also the basic remuneration which can be expected for these services. The chapter continues with a part on storage. Storage will be an important asset in the future grid. Several technologies are discussed and their applicability to the Belgian grid is evaluated.

In chapter 4, the link between VPPs and thermal systems is made. Chapter 5, general considerations are made on a complete VPP, comprising different techniques, presented trough chapter 2 - 4. Chapter 6 presents the final conclusions.

Publications

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2

Commercial Virtual Power Plant

2.1 Introduction

Depending on the functionality, one can divide VPPs in two categories: Technical VPPs (TVPP, see §3.2) and Commercial VPPs (CVPP). A Commercial Virtual Power Plant (CVPP) clusters the production and/or consumption from different sources to trade the energy in a more profitable way. In its simplest form, it consists of installations of a company with a multisite metering contract. If combined in a multisite contract, the installations essentially form a CVPP. A more advanced version would offer (semi)real-time metering and sell (buy) the energy as one volume to (from) a retailer or the energy markets. Because of aggregating these installations, the transactions are larger and variations are smoothed and as a result better prices can be negotiated. Due to their purely economical character, these VPPs are not geographically constrained. The only limitation is the operational area of the contracting energy retailer or energy market.

A more advanced version of a CVPP is one which is capable of predicting its profile and trading its energy on the stock market such as APX-ENDEX, Belpex Day Ahead Market (DAM), Belpex Continuous Intraday Market (CIM), EPEX Spot FR, EPEX Spot DE or EMCC. In the ideal case, the CVPP can also influence the energy profile of (part) of its participants. In most cases, this provides the participants a more interesting price than that obtained on the retail market. Although on average the price is better, the volatility is also much higher. This provides opportunities for flexible participants. During low prices on the stock market, clusters with mainly consumers can buy cheap energy. During peak prices, production of electricity is more interesting and consumption disadvantageous. This

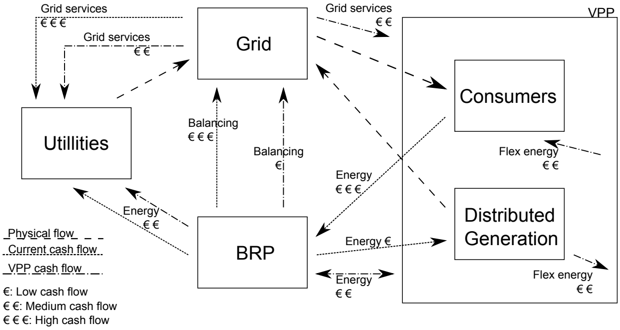

Figure 2.1: Economy of a VPP

system enables small consumers and DER to participate on the stock market. Due to the entrance fees [17, 18], minimum transaction volume [19, 20] and extra responsibilities, this is not possible for individual small (LV clients) or even most medium (MV client) participants. The order of magnitude to be profitable is tens of megawatts. Only the portfolio effect enables the smaller units to participate on the stock market as a group (Fig. 2.1).

The reason why traditional buyers get a higher price and sellers of decentralised energy get a lower price compared to the wholesale market prices is that others need to take responsibility for the prediction of energy exchanges with the grid. The TSO requires all traders affecting the transmission system, i.e. those who use the wholesale market, to deposit their expected energy exchange with the grid the day before delivery [21]. This is the responsibility of the Balance Responsible Partner (BRP). The TSO needs this information to ensure secure operation of the transmission system. If the real-time exchanges differ from the submitted profiles, a compensation is due to the TSO. The TSO will use part these compensations to buy ancillary services from other market players in order to ensure production and demand stay in equilibrium at all times. This process will be explained in detail in §3.3.

As a result of the requirement of prior notice of energy exchange with the transmission grid and the required compensation for error, suppliers need to ask more to consumers and offer less to producers [22]. This difference is needed to cover the imbalance risk. A CVPP which will trade directly in the wholesale market, essentially takes the role of the BRP/supplier and takes the risk. However, a CVPP has access to more information and can activate spare resources to reduce the mismatch between the predicted portfolio and the real time portfolio. If active steering of DER becomes part of the CVPP, the line with a TVPP becomes really thin. In this dissertation, the difference is where the VPP will deliver balancing services to other parties, not directly involved within the VPP itself. So if steering and control is applied only to match the real time profile to the predicted profile, it can be considered as a CVPP, otherwise is becomes a TVPP.

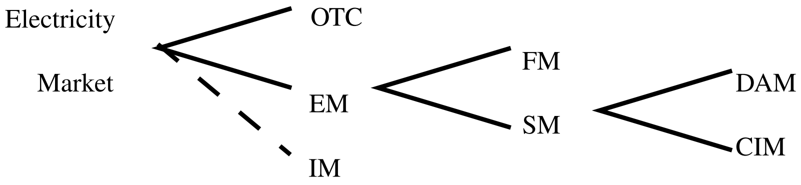

Figure 2.2: Energy trading markets

In this chapter, first the different electricity markets are discussed. Next, in §2.5, the different costs affecting the price of the end user are elaborated. In §2.6, the role of a CVPP will be explained.

Next, in §2.7, a CVPP based on solar energy is presented. In this paragraph, it will be determined if it would be beneficial to combine many photovoltaic solar plants in a CVPP to obtain a better price compared to individual contracts.

In §2.8, this is further elaborated. The risks of trading on the stock markets are further investigated based on a solar CVPP. Sections 2.7 and 2.8 have been published as articles [11] and [13] respectively.

2.2 Electricity trading options

Different methods are available to trade electricity. The options range from bilateral contracts to the intraday auction system. Prices vary significantly between these different contracts. Most prices are published publicly, except for the bilateral contracts which are confidential. Deciding which type of contract is most suited depends on the type of resource. Long-term contracts provide financial certainty, but limit flexibility, whereas intra-day trading provides the largest flexibility but less predictability.

However, independent of the type of contract, the injections and off-takes need to be nominated to the transmission system operator. For every contract, both the supplier and consumer need to nominate the transaction. Consistency is checked by the TSO to ensure the technical feasibility of every transaction. Due to operational limits of the TSO, the use of the CIM by an ARP was limited to three consecutive days or five days per month to prevent the circumvention of balancing obligations. However, this requirement is weakened during the course of this thesis and upon publication the intra-day market is considered a full market. This opens new opportunities for trading and flexibility.

2.2.1 Over the counter

The first electricity trading option is Over The Counter (OTC). In the OTC market where, the contract is made directly between the seller and the buyer. A major part of the total traded volume is sold by bilateral contracts. Especially long-term base load or predictable load is traded directly between supplier and retailer/consumer. No intermediate parties are involved.

Over-the-counter trade concerns a bilateral contract between two parties. Price and terms are agreed upon in a closed contract. As a result, the conditions of these contracts are not available to study. Personal contacts revealed that often a long-term price and volume are agreed upon. Sometimes the price is fixed, but often the price is based on the long-term wholesale-market price, adjusted with a correction factor. In the end, the parties involved are free to negotiate whatsoever contract details as they deem necessary. This includes the power profile, price for each moment, possible profile changes, minimum and maximum volume and many more options. As a result, this is a very popular contract type. Comparison of the system load and volumes published in public markets indicate a majority of power is traded via this type of contracts.

2.2.2 Wholesale markets

The second option is to trade energy on the exchange market (EM), which can further be classified into two largely distinctive markets. The first one is the futures market (FM). Futures are contracts to deliver a certain quantity of electricity on a date in the future. This is an easy way of trading large quantities of base capacity, as these contracts are often concluded for months or years at a time.

The second exchange market is the spot market (SM). On this market, energy is traded close to the delivery time. The spot market has two separate parts: the Day Ahead Market (DAM) [23] and the Continuous Intraday Market (CIM) [24]. Of the two, DAM is most widely used due to technical constraints of the CIM.

As the name suggests, on the DAM, the energy is traded the day before delivery. Sellers and buyers submit their supply and demand curves. Once a day, these are matched via an auction process and a price for each trading hour of the following day is determined. This ensures an anonymous and transparent price fixing process. In contrast, the CIM provides the parties a platform to trade energy very close to the delivery time, up to a few minutes before actual delivery. Since for every physical transfer on the transmission grid acknowledgment of the grid operator is additionally needed, this is a limited market. The CIM is only used to settle large unbalance positions after gate closure on the DAM (e.g. production unit breakdown). As a result, often only a few hours a day energy is traded in this market. In Belgium, recently the transmission system operator (Elia) made also the Imbalance Market (IM) available. The possibility to trade on this market is also limited as it depends on the system state (net regulation volume).

2.2.2.1 Futures market

Electricity can be traded for years before actual delivery through an anonymous trading market: the ICE ENDEX. This provides an anonymous system where markets participants can buy or sell electricity for delivery in Belgium.

Trading for each block ends two business days prior to the start of the delivery. In table 2.1 [25], an overview of the different forward markets available are presented.

Product	Number of blocks	Spec
Year baseload	3 years	Only calendar years
Quarter	5 quarters	Blocks Jan-Mar, Apr-Jun, Jul-Sept, Oct-Dec
Month	47 months	

Table 2.1: Belgian Futures market products

These products have the limitation that the power need to be equal during the total delivery period. Using these products, granularity is only down to a monthly basis. As seller and buyer do not know each other, no options exist to negotiate a specific delivery pattern within these blocks. Other contract types are needed to make up for daily and hourly differences.

However, other market regions can have different trading instruments. The Dutch futures market for example also has peak-load instruments. These peak-load instruments have almost the same characteristics as the Belgian products, except that delivery is made on every day only during peak hours; 8-20h [26].

As this products are continuously traded, contracts for the same delivery period can have a different price, depending on the time of trading. This products hence are prone to speculation. Major technical changes, policy or just market sentiment can affect the price. Therefore, a thorough market insight is very advantageous to really profit from these products. This is also a reason why smaller participants have a disadvantage, as they do not have the resources to monitor the market as close as large players.

2.2.3 Day ahead market

The day ahead market is also an anonymous market place to trade electricity. However, in contradiction to the forward markets, there is no continuous trading. Bids need to be placed in advance, and after gate closure a market price is fixed. As a result, all transactions for the same delivery period get the same price.

In Fig. 2.3, the market model of the Belpex and similar markets is displayed. Trading is obtained via the Belpex auction platform between buying and selling participants. After a total price and volume is fixed, payments go through a central counter party to ensure anonymity and security. Collateral deposits are required by the central counter party to ensure payments. After all participants have been notified of their completed transactions, they should nominate their position to the TSO. Belpex will counter nominate the volumes with the TSO as a last step in the trading process.

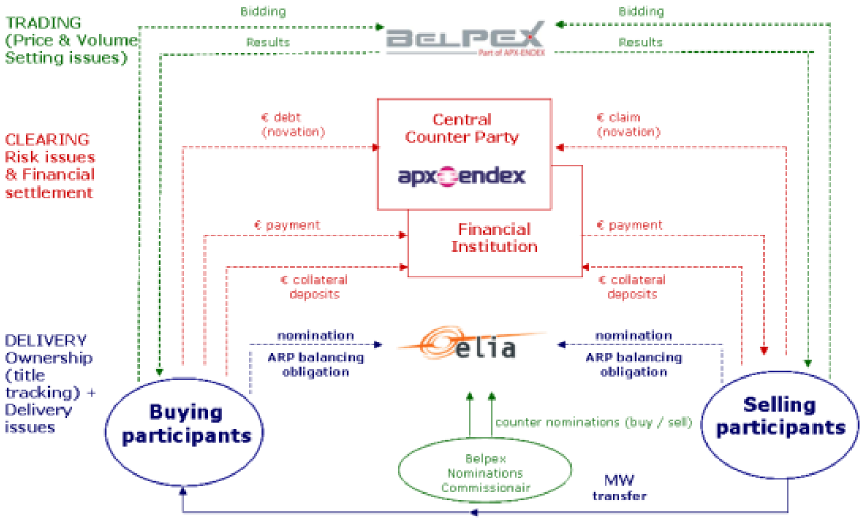

Figure 2.3: Belpex market model

The Belgian market is in normal situations coupled to the neighbouring markets of the Netherlands (APX Power NL), the United Kingdom (APX Power UK), France (EPEX Spot FR), Germany (EPEX Spot DE) and the Nordic region (Nord Pool Spot). Due to limited transmission capacity, at certain moments the price is decoupled if congestion at the borders occurs. If transmission lines are congested, cross border transactions are rejected by the TSO and hence an effective market split is established. Several mechanisms have been adopted during the last decade to decide upon the cross border capacity, including auctions. However, the most recent method is the Flow Based Market Coupling [27].

The DAM offers energy blocks of one hour. As a result, this is a very flexible market. Figs. 2.4, 2.5 2.6 and 2.7 show price maps of the Belpex DAM for 2012-2015. Price trends and ranges can be observed in these graphs. Generally, prices are lowest during the early morning hours, ranging between €10-25/MWh. High peaks of €70-110/MWh can be observed during the winter evenings and at noon. These figures indicate that savings can be made if consumption is shifted towards the low price regions or production is active during peak hours. An opportunity for CVPPs exists if processes can be shifted towards these general times, according to their connection with other systems.

2.2.4 Continuous intraday market

The continuous intraday market is a special system. In this system, energy can be traded even after delivery, in contradiction to the other markets, where only before delivery transactions can be made. This market is available if certain sudden actions need to be taken after gate closure of the DAM. However, as all transactions

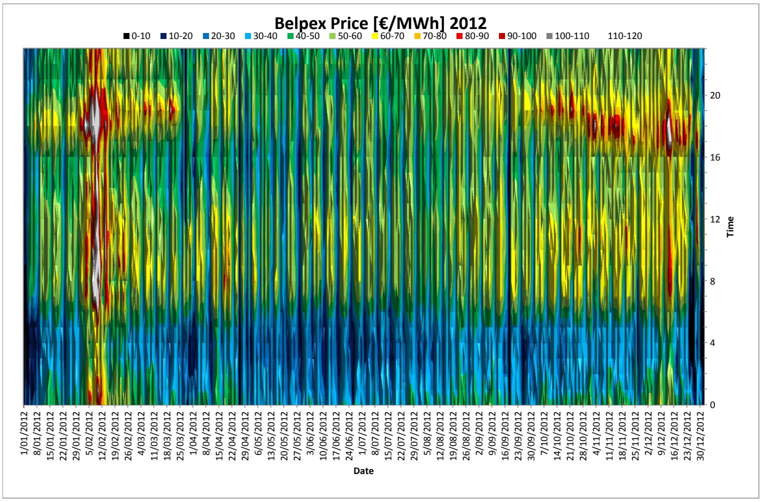

Figure 2.4: Hourly Belpex prices in 2012

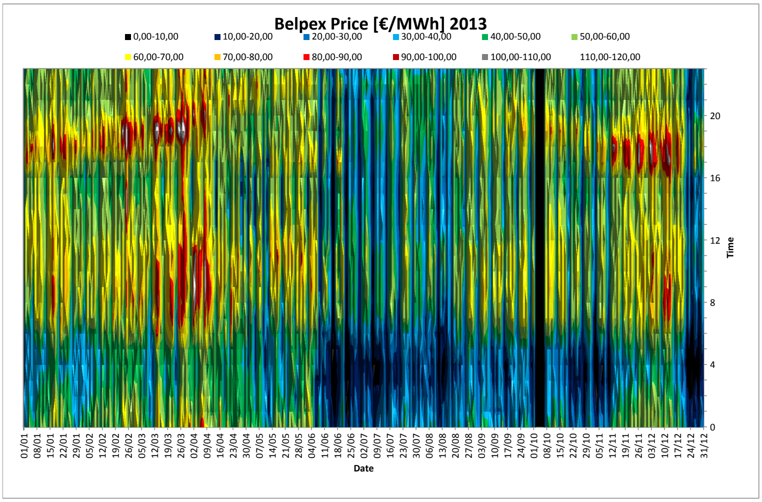

Figure 2.5: Hourly Belpex prices in 2013

should be registered with the TSO, certain limits are applicable. In Belgium, the CIM may only be used 3 days in a row or up to 5 times a month [24]. This limitation is enforced by the TSO in order to encourage BRPs to maintain high quality predictions. However, during the last year of this thesis, the position of

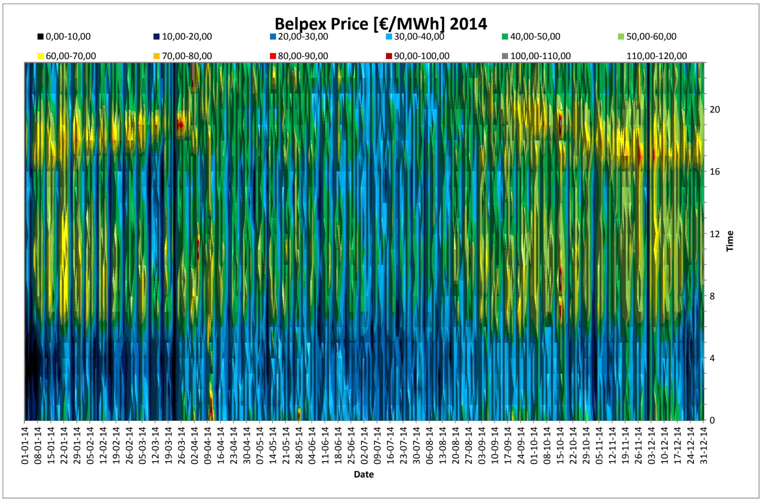

Figure 2.6: Hourly Belpex prices in 2014

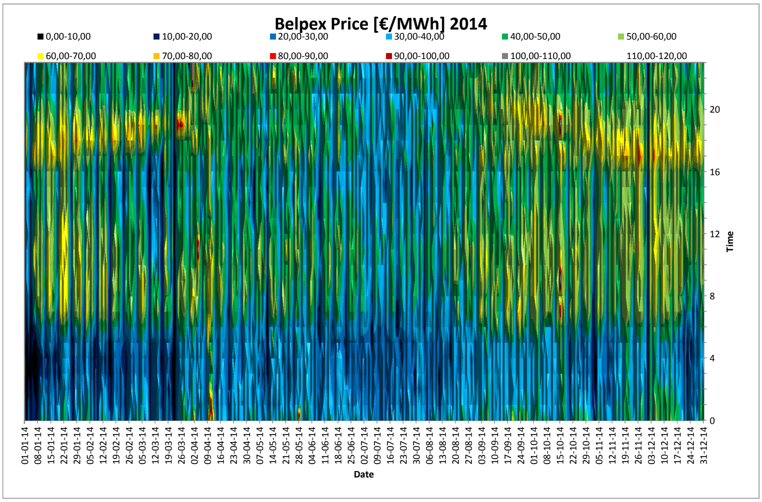

Figure 2.7: Hourly Belpex prices in 2015

the TSO in Belgium regarding the CIM shifted. The CIM is now considered as a full option, but still with the requirement to predict the market position in advance. Abuse will be penalised, as this could still endanger system stability.

2.3 Ancillary markets

Next to the pure energy markets, electricity can also be traded in the ancillary markets. However, this involves technical actions as it is a dynamic product and will hence be detailed in §3.2. Activations of these ancillary services are not free to the operator, but are upon request by the system operator or other beneficiaries.

2.4 Implications of wholesale market participation

Trading in wholesale markets has certain implications. First, a precise power profile is required. This profile needs to be submitted to the TSO at the latest the day before actual delivery. In order to actually profit from the wholesale markets, a company need to send the 15 minutes profile and keep to this profile in real time. As a result, this requires a precisely predictable process or some form of near real time load and/or production management.

If the profile in real time differs from the submitted profile, an imbalance fee will be applied by the TSO. This fee can be positive or negative, but is generally encouraging BRPs to follow the submitted profile. In [13], it was proven however that in certain cases profit could be made by submitting a false profile. This will be detailed in §2.8.

However, during the course of this PhD research, part of the rules changed. In the beginning of the research, the intra-day market was explicitly discouraged. However, the Belgian TSO (Elia) currently encourages BRPs to trade energy intra-day up to five minutes before the start of a quarter. This enables BRPs to correct previous errors in their predictions. Although the intra-day market is considered as a full market, the day ahead nominations should still be submitted as correctly as possible. BRPs which are trying to use the imbalance market to reduce the need for correctly predicted nominations can still be denied access to the intra-day market and will be fined.

2.5 Consumer electricity price

In the previous paragraphs, the wholesale energy markets were defined. However, the scale of these markets is to big for most individual customers. Therefore, retailers will collect the needs of many customers and buy the required energy in the wholesale market for their clients. Next, the energy needs to be transported from producer to the consumer. This is the responsibility of the TSO and the Distribution System Operator (DSO). All these intermediaries add a component to the consumer bill.

2.5.1 Energy component

The first component of the consumer bill is the price of the energy itself. The retailer will buy energy at the different markets detailed in §2.2.1-§2.2.4. Therefore, they need to predict the aggregated consumption profile of their clients. These combined profiles will then be divided into bids in the different markets. As these predictions will always be (slightly) wrong, the retailer will take an uncertainty margin on the wholesale price to ensure profitability. The task of a retailer is to manage its portfolio and make profit in the energy markets.

2.5.2 Grid fees

The next big component of the retail price of electricity are the grid fees. As transmission and distribution are two separate functions in the delivery of electricity, both are billed separately.

The transmission tariffs are the first component of the grid fee. In Belgium, Elia is responsible for the transmission system. Although Elia is a independent company, listed on the stock market, all costs claimed should be approved by the federal energy regulator CREG. Table 2.2 shows the different costs the TSO bills to the customer. No absolute values are presented as these changed often during the course of this thesis. As of 2016, for LV clients, these costs vary from € 13,2 / MWh to € 16,2 / MWh An overview of current and past tariffs can be found at [28].

Three major categories are present: grid usage, ancillary services and other costs. The grid usage costs are mainly determined by the capacity, simultaneity and energy usage. Other costs in this category are administrative costs and system management. These cost reflect mainly the Capital Expenditures (CAPEX) of the TSO.

A next group of costs are the ancillary services. These reflect the Operational Expenditures (CAPEX) of the TSO. Subcategories are defined for the organisation of the reserve markets, reactive power control, congestion management and compensation for grid losses.

The third category comprises mainly taxes, levies and secondary tasks of the TSO. These are further discussed in §2.5.3.

Table 2.3 gives an example of tariffs imposed by the distribution grid operators. However, as the DSOs are still in the process of merging, prices can vary widely depending on the local DSO. The connection type, e.g. low voltage, low voltage with own transformer or direct medium voltage client will also have an impact on the prices paid to the DSO.

An example of a cost breakdown for a small company is given in [29].

For a large group of customers, the cost of the TSO and DSO will be (much) higher than the actual energy cost. As the actual energy cost becomes smaller, potential profits of volatile markets become also smaller as the TSO and DSO

Tax / Levy	
Grid usage	Administrative costs Power System management
Ancillary services	Primary control, secundary control, black start Reactive power and voltage control Congestion management Grid losses
Other costs	Connection offshore wind Federal green certificates Strategic reserve Green certificates in Flanders Rational energy promotion in Flanders Renewable energy support in Wallonia Federal contribution Walloon public domain levy Brussels road network levy

Table 2.2: Transmission system fees, taxes and levies

Use of the distribution grid	Power fee System services Measurement
Public service requirements	Free electricity Public lightning Rational energy support Social measures Green certificates
Supporting services	Grid losses Voltage control
Taxes	

Table 2.3: Distribution system fees, taxes and levies

tariffs are fixed (sometimes with a day/night variation).

2.5.3 Taxes and levies

Table 2.2 gives an overview of taxes and levies charged to all customers via the transmission tariff. These levies are used to promote rational energy usage, cover green power certificates of federal wind turbines,. . .

A major component of these costs is the strategic reserve. This is used to support old power plants as 'back-up' in case of peak demand. These units are not allowed to bid in the energy market, but are only used during peak consumption.

Also on the regional level, a lot of taxes and levies are mentioned in table 2.3. The public service requirements are debatable weather they belong on the electricity bill or within the regional budgets.

2.5.4 Variable transmission and distribution costs

Currently the transmission and distribution costs are (almost) fixed. The only differentiation in distribution tariffs is between off- and on-peak prices. If the average prices of the forward and day-ahead markets are combined with the prices of the transmission and distribution tariffs, the energy component for a large group of small consumers is roughly one third of the total cost [29]. As a result, the energy price variation in the final bill is largely reduced. To promote more flexible consumption, more differentiation in the transmission and distribution would be beneficial. In the next subsections, some suggestions are made. However, this is not studied in details, and might be subject of further research.

2.5.4.1 Coupling with commodity price

The day ahead market is a very flexible market. This could thus be a good resource to base the transmission and distribution costs upon. It should be noted that other forward markets are not suited as a resource due to their distance from real time and their lack of granularity.

Although as the DAM is closely coupled to the real time operation of the system, it does not reflect the real time situation since the prices are based on the prediction of the market 12-36h in advance. With an increasing share of flexibility and unpredictability in the system, the difference between the DAM price and the real time situation can differ significantly. A system based purely on DAM prices can not react upon real time system changes such as an unexpected outage or low RES production.

2.5.4.2 Coupling with system load

System loading might be a good reference to determine transmission costs. The cost of the transmission system is determined by the peak capacity needed. Increasing the transmission cost during high load will encourage users to reschedule load to low capacity times and hence reduce the need to increase system capacity and load factor. However, in a system with a high RES penetration, it could be beneficial to encourage users to use energy when a lot of resources are available. This can conflict with the price signal based on system loading.

If transmission and distribution tariffs are coupled with the system load, there are still options regarding implementation. The price formation can be based upon the predicted system load. This offers the advantage of prior notice of the price to the consumers. The second option is to couple the price to the real time system load to be able to cope with unforeseen circumstances. This removes the opportunity of prior notice and increases the uncertainty of pricing.

2.5.4.3 Coupling with local load

A third option is to refer to the local load to determine network costs. However, as local load can differ significantly from location to location, depending on the local situation, it can be a more difficult option. The distribution transformer can even change for a fixed location, as the network is switched dynamically due to normal operation procedures.

However, this method could encourage local consumers to use local produced energy, therefore reducing network losses as energy is consumed more locally. This could be beneficial in neighbourhoods with a large concentration of solar energy and congested distribution grids.

2.6 Why Commercial Virtual Power Plants

As described in the beginning of this chapter, the current energy markets are efficient and complete systems to trade electricity. However, these markets are designed for large power and energy transactions. The whole structure is not designed to trade relative small amounts of energy. The smallest fraction which is taken into account is 0,1 MW for 15 minutes.

A second problem, next to scale, are the liabilities connected to the current market system. As an Access Responsible Party (ARP), a company accepts certain liabilities which can be prohibitive for small companies with comparatively small energy requirements. A commercial VPP can pool resources and share liabilities among many smaller subsystems. Due to the pooling concept, capacity, predictability and reliability increase at a cost of added complexity.

A (C)VPP can increase volume and share liabilities. In essence, ARPs are simple VPPs. The difference between a classic ARP and a VPP operator is in the information exchange between a VPP and its customers. A VPP has real time knowledge about the energy exchanges of his clients and could potentially influence these exchanges to react to market signals. A traditional ARP has only post factum data and need to predict energy profiles without much process information and can not directly influence client behaviour.

A CVPP is thus a more advanced version of an ARP. The CVPP operator can rely on real time energy and process data to obtain the best price for the energy. Also, by being closely integrated in the process, changes in the energy profile can be made to react to real time circumstances. However, the reactions made are only to optimise the financial position of the VPP itself. Failure to react in time will likely result in an increased imbalance fine, but no technical repercussions are to be expected in case the required actions are not taken care of.

2.7 Case study: CVPP with only solar energy

In this section it will be investigated if trading the energy produced by a CVPP solely consisting of 100 MW photovoltaic peak power would be viable? As is shown in Table 2.4 [30], installed solar energy capacity increased significantly during the last decade.

[Mw]	Private	Industrial	Total
Pre 2006	1.4	0.0	1.5
2006	2.8	0.8	3.6
2007	13.5	8.4	22.0
2008	55.9	33.3	89.1
2009	264.4	278.3	542.7
2010	416.7	479.8	896.7
2011	832.4	876.3	1708.7
2012	1056.4	985.7	2042.1

Table 2.4: Installed PV capacity in Flanders

To determine the feasibility of a CVPP with only solar energy, historical PV energy production data and Belpex trading prices for a period of one year are examined. The PV energy production is based on measurements of actual PV plants in Flanders, the trading prices are provided by Belpex. All datasets comprise the twelve months between 3 November 2011 and 3 November 2012 and contain data with 1 hour interval. With such datasets a 'perfect' CVPP can be simulated, a CVPP that has 100% accurate predictions of the day-ahead PV energy generation and without any technical or economical limitations to provide this power to the consumer. This means that all the generated energy is sold at Belpex prices and no injection fees are levied. The size of this simulated CVPP is established at 100MW or around 11% of the combined power of all Flemish 'large' ($P \geq$10kW) PV plants. In the assumed time period, this VPP yielded an energy production of 99235 MWh. In this section, the comparison will be made between five cases: 1) fixed contract, 2) 100% accurate predicted production traded at market prices, 3) stock market trading with 10% prediction error 4) trading 10% less than predicted and curtailing excess energy and 5) Use the curtailed energy to supply own controllable loads.

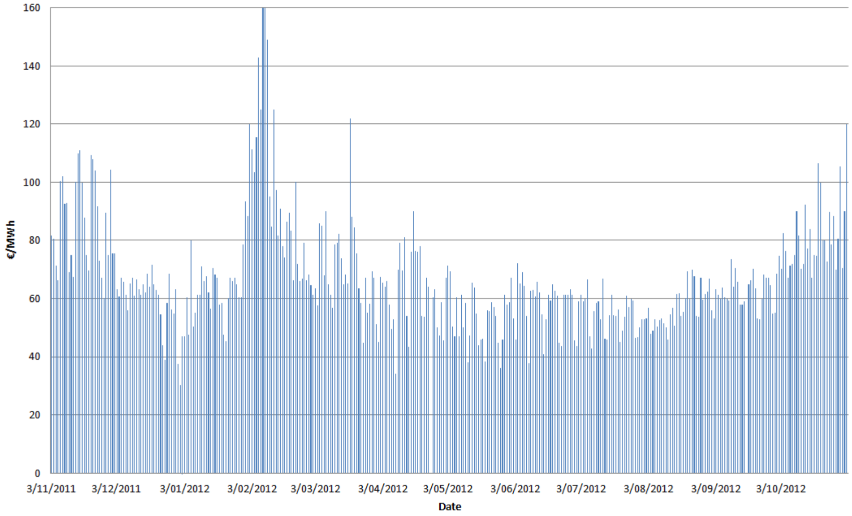

Figure 2.8: Daily Belpex trading price [€/MWh]

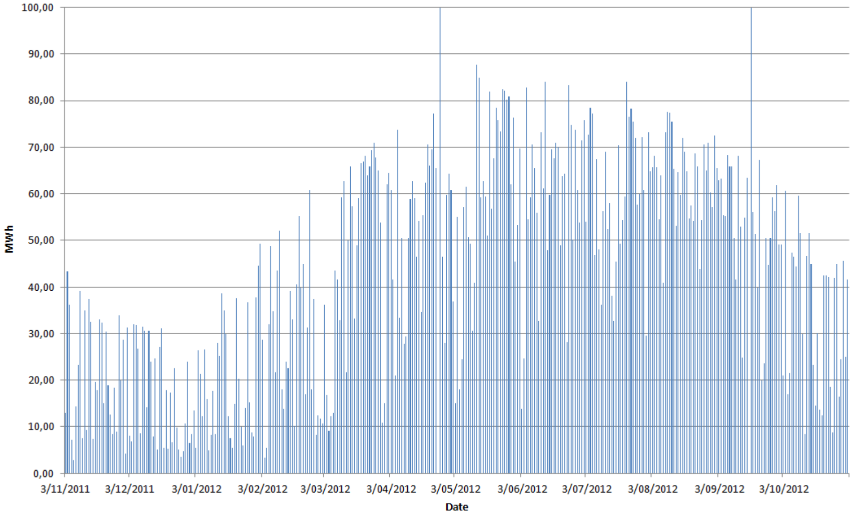

Figure 2.9: Daily PV energy production of a 100 MW PV plant [MWh]

2.7.1 Comparison with fixed contract

Most PV plants operate with a contract which provides a fixed injection fee for the duration of this contract. The average Belpex trading fee during daylight hours for the concerned period amounts to €51.9/MWh. A inquiry among PV plant owners determined a fixed injection fee of €44/MWh is a realistic figure for a 1-year contract in the same period. By integrating the daily energy production (fig. 2.9) and associated daily Belpex prices (fig. 2.8) for every interval in the dataset, a financial yield of €4,833,635 is obtained. On the other hand, the conventional fixed contract would have resulted in a financial yield of €4,366,340 (99,235MWh x €44/MWh), which is €467,295 less than in CVPP operation.

In both cases, this revenue is supplemented by €26,793,180 of Green Power Certificates (GPCs). The sale of generated energy only contributes around 14% of the total revenue generated by this 100MW PV plant, and the difference between fixed contract or CVPP operation only amounts to 1,5%.

However, if the CVPP was built in the second half of 2012, when the reformed Flemish subsidy mechanism was put in effect, GPC revenue would fall to €8,931,060 meaning the share of the sale of energy in the total revenue would rise to 33%. The difference between fixed contract and CVPP operation would now amount to 3,5%. It is clear that the CVPP concept offers some interesting but challenging opportunities.

2.7.2 Prediction errors

The above simulation assumes the ability to predict the day-ahead energy production of the CVPP with 100% accuracy. In reality, several uncertainty factors will influence the exactness of this prediction. The most influential uncertainty factors are meteorological conditions and technical failures.

If the ARP, in this case the CVPP operator, fails to abide to the specified day-ahead energy production, a penalty fee dependent on the deviation has to be paid to the TSO. This penalty is a compensation for the TSO which is responsible for maintaining the grid balance. The penalty price is fixed every 15 minutes and is dependent on grid conditions and the nature of the ARP imbalance (energy production surplus or deficit).

There is also the possibility to use the intraday market to compensate production deficits by buying surpluses from other ARPs. However, this is considered an exception and ARPs can regulatory only use this option very sparsely, e.g. no more than three consecutive days. With this restriction the TSO wants to limit the speculative trading that might otherwise arise on the intraday market.

If an average day-ahead negative prediction error of 10% (the plant performs 10% less than predicted) is assumed, the resulting total penalty fee amounts to €448,833, reducing the CVPP profit to €18,472 compared to fixed contract operation.

If positive prediction errors occur (the plant performs better than predicted) it is assumed that the CVPP operator will make a downward adjustment of the power output of the plant so penalty fees for production surplus will be avoided. This way a CVPP operator can build in a safety margin. This also means the GPC revenue will be lower. In this case the CVPP operator will generate a revenue of €28,464,133 or €2,695,375 less than on a fixed contract.

2.7.3 Increasing profits

From the sections above, it is clear that a purely ‘injection based’ CVPP offers little financial benefits while heavily increasing operator risks. Profits are heavily dependent on the ability to correctly forecast day-ahead energy production and the relative share of energy sales in the total plant revenue.

Another way to increase profits is to not only use the CVPP for energy production but also for intelligent load management. This way, the CVPP operator can safely underestimate the day-ahead energy production of the plant and use any excess energy production to supply the local electrical loads. Grid imbalance and the purchase of energy for the loads is avoided, and GPCs are awarded for the actual total energy production. If the CVPP operator underestimates its day-ahead production by 10% and uses the excess energy to power loads that otherwise would have to purchase energy at Belpex prices, the total revenue becomes €31,658,476 or €499,967 more than on a fixed contract.

Prices in €1000	Fixed contract	CVPP 0% err.	CVPP 10% err.	CVPP 10% marg. 10% error	CVPP 10% err. consump.
Energy sales	€4,366	€4,833	€4,385	€4,350	€4,350
GPC	€26,793	€26,793	€26,793	€24,114	€26,793
Avoided / purchase	/	/	/	/	€515
Total	€31,159	€31,626	€31,178	€28,464	€31,658
Margin	100%	101,5%	100,1%	91,35%	101,6%

Table 2.5: Comparison of different scenarios

2.7.4 Conclusion pure solar CVPP

The preliminary result is that a plain ‘injection based’ CVPP offers little to no financial benefits as opposed to conventional fixed contract operation of PV plants. While revenue generated from selling the generated power at the energy exchange is higher, the impact of difficult-to-predict influencing factors also increases the risk of penalty fees. However, when the ‘injection based’ CVPP is supplemented by manageable electrical loads that can sink excess generated power the economic case for a CVPP becomes more convincing.

Furthermore, as will be discussed in 2.8, the risks are very high if energy is traded based upon bad predictions and the operator is not able to intervene in the production. §2.7 has been published as part of article [11].

2.8 Extended CVPP and CVPP risks

The main purpose of a CVPP will be predictability. As has been seen in previous paragraphs, the electricity market relies on the prediction of production and consumption. The granularity of this predictions should be 15 minutes. Therefore, a CVPP should be able to predict its composite profile with 15 minutes intervals and submit this profile at least the day before the actual exchange. As a CVPP has a lot more information to predict its profile than a normal supplier has, it will use this information to predict its profile with more accuracy than an external supplier could. Therefore, the trading margin an external supplier uses can be reduced or avoided.

Deciding how to bid in the energy markets is not straightforward, as one does not know the price evolution in advance. Different studies [31–33] suggest methods on how to bid in energy markets. The decision on how to bid will depend on the risk mitigation policy of the CVPP.

Next, the CVPP should take measures in real time to follow the submitted load. This can be implemented via different measures, e.g. demand side management, backup generators or curtailment of production or load. As has been explained in [13], the possibility exists to deliberately deviate from the submitted profile, but the risk is high. The imbalance market is very volatile and very difficult to predict, so the main purpose should be to minimise the deviation of the submitted profile.

The third benefit of a CVPP is in the increased awareness of the electricity market dynamics. As the CVPP has knowledge of both the process and the market, the process could be adjusted or planned to take advantage of these dynamics. High loads could be (re)scheduled to low price periods and high exports can be timed to sell the energy at maximum market price. This can increase the profitability of the overall process. As will be detailed in chapter 4, this could be especially useful for processes with a direct link between thermal and electrical energy, e.g. heat pumps and co-generation units. In [34], it is for example concluded that an optimal bidding strategy of a CHP can result in a 6% increase of revenue generated.

2.8.1 Problem statement

As already mentioned in §2.7, installed PV power capacity rose quickly during the last decade. In Flanders (Belgium), the abundant subsidies where a major driver for this expansion. However, the government reduced the support rapidly in the 2012-2013 period. As mentioned in [11], the former subsidies largely surpassed the commodity revenues. As these subsidies are now brought to a more modest level, the balance with the commodity revenue is restored. Although PV power is now economically viable and competitive with traditional electricity generation, wholesale market participation is still not evident.

The first barrier to wholesale market participation encountered by solar power is the relatively low predictability. In [35], different PV forecasting methods are

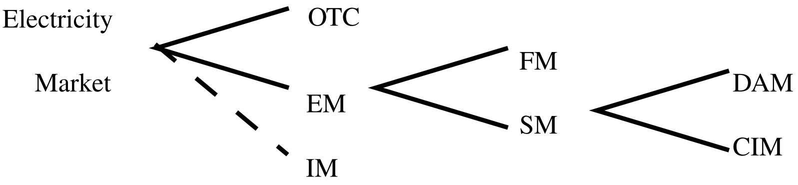

Figure 2.10: Energy trading markets

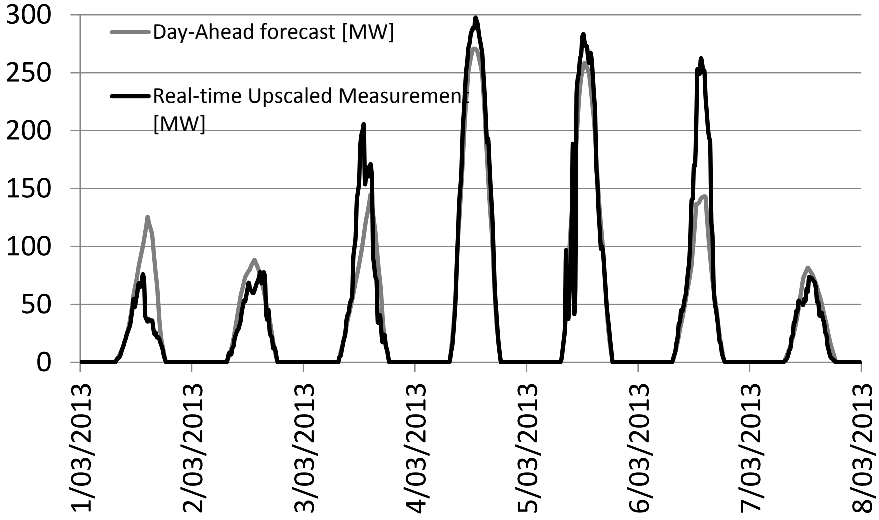

Figure 2.11: Excerpt of day ahead prediction and cumulative up-scaled measurement

presented. Depending on the time horizon and the weather (mostly sunny or cloudy), different forecasting methods are best. Values for the root mean square error of 17% at one hour, to 22% for three days for mostly clear weather are given. For mostly cloudy weather, they range from 33% to 44%. As shown in Fig. 2.10, the energy markets are forward markets. As such, the output power of a generator should be predicted. As PV power is dependant on atmospheric circumstances, this becomes difficult. In Fig. 2.11, an excerpt of data provided by Elia [36], the Belgium transmission system operator, is shown. This chart shows the difference of the predicted day ahead power and the measured power of PV installations in the Belgian province of West-Flanders.

2.8.2 Timescale of CVPP operations

As the main objective of a CVPP is financial optimisation, energy should be bought/sold at the best possible price. As renewable energy production, and especially solar power, is hard to predict on longer time scales, the CVPP should try to sell the energy as close as possible to the actual production time to reduce the

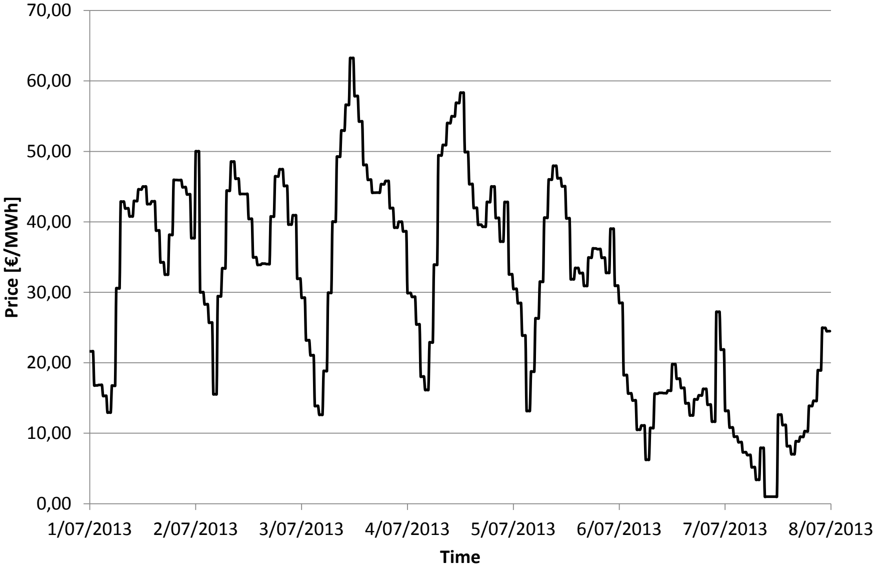

Figure 2.12: Time series of electricity price on Belpex

needed prediction horizon. As has been clarified in [11], the Day Ahead Market (DAM) is the best option in Belgium. This requires traders to submit their position before noon the day before delivery. But as delivery takes place through the Elia Day Ahead Hub, the trader should also be granted grid access from Elia (TSO). The TSO requires the BRP to nominate the required power (injection or off-take) on a fifteen minutes basis before 14h the day before delivery. This requires traders to have accurate fifteen minute average power predictions.

In the day ahead market, a price is formed for every hour of the next day. This price is dependant on the submitted positions (volumes and prices) of suppliers and customers. As can be seen in Fig. 2.12, this is highly volatile with prices ranging from €10/MWh to €120/MWh. Price differences of €60/MWh within one day are no exceptions.

Once market positions are known, the traded volumes should be nominated to the TSO. The TSO will check if the balance between production and consumption will be met. The TSO (Elia in Belgium) will check on a 15 minute basis if the nominations are effectively followed. If a BRP has an imbalance compared to its nomination, an imbalance fine will be applied.

2.8.3 Market operation

As described in section 2.2.3, the market is a day ahead market. As such, the volumes are traded the day before actual delivery. Before 12h (in Belgium, rules of Belpex), a BRP needs to submit his position (price and volume) for every quarter of the next day (from 0h00 till 23h59). As a result, the position is a prediction of production and consumption 12-36 hour before actual delivery. Furthermore, after market clearing, the BRP needs to nominate its power ratings to the TSO for every 15 minutes. If the actual power exchanged by the BRP is different to this nominated power, the need to pay a fine. This fine is determined by the TSO according to the price paid for regulation services, the direction of the imbalance of the BRP and the system imbalance. Table 2.6 depicts the possible combinations. The basis for this tariffs are the marginal downward price (MDP) and the marginal incremental price (MIP). These reference prices will be further explained in §3.4.3.2. The factor α is utilised to apply an extra fee if the total system imbalance is larger than 140MW. This will be further explained in §3.4.3.2.

	Control zone imbalance	
	Too much power	Not enough power
ARP +	TSO pays BRP MDP -α	TSO pays BRP MIP
ARP -	BRP pays TSO MDP	BRP pays TSO MIP+α

Table 2.6: Imbalance fee

As a result, BRPs need to predict their power (production or consumption) and maintain this prediction on the end of every fifteen minutes. For solar power, this is not easily feasible. Weather predictions in this time horizon are not accurate enough to predict the output power accurately to evade imbalance fines. So a VPP would need to adjust the total real time power to match the day ahead predictions. Obviously, the PV power can not be adjusted upwards as it is dependant on the momentary solar irradiation. Downward adjustment is also not desirable as clean primary energy is lost and thus also green power certificates.

2.8.4 VPP Role

Individual solar installations are too small to trade their energy in the markets. Power needs to be rounded to 0.1MW, which means a large installation is needed to be able to trade. In this section, it is suggested to aggregate the power of several solar plants together up to a volume of 100MW installed power, this is about the total installed power in the province West-Flanders (Belgium) and less than 10% of total power in Flanders as a whole. This aggregation will ensure enough installed capacity so the sum can be traded on the spot market.

2.8.5 Assessment

2.8.5.1 Average market price

At first, the average market price in Belgium is compared. As a base case, one needs to estimate the price obtained by bilateral contracts. An enquiry among PV owners in Belgium revealed that an average price of €40/MWh - €45/MWh can be obtained. In this paragraph, we will compare to a fixed price of the lowest price of €40/MWh. As can be seen in Fig. 2.13, the average price obtained on the Belgian day-ahead market Belpex is slightly higher. In 2012, the average price was €46.98/MWh. As this average also incorporates off-peak hours and off-peak hours have normally lower prices, the average price during sun hours will be higher. Next to this, also seasonality needs to be taken into account. During summer months, the average price is lower, but the largest production is during this same time frame. Table 2.7 shows the average price for every month and the average energy production for these months.

Month	Belpex DAM price [€/MWh]	Total solar energy [MWh]
Dec '12	50,12	1832
Jan '13	53,91	1582
Feb '13	55,56	4112
Mar '13	60,42	7346
Apr '13	57,50	12676
May '13	49,73	12427
June '13	33,29	13707
July '13	34,65	15797
Aug '13	37,68	13667
Sept '13	45,42	9806
Oct '13	45,04	6108
Nov '13	49,17	2633

Table 2.7: Energy yield and DAM price

As a preliminary conclusion, one could state it would be beneficial to trade solar energy on the day-ahead market. However, this would mean a perfect production would be necessary to avoid extra risks of imbalance. Also, next to the revenue of the energy itself, also a large share of revenue comes from the green power certificates. For new installations in Flanders, this is about €90/MWh. Although this is much lower than the €450/MWh of older installations, this still has a significant impact on the relative gain. As a result, on average, only a couple of percent could be gained in total by trading on the day ahead market.

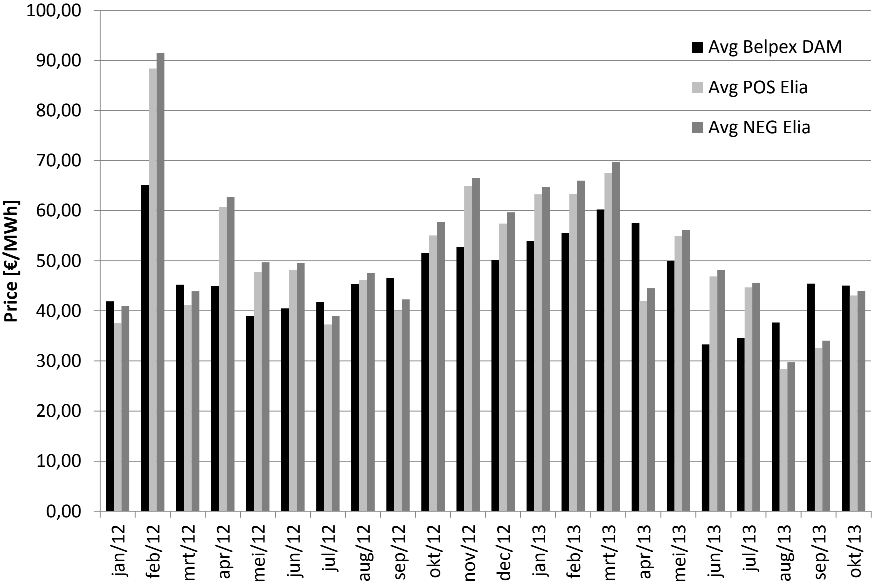

Figure 2.13: Monthly average DAM, POS and NEG prices in Belgium

2.8.5.2 Imbalance settlement

As previously mentioned, not only the DAM price should be taken into account. As positions in the DAM should be nominated 12-36h before delivery, this relies on prediction of solar energy. In Fig. 2.11, an excerpt of day ahead solar prediction for the province of West-Flanders and the up-scaled measurement for the same period are shown. This illustrates that there will always be an imbalance between prediction of solar energy and the actual output. However, due to the relatively large region taken into account, short fluctuations are already smoothed out.

As described in §2.8.3, no direct imbalance fine applies to mismatch of energy sold day ahead on the market applies. However, a ARPs obliged to nominate its traded volume to the TSO, and the market operator will counter-nominate. As a result, the TSO can (and will) settle imbalances between predicted (and sold) energy and actual production. However, a ARP will normally receive money for a positive imbalance (more produced/less consumed than predicted), and needs to pay the TSO for a negative imbalance (less produced / more consumed than predicted). Next to the average DAM prices, Fig. 2.13 shows the average imbalance prices. As can be seen, for most months (January 2012 till October 2013), the average imbalance prices are higher than the average DAM prices. As both the positive imbalance price POS and the negative imbalance price NEG are either together higher or lower than the DAM prices, this could possibly encourage speculation. The value of POS and NEG is dependant on the combined states of the ARP and the control zone. The four cases are explained in table 2.6. If an ARP has

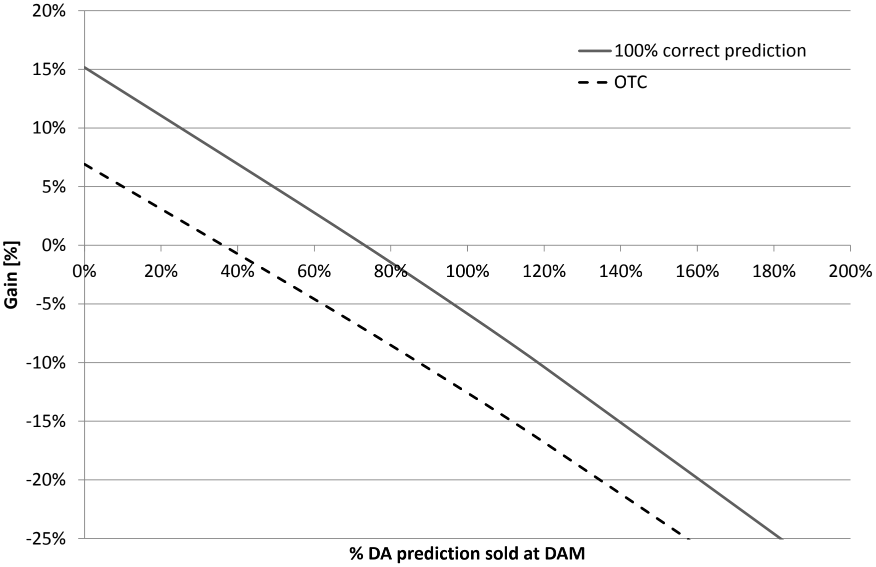

Figure 2.14: Relative gain of partially selling predicted power day ahead (2013/07)

an energy surplus, the POS price will be received from the TSO. If the ARP has an energy shortage during the interval, the NEG price should be paid to the TSO. It should be remarked that both these prices can be negative. This could result in getting paid for consuming energy or the ARP needs to pay to sell its energy.

If the average POS price is expected to be higher than the average DAM price, a ARP could possibly gamble and sell no solar energy day ahead. As no solar power is curtailed, this would result in a positive imbalance with magnitude of the produced solar power. The gain has been calculated (post factum) for July 2013. The average DAM price for that month was €34.61/MWh. Compared to a low fixed contract price of €40/MWh, this would result in a loss of revenue. However, the POS imbalance price was €44.7/MWh, resulting in a positive net result compared to the fixed price. So if no energy was nominated, the ARP could still benefit. Fig. 2.14 shows the possible relative gain (or loss) if only a percentage of the predicted energy is sold day ahead. The bottom line shows the relative gain compared to over the counter (fixed price) profit, and the upper line the benefit compared to a 100% perfect day ahead prediction. So in this situation, it would be beneficial to nominate no production and deliberately engineer a positive imbalance.

In March 2013, the balance between the average POS and NEG imbalance price and the average DAM price was different. As can be seen in Fig. 2.13, the month average DAM price was €60/MWh. The average POS imbalance price was only €44.70/MWh. Applying the same strategy as above would so result in a relative loss compared to perfect prediction. More importantly in this situation, the average NEG imbalance price was also lower than the average DAM price.

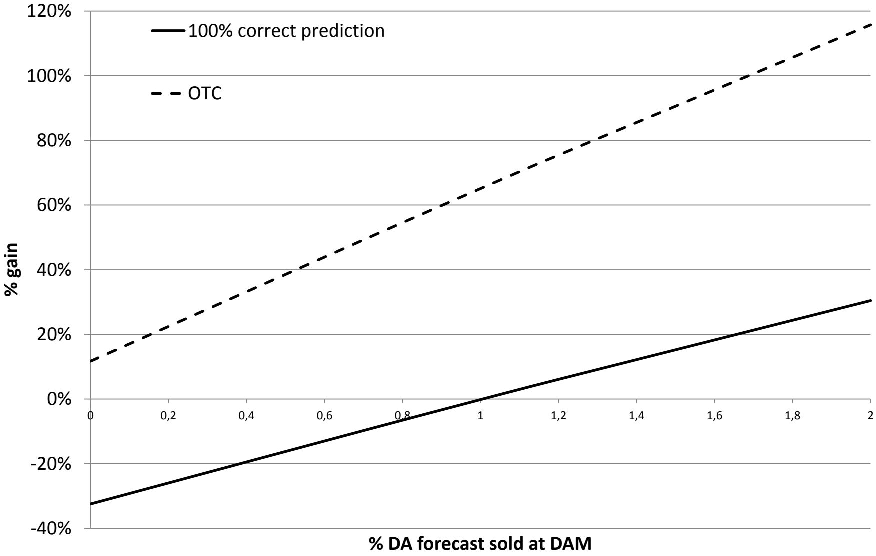

Figure 2.15: Relative gain of partially selling predicted power day ahead (2013/03)

As selling too much is only penalised by the TSO, this could lead to a different speculation, namely selling more than expected. As can be seen in Fig. 2.15, selling more than predicted power would still result in a gain. This seems somewhat contradictory to the purpose of the imbalance penalty system.

2.8.6 Challenges and risks

As illustrated in §2.8.5, it could be beneficial to sell solar power on the wholesale market. However, this would require some sort of VPP to be installed, as real time production measurement is necessary. A ARP combined with a supplier could possibly take this role. However, the risks are very high. As Fig. 2.14 and Fig. 2.15 show, the possible gains are large, but so are the possible losses. All above calculations are made post factum. As no one can reliably predict the prices for the day ahead market, the positive and negative imbalance prices, the risks are high. Taking the wrong position and nominating too much can yield significant losses or gain.

A second risk is the viability of this system on the long run. As the goal of the imbalance prices is to be a deterrent to gambling on electricity, it is questionable how long the TSOs, the regulation authorities and the government would tolerate this. It should be stressed that deliberately nominating large imbalances for financial profit pose a great risk towards the stability of the grid and hence this should be discouraged. Correct nominations are important for the TSO to determine safety margins in the transmission system and hence the stability of the system as a whole.

2.8.7 Conclusion solar CVPP risks

As a conclusion, although direct participation of RES, especially solar energy, in the wholesale electricity market could possibly lead to higher revenues for PV owners in Flanders (Belgium), this is not without risk. Depending on the trading strategy, large gains or losses are possible. As this depends on the outcome of a daily settled, complex market, this is of high risk. Also, deliberately engineering imbalances is illegal and should be discouraged as the stability of the power system is of extremely high economic importance. This research presented above discovered a loophole in the imbalance settlement system. Communication with the transmission system operator resulted in increased awareness of this potential problem.

The work in §2.8 has been published as paper [13].

2.9 Conclusions Commercial VPP

A commercial VPP is a very limited solution. It is currently being used to sell or buy smaller volumes in the wholesale markets at a more flexible cost, but will increase the risk due to the market volatility and imbalance cost. If the CVPP is only used as a vehicle to trade energy in the wholesale market, the benefit to be expected is minute as has been demonstrated in §2.7. Proper use of a CVPP would require to predict the energy profile and the market situation. Actions could then be taken to change the expected profile in order to profit from the market dynamics.

A CVPP will need to predict the total portfolio and decide which market instrument is most suited to trade this profile. Essentially, this is what a general supplier does. However, a CVPP will probably be able to predict the profile much more accurate due to the availability of plant data and can hence submit a profile which will be closer to the actual consumption. However, as a supplier has the opportunity to spread the risk of its portfolio, a CVPP will need to manage the risks itself. Real time profile adjustment becomes possible and therefore the risk of mismatch between the predicted and actual profile can be managed.

In this chapter, first the different energy markets have been discussed. This provides an introduction to the operational environment of a commercial VPP. Commercial VPPs are required to adapt the scale of distributed resources to the scale of the existing electricity markets. As such, they provide a tool to further implement the energy market liberalisation as they enable a level playing field. Smaller resources have no reasonable access to the energy markets as the market is not designed for such small power and energy levels.

Next, it was investigated if a large scale solar power VPP could benefit from clustering and trading its energy to the market. At the time of publication, it was shown that the effort was not up to the potential gain due to the large impact of the green power certificates. But also without the GPCs, the risk is quite high as no corrective means are possible.

The risk of trading on wholesale markets was further investigated in §2.8. There the risks of selling energy on the wholesale markets under uncertain situations was investigated. It was proven that under certain circumstances, large gains or losses are possible. Especially in the case of the strategic reserve which was introduced during this research. In case that the activation of the strategic reserve has high probability, deliberately nominating wrong positions to the market could lead to enormous profits. However, a wrong decision can also cost a lot of money. A remark should be placed on this: the proposed strategy is illegal as it circumvents the obligation to correctly predict ones market position. Deliberately nominating wrong positions is not allowed by the transmission system regulator due to safety reasons. However, this research discovered a vulnerability of the system.

This research has been applied to the Flanders region in Belgium. Many aspects of market operation are very specific to the location. This should however not limit the applicability of CVPPs in general. Similar systems exist all over Europe, and many markets are converging. The legal framework within the West-European grid is slowly being harmonised, further promoting integration of the separate market regions.

The main challenge for CVPPs in general is predicting a suitable power profile. In combination with flexible capacity, optimal use can be made of the market dynamics. Changing the production or consumption profile of a cluster can result in significant margins on the traded energy. This is applicable to the whole interconnected region as the markets are effectively coupled, despite local differences in the legal framework.

3

Technical Virtual Power Plant

3.1 Introduction

Technical VPP's are designed to provide a better physical integration of DER into the grid. These DER should ideally be a mix of (renewable) energy production units, flexible consumers and possible storage. The VPP receives production targets from the grid operators or other ARPs, depending on the grid state. The VPP translates these objectives to the different units that it is composed of. With a Technical Virtual Power Plant (TVPP), the grid operators can control the physical output of the DER units. So if e.g. congestion on a transmission line occurs, the output of the dispersed resources affecting the line can be gradually limited. Not only congestion management is possible with a TVPP, also other ancillary services like reactive power / voltage control, secondary reserve or fault ride-through and system restoration assistance can be delivered to the grid. With local intelligence within the DER controller, even primary reserves could be delivered. Delivering balancing services to the grid can be a profitable business. This is estimated from €50/kW flex capacity today to €75/kW flex capacity by 2020 [37]. In this regard, CVPP and TVPP are tightly coupled. The difference between a TVPP and a CVPP within this dissertation is considered as whether the VPP takes control parameters from an external entity or not. A CVPP will only optimise internally, based on internal financial optimisation parameters, whereas a TVPP will also react to requests from the grid operator or a different operator.

The VPP can distribute the targets in different ways to the individual participants. This can be based on physical constraints such as congestion or voltage profile. Due to these physical goals a TVPP is more geographical limited. Eligible units are so dependent on the type of service delivered. Voltage control or congestion management are for example more limiting than frequency control. A TVPP can also be dynamical reconfigured due to network switching, as units become part of a different part of the grid structure.

Most of this work is based on the Belgian power system. Hence, the data of Elia and Belpex, the Belgian transmission system operator and market operator are used. However, as many power systems are organised in a similar way, the results are applicable to other systems as well. Also, a lot of this research is based on solar energy. However, wind was also investigated, but to a lesser degree. Similar results could be obtained however.

In this chapter, first an overview of ancillary services will be presented (§3.3). Next, in §3.5, a link is made to microgrids. The chapter continues with a section on storage in §3.6.4. Then a combination is made of two distinct services: congestion management and frequency regulation in §3.7. Next a section (3.7) is devoted to the combination of balancing services provided by PV energy. The last part of this chapter (§3.9)discusses the residential potential of load shedding as an emergency measure. Finally, in §3.10, a conclusion on TVPPs is drawn.

3.2 Technical Virtual Power Plants

As has already been defined in §2.1, a VPP is defined as a flexible representation of a portfolio of Distributed Energy Resources (DER) that can be used to make contracts in wholesale markets and to offer services to system operators [37]. In §2.1, the CVPP has been described as an economical concept. A Technical Virtual Power Plant is a control concept to manage many small electrical units in order to deliver technical services.

Many small units are combined by software, hence virtually, into a controllable entity (power plant). From the grid operator's perspective, the VPP behaves as a single unit. The VPP aggregates all the information from the different small entities to provide a single 'image' of the DER state in its operating region. Likewise, the VPP translates the grid operators requests into commands for the individual participants. The VPP is an intermediate level between the grid operators and the DER units. It facilitates the interaction between all actors and enables the grid operators to have (some) control over the instantaneous DER power [38].

A TVPP is optimised to deliver technical services to the grid, e.g. congestion management (§3.3.1), power flow control (§3.3.2), voltage control (§3.3.3), frequency control (§3.4.1), fault ride through capability (§3.3.4) or system restoration (black start) (§3.3.5). CVPPs are financial instruments to sell the energy of the DER (§3.3.6). Ideally, a VPP is a combination of the two functionalities.

Different resources are available to deliver these services. DER can be about anything, from CHPs, solar panels, wind turbines, electric vehicles...All these appliances have their own particularities. Some are always available, but require some time to deliver their output, e.g. CHPs. Others are dependant on the weather but can react very fast, e.g. solar panels. Others are also very dynamic, but are somewhat limited due to mechanical inertia, e.g. wind turbines. By combining the dynamic behaviour of the slow(er) (thermal sources) and the high dynamics of power-electronic converter coupled RES in a TVPP, cooperation can result in the ability to deliver fast reaction times to deliver frequency regulation services. The low internal energy storage of the RES, and hence the dependence on availability of the primary energy source, can be compensated for by the large capacity thermal sources. The primary heat source can, however, be decoupled from electricity production by shifting thermal load from an energy recovery turbine to a thermal grid. Hence, the flexibility added to waste heat recovery systems in combination with RES based electricity can be managed together in a VPP to provide services to the grid. However, in chapter 4, the combination of thermal and electrical energy will be further detailed.

3.3 Ancillary services for the electrical grid

In order to obtain a stable electrical system operation with a large penetration level of RES, not only the power equilibrium should be maintained. Additional grid services are equally necessary to provide a reliable power delivery to the end customers [39]. In this section, different services a VPP could offer to system operators and other stakeholders are described. Through §3.3.1 to §3.3.5, different technical services which can be provided by a VPP are presented. In §3.3.6, it is described how a VPP can assist in wholesale market participation and earn additional revenues for the participants. Section 3.4 will then further cover frequency management services.

3.3.1 Congestion management

System congestion can be considered on different levels. The most considered congestion is on the transformer and/or line level. When the generated power minus local consumption is larger than the rated transformer and/or line capacity, the protection will trip. To prevent this, grid operators do not allow any installed capacity on an access point more than the annual minimum consumption plus the rated transformer and/or line capacity. As the coincidence factor of renewables is seldom equal to one, the maximum share of RES connected to the grid is significantly limited. This is a very conservative approach, but as long as no reliable alternative exists, the grid operators have no choice. Hence, only a few hours a year of insufficient grid capacity can prevent the installation of a larger share of renewables in the grid. The ATC used in these calculations by most system operators considers worst case scenarios. For many transformers and lines, a fixed capacity is allocated. More critical connections are assessed on a seasonal basis.

On highly loaded connections, permanent monitoring is installed. As this is a very costly option, the use is not very widely spread.

Another type of congestion induced by uncontrolled RES is system-wide congestion. If generated capacity on system level is larger than total demand, grid-wide congestion will follow. In [40], some scenarios are presented with low load and high RES capacity. If no intervention is possible, this will also result in system congestion and subsequently system instability. In May 2012, this happened on a small scale in the Belgian power system. Due to prediction errors of wind and solar capacity, excess power had to be sold to France at negative price levels. If the neighboring countries were not able to absorb the energy, a (rolling) black-out in the Belgian power system would have occurred. However, as the export capacity was marginally sufficient, no actual measures had to be taken to curtail some production.

As has been defined in §3.2, a VPP is a dynamic (software) collection of distributed resources. Therefore, a VPP can be reconfigured as required. If a certain area is affected by congestion, the VPP can reconfigure itself in order to send different commands to resources within the affected area compared to the resources which are located outside the affected area. This has been proposed in [15] and is further presented in §3.7.

3.3.2 Power flow control

To be able to plan the physical power flows and allocate the transmission and generation capacity, the users of the transmission system need to nominate their expected capacity to the transmission system operator (TSO). In case of Belgium, balance responsible parties (BRPs) need to nominate their planned transmission capacity before 14h00 in case of consumption and 15h00 in case of power delivery [23], the day before the actual power exchange. Other system operators use similar deadlines. The capacity needs to be nominated on a quarterly hour basis. A mismatch between nominated and physically transfered volume will result in an extra cost, the imbalance tariff [41]. As a result, precise planning of the consumed or delivered power is of high economic importance to BRPs. Without DER, only the consumption need to be estimated. But with the continuously increasing share of DER and especially RES, the estimation of the transfer volume becomes much harder and prone to errors. A VPP provides controllability to the BRP and can hence reduce penalty cost. Adding flexibility by integrating flexible waste heat recuperation in the equation provides a potential cost saving for the BRPs. Matching power production and consumption is basically a task for a CVPP, as has been explained in §2.9.

3.3.3 Voltage control / Reactive power

The voltage of a transmission system fluctuates as a function of the network state [42], e.g. grid topology, generation, load, transmission and transformer loading. The voltage stability on the high voltage grid is ensured by reactive power injection by different facilities. On the transition to and within the distribution grid, on-load tap changing transformers can also be used to manage the voltage profile. Reactive power injection can be done in a generation facility by changing the excitation of synchronous generators or capacitors. In a transmission/distribution substation static var compensators can be used. But also DER units can deliver or consume reactive power to maintain voltage stability. Due to the increasing share of decentralised power in the electrical system, several TSOs require wind farms to control the reactive power at the Point of Common Coupling (PCC) [43]. By combining wind turbines in wind farm clusters, wind turbines are able to participate in grid operation [44]. This can be regarded as a VPP, but still suffers from using only one primary energy source.

By providing a coordinated control structure, also thermal generators can deliver voltage control. If the generator is equipped with a anchor winding or power electronic inverter, the reactive power can be controlled. This can be very interesting to distribution grid operators, as this could provide power flow control in their grids.

3.3.4 Fault ride-through and system stability

Only a few years ago, ENTSO-E (European Network of Transmission System Operators for Electricity) grid codes obliged DER installations to disconnect from the grid in case of any disturbance. With an increasing share of renewables, this is no longer acceptable. Disconnection of e.g. a large wind farm, CHP system, solar park due to a transient error can result in a large power swing with possible fatal grid consequences [45]. As a result, fault ride-through capability for wind turbines is mandatory. Different grid codes require certain installations like wind farms to withstand short voltage drops and provide Fault Ride-Through Capability (FRTC) [40, 43]. FRTC is a very demanding requirement on equipment. To deliver the necessary active, reactive and short circuit power in the case of a grid fault, the equipment must withstand large stresses [46]. Future grid codes may even demand Zero-Voltage-Ride-Through for large DER installations, further increasing the short circuit capacity of the grid. In [47], the influence of adding storage to large scale PV systems on grid damping and system stability has been investigated. Certain improvements have been found, but more research is needed to make general conclusions.

Due to the varying nature of RES, also the short circuit capacity of the grid can vary. Dynamic adjustment of the FRTC of the VPP members could be a service delivered by the VPP to the grid operators. This capability can reduce the nec-

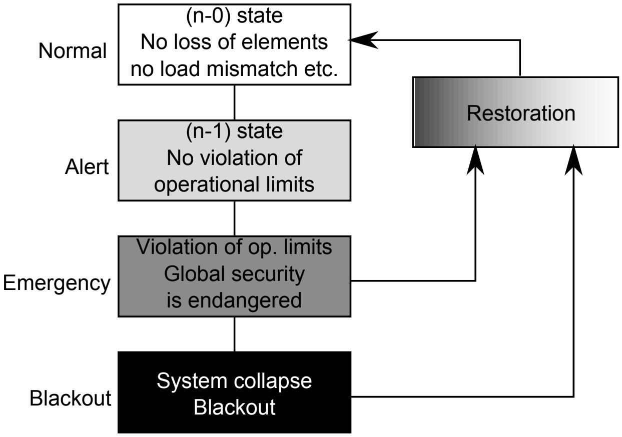

Figure 3.1: System states

essary breaker capacity of protection devices while maintaining minimum short circuit power to reliably trip the breaker in case of a prolonged fault.

3.3.5 Black start

In [48], the recovery process after a major incident is described. System states and the recovery process are depicted in Fig. 3.1. To restore system operation concerning more than one TSO, two kinds of system leaders are needed: the frequency leader(s) and the resynchronisation leader. As temporary controlled frequency deviations are needed to restore the system, uncontrolled behaviour of DER can impede the process.

After a complete system shut-down, a blackout, even without DER, it is hard to restore the grid. As there is no reference signal nor power to support controls, pumps or even communications, recovering from a black-out is a delicate procedure. Historically, only a few generation units are capable of starting up without a strong grid. From those, the grid is restored and reconnected gradually. Reconnecting separate islands after a blackout or grid separation requires delicate and frequent adjustments of the frequency in the system. DG units can hinder these actions if they try to reconnect as after a local grid fault. Coordinating major DG units after a black-out can help to stabilise the grid while the system is being rebuilt.

Because intelligent DER with an active P/f droop control will assist the grid to maintain the nominal frequency during normal operation, they will resist purposely applied frequency deviations and hence counteract phase alignment between zones. As a VPP can control the active and reactive setpoint and the droop factor of the DER units, it can provide a more easy system and hence faster system restoration process.

3.3.5.1 Control structure

After a blackout, nothing should be taken for granted. Fuel supply can be interrupted and communication networks could be down. Most communication networks have some sort of backup power supply. However, after a major blackout, risks are real that these supplies are not enough to survive to remain operational. Therefore, only dedicated communication channels can guarantee the control center is able to communicate with the remote resource.

3.3.5.2 Recommended resources

As waste heat recovery units are often quite large compared to other DER units, they are very appealing to TSOs to provide system restoration capabilities. They can provide a stable output to build the grid upon. However, this requires these units to be manageable. Clustering them into a VPP can provide the necessary communication and control abilities needed to deliver this service.

3.3.6 Wholesale market participation

As Virtual Power Plants represent a large amount of DER, it becomes easier to have wholesale market access. As a VPP is constituted of many (different) resources, the reliability and availability is larger than that of one single resource. This is a necessary requirement for wholesale market participation. Load aggregators are therefore potential users of VPPs as this will facilitate their operations and enable them to deliver also technical services to the grid operators, which are also highly valued but require high reliability and availability. Due to the portfolio effect and the larger available power, a VPP enables DER to deliver these services also and hence gain access to this revenues. This has been discussed in chapter 2.

3.4 Power management

As the European grid is one synchronous zone, the frequency is the same all over this system. Many generators actively monitor the frequency to determine the actual power balance within the grid as the frequency is a reliable indicator of the instantaneous active power balance. If more electrical energy is consumed compared to the injection, kinetic energy will be converted to electrical energy. Hence the frequency will drop. In the case of more production than consumption, the excess electrical energy will be converted to mechanical (rotational) energy and hence the frequency will rise.

All the European transmission system operators cooperate to maintain a frequency of 50 Hz. All connected production units larger than 25 MW need to reserve a power control band in order to be able to respond to frequency deviations [49].

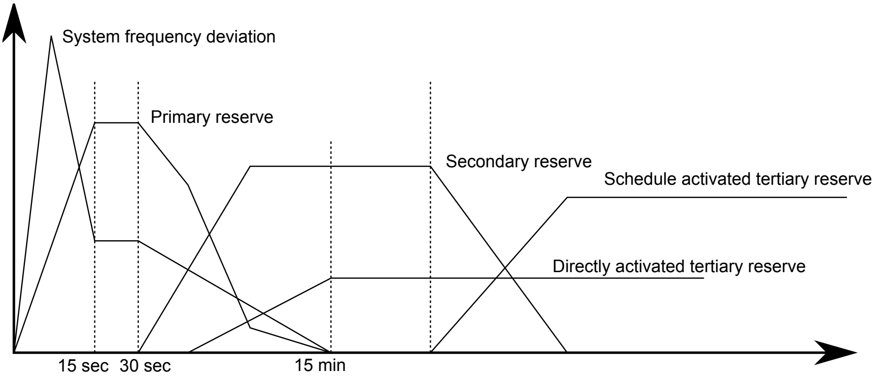

Figure 3.2: Principle frequency deviation and subsequent activation of reserves

3.4.1 Frequency control

The frequency control is divided in several levels. The primary control is in place to limit the deviation of the frequency from the nominal value. The secondary control then takes over in order to restore the nominal value. Tertiary reserve is used to free the secondary reserves.

In Fig.3.2 [50], the timing sequence for the activation of these reserves is shown. In [50], primary reserve is stated to be a joint action of all involved parties following a frequency deviation within seconds. This is to maintain a balance between generation and consumption and to prevent the system frequency from drifting away from its nominal frequency. This primary reserve is activated within seconds of a measured deviation.

Secondary control replaces primary control over minutes and is put into action by the TSOs. The secondary control will restore the primary capacity after its activation. Whereas primary control is activated all over the synchronous zone, secondary control will only be activated in the control zone which caused the deviation.

As shown in Fig.3.2, secondary reserve is activated between tens of seconds up to 15 min after an incident and should be maintained until tertiary reserve can take over or the balance is otherwise restored. Secondary control makes use of a centrally and continuously operated automatic generation control to modify active power setpoints. Adequate secondary reserve depends on generation reserve supplied by generation companies to the TSOs.

The contracting generation company receives payments from the TSO to provide the reserve as well as for activating the reserve. The provision of secondary reserve is expressed in €/MW/hour availability. For activation of reserve, the bids are submitted and selected by financial merit order. The bids must be at least 5 MW per production unit. Prices are positive for upward activation and negative for downward activation [51].

Tertiary reserve is mainly used to replace secondary reserve. It can be manually activated by the TSO in the follow up of an incident. Schedule activated control reserve is operated according a predetermined time frame.

3.4.2 Primary / frequency containment reserve

3.4.2.1 Introduction

Primary or Frequency Containment Reserve (FCR) is used to counteract and stabilise deviations from the nominal frequency [52]. 50% of the contracted power should be activated within 15 seconds and 100% within 30 seconds following the deviation. Full power should be maintained for at least 15 minutes. Contracted reserve should be available continuously.

Due to the relatively small amount of DER capacity in Europe at this moment, the traditional reserve capacity is sufficient to support consumption and production fluctuations. Traditionally, small distributed resources do not contribute to the power management. However, studies [53] expect that a 20% DER share is the limit with current capacity reserves. Currently, a large part of the DER consists of RES like wind turbines and solar energy.

However, the target of Europe is to provide at least 20% of energy by these RES. As the power output of RES is often quite variable, the instantaneous share of RES in the total grid power will be significantly higher. As a result, traditional resources (e.g. combined cycle gas turbines) will be less frequently needed to deliver energy and therefore be closed. These traditional power plants are however the main sources of frequency regulation services. This implies that DER and especially RES will need to provide reserve capacity themselves as the traditional resources are phased out. In [54], Elia expresses this concern as many of the traditional resources will be phased out after the studied time period.

3.4.2.2 Control structure

As defined in §3.4.2.1, the primary reserve is activated automatically based on frequency measurements. Therefore, the units need a local frequency measurement. Communication is only needed to adapt the gain of the control loop and post factum signalling of activation. The implications for the control structure are therefore relatively modest. A reliable frequency measurement is needed, but is easily achieved with standard equipment.

The needed communication infrastructure is also not critical, as no fast signalling is required. Network connection is only required to update control parameters and verify activation. This implies a short (seconds to minutes) communication interruption or delay is acceptable to ensure reliable functioning of the service.

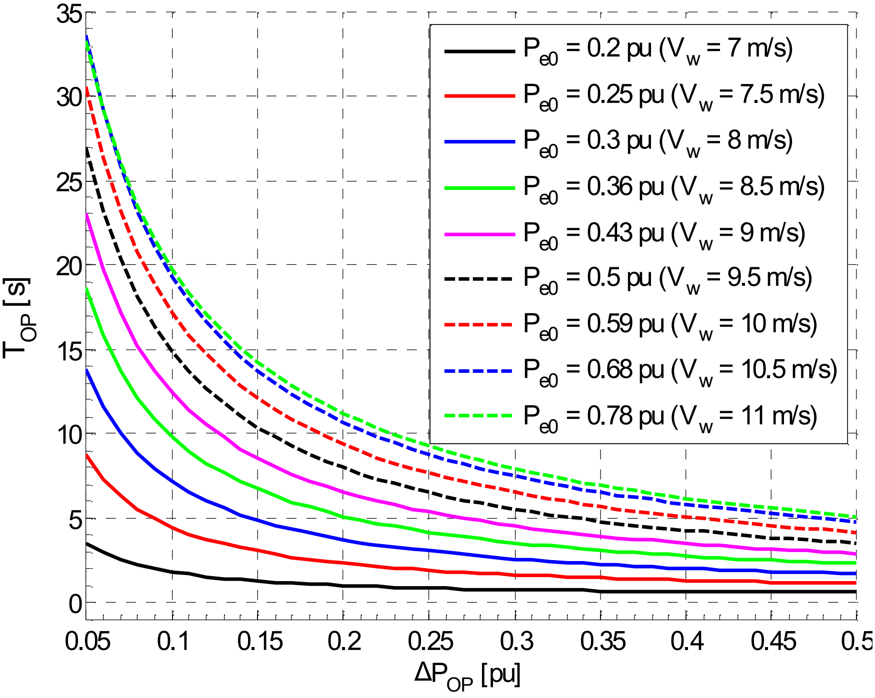

Figure 3.3: Maximum time a wind turbine can produce more than the available wind power [55]

3.4.2.3 Recommended resources

Wind turbines can deliver more than the available wind power for a short period by converting kinetic energy to electricity [55]. This temporarily power boost converts the kinetic energy within the rotor of a turbine to electrical energy, slowing down the turbine by doing this. This short burst of extra energy can be used to ease the reaction time of other DER to deliver the required power within the desired time interval. The time this overproduction can be maintained is shown in Fig. 3.3. This is based on an immediate activation of the overproduction and a significant immediate drop in production after the required period. However, the VPP can anticipate this drop and notify other resources to react and replace the wind turbines energy output after several seconds. This reduces the stress on the communication system to react very fast to frequency deviations.

3.4.2.4 Remuneration

In Belgium, FCR is remunerated with a provision fee. There is no extra fee for activation [52]. The exact value is not publicly known and varies depending on the source of information.

3.4.3 Secondary / frequency restoration reserve

Secondary control replaces primary control over minutes and is put into action by the TSO. This is activated within 30 seconds and should be maintaining its setpoint for at least 15 minutes [51]. Secondary control makes use of a centrally and continuously operated automatic generation control to modify active power setpoints. Adequate secondary reserve depends on generation reserve supplied by generation companies to the TSOs.

3.4.3.1 Control structure

Secondary restoration reserve activation is calculated by the TSO every 10 seconds. This new setpoint is communicated to each participant. The communication infrastructure should therefore be able to reach most of the participants within this timeframe.

3.4.3.2 Remuneration and cost

Secondary reserve is a much more complex product. There are multiple prices which affect secondary reserve: as a reserve user after an imbalance and as an reserve provider.

Prices as access responsible party

As has been covered in table 2.6 in §2.8.3, four possible situations exists. The control zone can require downward regulation or upward regulation and the ARP can have too much energy or not enough energy.

In case both the control zone and the ARP have to much power, the ARP is delivering energy to the grid when this is not needed. The ARP will get paid by the TSO, but normally not as much as via the normal energy markets.

In case the ARP is long (has to much energy) and the control zone is short (not enough power), the imbalance of the ARP is helping to alleviate the error in the control zone. As a result, the TSO will pay the ARP for this energy. This price could well be higher than the normal energy price in the regular markets.

The third possible case is ARP short and control zone long. In this case the ARP is also helping the control zone. But as the ARP is using more power than paid for in the energy market, the ARP needs to buy this energy from the TSO. As the TSO has surplus power in this case, the price paid will normally be lower than the market price.

The last possible situation is ARP short and control zone short. In this case, the ARP is increasing the already existing shortage of the control zone. It will therefore pay the TSO a premium price for the required energy.

Prices for ancillary service providers

As is shown in table 2.6, the prices paid are based on the Marginal Incremental Price (MIP) and the Marginal Decremental Price (MDP). This is the price the TSO pays to the last activated reserve provider for respectively upwards or downwards reserve activation. These are the prices set by secondary reserve providers for activating their control actions. Several ways are possible to offer secondary control reserves to the TSO.

First a service provider can contract a certain power band to the TSO. This band may be asymmetrical. The TSO will provide a fee to the reserve supplier as an availability payment. This is expressed as €/MW/hour availability. On activation, the supplier will receive money for a production increase or need to pay some money in case of power reduction [51]. The price for power reduction will however be lower than the price the facility sold the energy for, resulting in a net profit.

Other contractual ways of providing secondary reserve exists: paid off-take reduction. Consumers can choose to reduce their power level in case the TSO requests this. The grid user will also be paid a stand-by fee and an activation fee [56].

3.4.4 Tertiary reserve

According to [57], two types of tertiary reserve exists: production reserve and offtake reserve. This reserve is used to replenish primary and secondary reserve in case of major imbalance and congestion problems. Tertiary reserve is manually activated, in contradiction of primary and secondary reserve. Tertiary reserve is mainly used to replace secondary reserve. It can be manually activated by the TSO in the follow up of an incident. Schedule activated control reserve is operated according a predetermined time frame.

3.5 VPPs vs microgrids

The main goal of aggregating DER into VPPs is to enable them to participate in the markets and act as a conventional generator. Therefore, the VPP coordinator is responsible for supervision, balancing control, ancillary services and market interface. This paragraph focusses on active power set point changes of the DG units triggered by the VPP coordinator.

This set point change is slow compared to the primary control of the network, and hence is included in the secondary/tertiary grid control. In this way, the primary control strategy is not influenced by the VPP and the VPP coordinator can take advantage from the communication opportunities brought by the microgrid concept.

The DER in the VPPs can, in turn, also be aggregated into microgrids. In this way, microgrids and VPPs are layered on top of each other. The VPP influences the local controllers by distributing power set point changes to:

1. the DERs separately;
2. the microgrids

For the VPP coordinator, microgrids offer the advantage of presenting themselves as entities, which reduces the communication and computational burden of the VPP coordinator. The VPP coordinator only adjusts the power through the PCC, while inside the microgrid, this power change can be dealt with taking into account all details of the microgrid in order to obtain an optimal operation. The VPP coordinator calculates a total desired output power change of the VPP from information received from the DNO or from the VPP elements, e.g., for the balancing of the VPP.

In order to realize this power change, two strategies are possible. In the direct control, the VPP coordinator determines a separate power change for each DER/microgrid and distributes this information to all the DER/microgrids in the system. The VPP coordinator has, thus, a direct control of its portfolio of DER and the performance of the system is highly linked with the intelligence of the VPP coordinator. Ideally, an optimal operation can be achieved when the two-way communication is fully exploited, but this can lead to problems of scalability, adaptability and computational burden.

In case of a market-based control, the VPP coordinator uses a VPP market to send price signals to the DER or approves DER bids [58]. Opposed to the direct control strategy, the decisions for power changes are made by the DER units locally in order to maximize their profit. The VPP coordinator can not directly control the DER but has some controllability by changing the incentives.

Both methods require two-way communication, intelligence and computational burden. Here, only the control method is studied, so active power changes are defined as such, but can result from pricing or bidding strategies as well.

The primary control is not determined by the VPP coordinator, hence, analogous to primary control in microgrids, it is determined by the DER locally. The output power of the DG units can be altered according to the state of the network by means of (modified) P/f, P/V and voltage-based droop controllers to enable the VPP units to react on local voltage/frequency changes for local power quality improvements and a stable VPP operation. In case the VPP should change its behaviour to frequency changes, communication to each individual unit is required. However, once each unit has received its control curve, it can operate without communication [59, 60].

This primary control can be overlayed with a secondary control scheme to obtain an optimal operation inside the VPP For example, the VPP coordinator can undo a primary output power change of one unit by changing the output power of another unit, e.g., to reach an economic optimum.

In the tertiary control strategy, with a slower time frame, the VPP coordinator communicates with the DNO to change the power of the DG units in the VPP to reach an optimal operation on the utility-scale. In this tertiary control, the VPP coordinator forms the link between the DER and the electricity markets.

The tertiary control delivers set points for the secondary control strategy, that in turn changes the nominal power in the primary control strategy.

Based on the primary and secondary control strategies of microgrids and the VPP control, as discussed above, a hierarchical VPP/microgrid control strategy is presented in this paragraph.

The primary control is responsible for a stable network operation and ideally operates based on local measurements only. This primary control is equal in grid-connected microgrids and VPPs. The DER typically lean on the conventional large generators for the primary control. However, in the future, with more and more DER, these units will also need to contribute to the networks primary control. This can be done by including P/f droop controllers analogous to these in the conventional network such that these units can contribute to the frequency control of the electrical network.

Another example is the usage of the voltage-based droop control like presented for the case of the islanded resistive microgrids. This method is especially interesting for dealing with local problems of the low-voltage networks that the considered DER are linked to. In this control strategy, the DER respond to local voltage changes in a delayed manner if they consist of renewable energy sources. In this way, a better power quality can be achieved and the penetration limit of renewables can be extended.

The work in §1.4.2 and §3.5 has been published as an article [9].

3.6 The role of storage in VPPs

3.6.1 Frame for storage

Energy storage is becoming an essential element in today's electrical power systems. Electricity is a man-made (and non-natural) commodity that cannot be stored on a large scale and for long time in an economically viable sense. Efficient and (at the same time) economic transmission of electricity over long distances is also a concern. This means that the electricity production must be fine-tuned to consumption levels on a short-term basis (often every 15 minutes) as so to guarantee that the supply and demand are always balanced. This task is indeed the greatest responsibility of the Transmission Systems Operator, non-commercial (often) state-owned organizations which are independent of other commercial players in the competitive electricity market such as producers/suppliers, traders and retailers.

Today, with the increasing penetration of Renewable Energy Sources, the variable and intermittent nature of output power of RES arises serious reliability concerns regarding their seamless supply. The output power of wind turbines and solar panels varies considerably due to climate conditions as the wind does not blow and the sun does not shine all the time. This (unpredictable) uncontrollability in output power of most of RES can be somehow mitigated by introducing a storage component to RES in order to decouple the instantaneous generation from the consumption.

A Hybrid Renewable Energy System (HRES) is defined as a system consisting of single/multiple RES along with a (or a combination of several) storage element(s) [61]. Some examples are commercialised stand-alone solar-battery configuration for street lighting, or a wind-solar-fuel cell-hydrogen storage configuration for electrifying a remote rural area or an island. In the context of microgrids, storage can also be used as a possible countermeasure for transmission congestion management, where there is too much excessive power produced by e.g. wind and solar units beyond the maximum capacity of lines to transport that much power. Storage can however only be a limited solution, as the state of charge affects the storage units ability to react to certain conditions. Storage can therefore only reduce congestion during a limited number of consecutive hours with enough time to recover.

In this regard, the storage can be effectively used to store otherwise curtailed surplus green energy during the congested periods alleviating the congestion-induced wind/solar curtailment [62]. Note that generation curtailment may be necessary due to other factors as well such as low demand, underestimated wind forecast and/or network security reasons. The stored energy can be economically sold to a spot market when technically (transmission) network capacity is available for price-arbitrage purposes.

It is also noteworthy to mention that (wind) curtailment at first sight might seem as an ignorant waste of green energy which is indeed a lost revenue for the turbine owner. However, considering that congestion-induced curtailment does only become necessary in a relatively short time span of the year for a limited number of wind units, curtailment can provide a suitable tool to allow connecting additional RES to the grid during a lot longer non-congested periods, ultimately increasing the capacity share of green energy.

The techno-economic assessment of different available storage technologies is of utmost concern when deciding upon their use. This paragraph aims at outlining the different storage technologies and their characteristics, and discusses their potential application to the Belgian power network.

This section is further organised as follows. In §3.6.2, first the electricity market operation is clarified, and then the role of storage in mitigating risks arising from integration of RES into electricity market is discussed. §3.6.4 provides an overview of widely-used energy storage technologies, their benefits and shortcomings. The potential applicability of different storage elements to the Belgian power network is discussed in §3.6.5.

3.6.2 Storage market integration

Market integration of RES heavily depends on the predictability of these sources as electricity cannot be stored directly. Energy trading relies on forward markets to

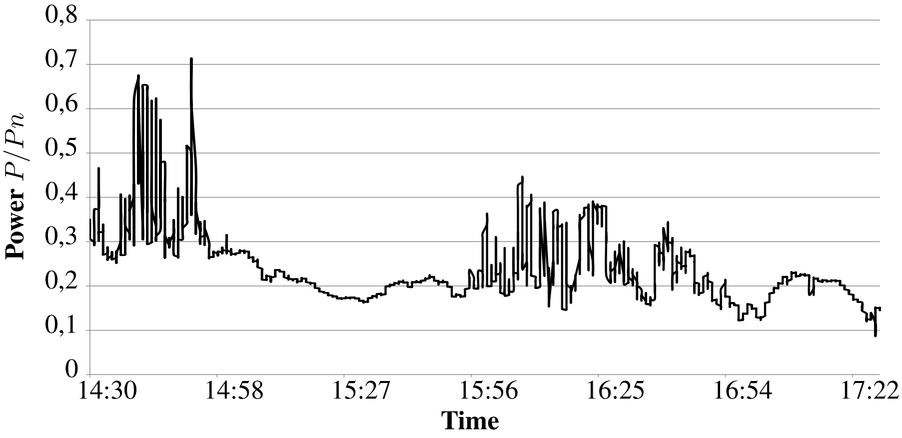

Figure 3.4: Variability of RES (Solar)

buy and sell energy from days, weeks, months or even years before actual delivery. Hence, increasing predictability will reduce the costs of the imbalance fines.

3.6.2.1 Electricity market structure

As has been explained in §2.2, suppliers and retailers (or large consumers) have different possibilities to trade electricity, as shown in Fig. 2.2.

In Europe, several regional markets are connected. Since 17 January 2011, five exchange markets are effectively coupled: APX-ENDEX (The Netherlands), EPEX Spot FR (France), EPEX Spot DE (Germany), EMCC (Europe) and Belpex (Belgium). As a result, these markets share a common price as long as cross border capacity is available [63]. When the physical transfer capacity between the market areas is constrained, different price zones are formed.

3.6.3 The role of storage in RES integration

RES present new challenges to the existing energy markets. Traditionally, production and consumption could be predicted accurately [64]. This made it possible to plan the production schedules of power plants days and even weeks or months beforehand. However, as RES are often dependent on weather conditions which are more difficult to accurately predict, the real and predicted power flows differ more. This variability and more specifically the unpredictability makes efficient market integration of RES to the existing markets more difficult. Fig. 3.4 illustrates the intermittency of output power of a solar panel over several hours on 10 October 2011 in Oostende in Belgium. Additionally, the markets are designed for large quantities of energy, rounded to 0.1MW and time slots from 15 min. to 1 h. Storage can alleviate the unpredictability of RES and provide more certainty towards the markets.

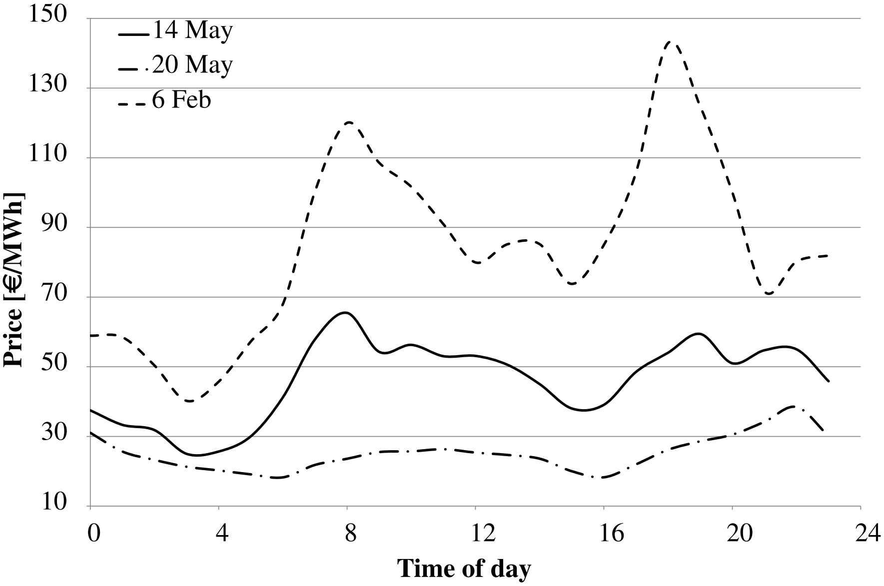

Figure 3.5: Evolution of electricity price on three different days in 2012 (Belpex)

Two distinct optimisation goals for the storage device can be defined: short-term optimisation to dampen power fluctuations and avoid penalties for imblanace prediction errors, and long-term optimisation to make maximal profit. Short-term optimisation can be used to mitigate the variable output of e.g. solar panels or wind turbines. In this way, storage can alleviate the difference between the nominated and effectively traded volume, and hence can avoid the balancing cost [41]. As Balance Responsible Parties (BRPs) need to balance their production/consumption and import/export -say- every fifteen minutes, only relative small amounts of storage are needed to level the actual and the predicted energy balance.

In [65] a multi-objective Particle Swarm Optimisation (PSO) is proposed to find the best PV-battery-H2 configurations in order to design a autonomous stand-alone HRES for a realistic case of a remote village called La Nouvelle in the French overseas island of La Réunion, in both short-term (2 years) and mid-term (10 years). In [66] an Linear Programming (LP) problem is solved to optimise the operation of energy storage for wind curtailment reduction and price-arbitrage, on a case study of 33 kV distribution network in the UK.

Storage units with a larger energy content can be used to sell energy on the most profitable moments on the market. As can be seen in Fig. 3.5, price evolution on the stock market can differ significantly from day to day and from month to month. Storage intended for market optimisation can be regarded as any storage from hours to even months. In case large price differences in one day are available (e.g. profile of 6 February 2012 in Fig. 3.5), storing energy produced in low price zones to sell the energy in time slots with high prices can be profitable. However, on days with a relatively flat price profile (e.g. profile of 20 May 2012 in Fig. 3.5), no significant financial gain should be expected from storage. In [32] a price-baced unit commitment strategy is presented to optimise total profit for a collection of Distributed Energy Resources (DER). This strategy utilises a VPP to consolidate different DER units to form a single entity.

3.6.4 Overview of energy storage technologies

Electrical energy storage is accomplished by devices or physical media through converting it into another form e.g. chemical, thermal, potential or kinetic energy. There exist different types of energy storage technologies which may suit grid-scale applications or small-scale application (e.g. (large) commercial/residential dwellings). Comparison among these highly application-dependent energy storage technologies seems to be pointless, and their use should, as a simple rule of thumb, be decided based upon an in-deep economical capital/maintenance cost analysis, efficiency (taking the losses into account) and/or their maturity/infancy of technology.

Although storage is seen to be absolutely necessary in the future, except for pumped-hydro no large scale operations are present in Belgium as of today. The facility near the city of COO is a Pumped-hydro energy storage facility build in 1979. It has a maximum power of 1100 MW and can be operated at maximum power for 5 hours.

This section provides a high-level overview of the most widely-used storage technologies namely *pumped hydro, compressed air energy storage (CAES), flywheel, battery, fuel cell (FC), hydrogen storage, thermal energy storage (TES),* and *(super)capacitor.* These are the most promising technologies which could be applied in Belgium in the near future.

3.6.4.1 Pumped-hydro energy storage (PHES)

A conventional PHES unit uses the height difference of two vertically-separated natural/man-made water reservoirs. A reversible pump-turbine with motor-generator set is employed to function in both charging mode (to drive the pumps) and discharging mode (to run the turbine). Excess (off-peak low-price) energy is used to pump the water from the lower reservoir to the upper reservoir storing electricity in the form of potential (gravitational) energy of water. During peak periods, the potential energy is released by reversing the water flow to turn the turbine in order to produce electricity. Some conventional hydro-electric power plants which only use the natural stream flow of water (no water pumping) may be also dispatched as a PHES facility by deferring the electric power output until required.

Pumped-hydro is technologically a very mature solution, being practically the most widespread energy storage system in current use in power systems accounting for more than 99% of bulk storage capacity worldwide. It is generally the most cost-effective solution for large-scale energy storage being available in the order of hundreds of MW and MWh. PHES system provides a suitable solution for long-term energy storage with the discharge times ranging from several hours to a few days with efficiency of 70%-85%. They have fast response time achieving high ramp rates, long lifetime (e.g. 50 years). The disadvantages, however, are their long/time-consuming construction time, high capital expenditures, inevitable time needed before switching between charge/discharge modes due to significant inertia of the water, and dependency on the availability of an appropriate geographical reservoir [67].

3.6.4.2 Compressed air energy storage (CAES)

A CAES system uses the excess (green) electricity during off-peak periods to power an electric motor functioning as air compressor. Compression of air to high pressure produces heat which is captured by a thermal energy storage unit. The compressed air is often stored in underground geological reservoirs such as salt caverns, rock mines, depleted oil and gas wells. During peak hours or high demand periods, the stored compressed air is re-heated using the excess heat which was created (and captured) during compression phase in the thermal store unit and then expanded in the turbine, in order to (in)directly generate electricity. Note that most existing CAES systems are installed in conjunction with natural gas-fired power plants, where the compressed air is fed into the gas turbine to boost efficiency (indirectly generating electricity). There are three types of CAES systems, depending on the thermodynamics of the process, namely *adiabatic (isentropic), diabatic* and *isothermal*:

- Diabatic or conventional CAES dissipates reasonable amount of the heat into the environment, which is produced during compression phase. They thus need to re-heat the compressed air prior to expansion in the turbine. This is often done by using the heat produced by natural gas-fired (combustion) turbine to heat the compressed air.
- Adiabatic CAES retains the heat produced during the compression phase to re-heat the compressed air during the expansion phase in order to generate electricity. The system is insulated against heat transfer to the environment avoiding the resulting energy losses.
- Isothermal CAES tends to keep operating temperature of the air at a constant level throughout compression/expansion processes by constant heat exchange to the environment. It allows air to be compressed to high pressures at near ambient temperature.

The CAES system provides a suitable solution for large-scale long-term storage as the small-scale CAES systems are not commercially available at the present time. A notable advantage of CAES is that air, unlike e.g. electrodes and electrolytes in batteries, is naturally available at zero marginal cost. The energy density, in kWh/m^3, is relatively high compared to e.g. pumped hydro storage system. One of the limitations is that it often takes several minutes to switch between charge and discharge modes. Another disadvantage is that the economical viability of CAES system depends on geographical-based natural formations.

3.6.4.3 Flywheel

A flywheel is nothing more than a rotor (flywheel) that can spin around a shaft at a very high speed. The rotor is a high-inertia cylindrical assembly made of steel or carbon-fiber composite that is directly coupled to a shaft on which a motor/generator is mounted. The excess green energy, during charging mode of the flywheel, is used to accelerate the rotor to a very high speed (e.g. 50000 rpm in some applications), with the motor/generator set acting in motor mode, and energy is stored as kinetic energy in the rotor. The amount of kinetic energy that a flywheel can store ($E_{\text{flywheel}} \simeq m\, r^2\, \omega^2$) is proportional to flywheel's mass m, the square of rotor's radius r and the square of angular velocity of the rotor ω. During peak periods, the motor/generator set is switched into generator mode, and the initial kinetic energy of the flywheel drives the generator in order to produce electricity, causing the flywheel to discharge and thus to slow down. In order to reduce the losses associated to friction, the rotor assembly is sealed in a vacuum chamber, and is additionally levitated with an electromagnetic bearing. Flywheels have high efficiency (about 85%), very high power/energy densities (power/energy per unit volume), fast (near immediate) response, long lifetime under constant cycling and low maintenance cost. They are very environmentally-friendly and can be applied to a wide range of applications. Considering very high specific power (power per unit mass) of flywheels, they seem to be an ideal solution when a fast charge/discharge of large quantity of energy is required, and when the overall energy capacity is not a critical issue. Flywheel technology has gained some commercial applications in automotive and rail industry for regenerative braking. Disadvantages are high capital cost, design complexity, overall system size and weight, possible destructive damages upon failure.

3.6.4.4 Battery

A (rechargeable) battery, in most basic form, consists of several electrochemical electrically-connected (in series or parallel) stacked cells that convert electricity into chemical energy and vice versa.

Each cell contains electrodes (negatively charged (anode), positively charged (cathode)) wherein reduction-oxidation (redox) reactions take place, and an electrolyte. There exist many different type of batteries depending on various chemicals used as electrodes and electrolyte. Upon discharging, a chemical reaction takes place inside the cell and the released electrons travel from anode to cathode supplying the load. When recharging the battery the reverse process occurs and again electricity is stored as chemical energy in the cell. Some well-known battery types are: lead-acid (Pb-A), nickel-cadmium (Ni-Cd), nickel metal hydrite (NiMH), lithium-ion (Li-ion), sodium-sulphur (Na-S), vanadium redox flow and metal-air. Note that energy storage devices are normally rated in terms of both their energy (expressed in kW or MW) and their power capacities (expressed in kWh or MWh) as it is equally important to know how long a battery can supply a given capacity of energy. Unfortunately, the energy and power capacities cannot be scaled up/down independently for most battery types as they are strongly correlated. Several important technical specifications are often used to characterize and compare battery operating conditions such as (roundtrip) efficiency, cycle life (lifetime/lifespan), depth of discharge, self-discharge, energy/power density, specific energy/power.

Battery storage is a relatively nascent technology. They have high cost, relatively small capacity, high maintenance and limited lifetime. Detailed techno-economic comparison of different battery types can be found in [68, 69], and are not discussed here.

In conventional batteries electrolyte is in direct contact with the electrodes (of the electrochemical cell/stack) as they are both contained in the same container. Flow battery is a special class of batteries in which the electrolytes (two different types) are separately stored in external storage tanks outside of the cell (electrodes and membrane separator) itself. To charge/discharge flow battery, the electrolytes should *flow* through the electrochemical cell by pumps. Thanks to this physical structure, the energy and power densities of flow batteries can be scaled up/down independently. Because the energy density is determined by the amount of separately stored electrolytes (size of the storage tanks), while the power density is independently determined by the rate at which chemical redox reactions occur at the electrodes inside the cell. This feature is very important for design optimization of energy and power densities for every specific application. Vanadium redox, regenerative fuel cell and zinc-bromin are three different types of flow batteries. They provide large-scale long-term storage capacity, and have no self-discharge. Disadvantages are their low efficiencies (due to consumed energy to run the electrolyte pumps) and design complexities.

3.6.4.5 Fuel cell (FC)

A fuel cell is an electrochemical energy conversion device that converts the chemical energy of a fuel, often hydrogen, into DC electricity (and water and heat as by-products) through chemical reaction with e.g. oxygen of the air. An FC generally consists of two electrodes (anode and cathode), an electrolyte and a catalyst. The chemical reactions take place at the electrodes, at the presence of catalyst to speed up the reactions, and an electrolyte which only allows the passage of appropriate ions between electrodes. In practice, single cells are often assembled together in series to form a stack. FC technologies in principle differ in type of electrolyte they use, and generally operate at different temperatures. A possible general classification for different FC technologies is given below:

- low temperature FC: alkaline FC (AFC), phosphoric acid FC (PAFC) and proton exchange membrane FC (PEM or PEMFC)
- high temperature FC: (molten) carbonate FC (CFC or MCFC) and solid oxide FC (SOFC)

The operating temperature determines the applicability of the FC technology to a particular application, as well as whether or not a particular fuel can be utilized. For example typical operating temperature of a SOFC (about 1000 C°) limits its safe use for homes and cars. Furthermore, low temperature FCs operate with hydrogen, while high temperature FCs can also be operated with different hydrocarbons e.g. natural gas or alcohols e.g. methanol. Fuel cells cannot generally store energy unless combined with electrolyzers and external storage systems.

FCs are clean with zero (in case of using pure hydrogen as fuel) or near-zero emissions, can achieve high efficiencies at any scale, and can be located almost anywhere. The efficiency can be even further improved if the waste heat of the FCs can be harnessed. FCs output scalable high power density such that doubling the operating time needs only doubling the amount of input fuel and not doubling the capacity of FC itself. They generally require low maintenance thanks to the absence of internal combustion mechanism and moving parts. The major disadvantage is that production, transportation and (on-site) storage of (hydrogen) fuel is costly. Like any other flammable fuel such as gasoline and natural gas, there are concerns about explosion of the hydrogen tank under specific conditions. FCs with liquid electrolyte (AFCs, MCFCs, PAFCs) might leak, and FCs with solid electrolyte (SOFCs) might crack. Note that PEMFCs contain solid and flexible electrolyte with no risk of leak or crack.

3.6.4.6 Hydrogen storage

Hydrogen, as one of the most abundant element on Earth, is nowadays considered as electricity storage medium. Unfortunately, the molecular hydrogen H_2 is not readily available and must be first produced from e.g. hydrocarbon fuels (e.g. methane, coal and heavy residual oil), various biological materials or from the electrolysis of water. Excess green energy can be used to produce gaseous hydrogen and then to compress or liquefy it in order to store it in storage tanks. The stored hydrogen is converted back to electricity during peak periods using e.g. fuel cell for which hydrogen acts as a fuel. Reformation with steam of natural gas (often methane) or biogas (also called renewable natural gas, biomethane, swamp gas or landfill gas) is the most prevalent way to produce hydrogen. Hydrogen can also be produced by gasification of hydrocarbon fuels (often coal) or biomass in the presence/absence of oxygen. Electrolysis of water is insignificantly used to produce a small portion of overall hydrogen production today. It is often done using alkaline (KOH) or proton exchange membrane (PEM) as electrolyte, and directly breaks down water into hydrogen and oxygen $(H_2O + e^- \rightarrow H_2 + \frac{1}{2}O_2)$. A very detailed review of critical challenges, major R&D needs and key benefits of all hydrogen-based storage technologies is given [70].

3.6.4.7 Thermal energy storage (TES)

A TES system can store off-peak excess electricity in the form of thermal energy, and releases the stored heat/cool during peak periods in order to be directly used for heating/cooling purposes or to be converted into electricity. One example is freezing water into ice (known as ice storage) in non-corrodible tanks and use the cool of the stored ice for air conditioning at a later point in time. Another newer form of TES is the molten salt technology where a mixture of molten salts (e.g. sodium nitrate and potassium nitrate) filled in the low-temperature tank (about e.g. 260 C°) is pumped through evacuated tubes to be heated up by solar collectors up to e.g. 550 C°. The hot molten salt then flows to a well-insulated high-temperature tank that can efficiently retain/store thermal energy for up to a week. When electricity is needed during peak periods, the stored hot molten salt flows into a heat exchanger into which feed water is also simultaneously piped from a water storage tank. The hot molten salt heats the water creating superheated steam. The cooled molten salt returns to the low-temperature tank, and the produced steam flows into a conventional steam turbine generating electricity. From the turbine the steam condenses back into water returning to the water storage tank.

3.6.4.8 Power to gas

With the technology currently available, the production chain of power-to-gas consists of electrolysis and optionally methanation can be included. Electrolysis relates to the conversion of electricity into hydrogen. Methanation is the synthesis of hydrogen and carbon dioxide to methane. Additional to the power-to-gas technologies mentioned in this paragraph it might be needed to consider gas compression and hydrogen storage in buffer tanks, depending on the specific power to gas chain [71].

The produced natural gas can be injected in the existing gas network. As the European gas network has significant dimensions, the gas content is also quite large. Even small variations in pressure can store a significant amount of energy.

3.6.4.9 (Super)capacitor

A conventional capacitor is an electrical device that basically consists of two electrical metal plates (conductors) e.g. aluminum, separated by a thin (often solid) insulating layer (dielectric) e.g. glass, mica, paper, air, plastic, ceramic. There are also electrolyte-based capacitors that employ moist dielectric. During charging process, electricity is stored in a static electric field that is being developed across the dielectric. The amount of electrical energy that a capacitor can store in its electric field is proportional to its capacitance and the square of the charging voltage ($E = \frac{1}{2}CV^2$). When needed, the capacitor can be discharged releasing the stored electric energy very much like a rechargeable battery.

Capacitance in general depends on geometry of the conductors (surface area as well as distance between conductors) and the dielectric properties (relative permittivity). These factors, thus, create fundamental practical limits for manufacturing high-capacitance standard capacitors. Moreover, the dielectric has a certain electric field strength resulting in a breakdown voltage limit.

Supercapacitors (also known as ultra or double-layer or electro-chemical capacitors) are special class of capacitors that do not have a conventional dielectric. They, instead, utilize two metal plates coated with a porous carbon-based materials soaked in an (aqueous or organic) electrolyte, that are separated by a vanishingly thin insulator. The super capacitors can achieve high capacitance (and thus much larger energy density compared to standard capacitors) (up to 12 kF) thanks to the much bigger surface area of porous carbon-based plates to more effectively store the charges, and extremely small separation distance between them.

The key disadvantage of supercapacitors is their low voltage limit (up to 5 V), lower specific energy, higher self-discharge and their higher price compared to e.g. lithium-ion batteries. However they have much longer cycle life (theoretically any/unlimited number of times), shorter charging times, high specific power, and are more resilient to temperature variation (functioning well in hot/cold operating conditions). Moreover, unlike batteries, they do not require full-charge detection as, according to the circuit laws, they cannot be overcharged. A detailed overview of different classes of supercapacitors and their comparison is given in [72].

3.6.5 Applicability of storage to the Belgian grid

In this section, the applicability of the above-mentioned storage technologies to the Belgian power system will be discussed. Obviously, not all mentioned storage devices are equally applicable. Hydro storage requires sufficient water head and flow rate to be useful. Currently, in Belgium, only the PHES unit in Coo-Trois-Ponts is operational. This installation of 1100 MW can provide five hours of power, totalling the stored energy to 5 GWh.

CAES systems could also be of interest to Belgium, because of the no longer operational coal mines in the east of the country. However, the utilisation of the caverns for air storage should be investigated. The process requires sufficiently large, stable and air-tight caverns to operate.

Flywheel storage and supercapacitors could be very interesting technologies as Belgium has a relative large amount of solar energy. As has been described in [11], trading solar energy on the stock market is not economically viable. The

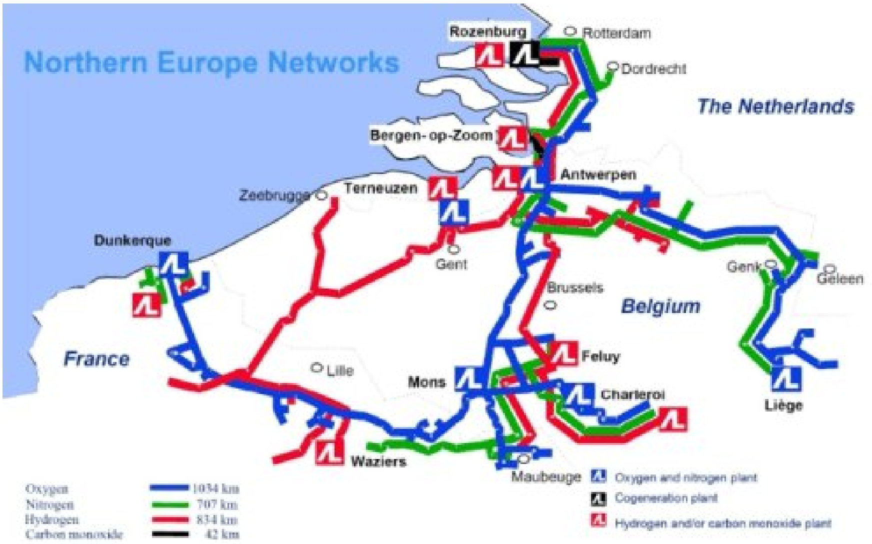

Figure 3.6: Hydrogen pipe system in Belgium (Source: Air Liquide)

gains of selling the energy at the higher stock prices than those offered by fixed contracts are offset by the added risk due to the unpredictability of solar energy. Adding very dynamic storage units could manage the short-term variability and hence provide better economic revenue for solar plant owners. The same could be applicable to small wind turbine clusters, as the spatial smoothing of small clusters (2-6 turbines) is not high enough. However, the generally larger power of wind turbine clusters compared to solar panels increases the required power of the storage systems, increasing also the investment cost. Supercapacitor and flywheel storage are technologies with relative small energy content, but can effectively track RES power fluctuations in real time as these technologies do not suffer from quick charge/discharge cycles. This mark these technologies as high potential for short term ($\leq$ (15–30) min.) optimisation.

Unlike flywheel and (super)capacitor, batteries have limited charge/discharge cycles. Although it should be noted that newer technologies are less vulnerable to cycling, undercharging, deep discharging and high current, due to the chemical processes involved, the dynamic behaviour of batteries is slower than the aforementioned technologies. This makes battery storage more suited to medium power and energy applications. In contrast to the former mentioned technologies, batteries are a mature technology and are readily available on the market. Since for stationary grid support and economic optimization the energy density is not a big concern (in contrast to automotive applications), cheaper technologies like lead-acid are also feasible.

Also hydrogen and fuel cells have potential in Belgium. In 2012, a 1 MW fuel cell has been installed in the Port of Antwerp. It utilises residual hydrogen from the Solvin plant. Although this plant is designed to produce base load, it can be the first step to incorporate hydrogen power in the electricity grid on a large scale. Belgium is also suited as a test location for hydrogen power plants, as there is an extended hydrogen pipe net available. This pipe grid is connected to the (sea) ports of Rotterdam (the Netherlands), Antwerp, Zeebrugge and Ghent (Belgium) and is also connected to industrial sites in Charleroi (Belgium) and Waziers (France), as shown in Fig. 3.6, totalling more than 800 km. As a gas pipeline has the potential to be utilised as a storage buffer, this is a major benefit to be available. However, it should be noted that the major part of hydrogen today is produced by steam reforming of natural gas and as by-product in chemical processing.

3.6.6 Conclusions storage

Reliable and affordable energy storage has a pivotal role in today's power systems with ever-increasing penetration of RES. Although comparing one energy storage solution with another one seems to be pointless as there exists no single optimal solution that suits all applications. However, a techno-economic assessment of different energy storage technologies can provide guidelines to find (the combination of) the best available solution(s) for a particular case. This section provides a high-level overview of widely-used storage technologies, their benefits and shortcomings. The structure of the Belgian electricity market is also presented. Finally, the technical applicability and economical viability of different storage devices to the Belgian power network is discussed.

Distributed storage can help to reduce the local impact of other decentralised resources. As has been expressed in 3.4, maintaining a stable system becomes more difficult with an increasing share of RES. As RES are often dependent on weather conditions which are more difficult to accurately predict, the real and predicted power flows differ more. This variability and more specifically the unpredictability makes efficient market integration of RES to the existing markets more difficult. Fig. 3.4 illustrates the intermittency of output power of a solar panel over several hours on 10 October 2011 in Oostende in Belgium. Additionally, the markets are designed for large quantities of energy, rounded to 0.1MW and time slots from 15 min. to 1 h. Storage can alleviate the unpredictability of RES and provide more certainty towards the markets.

3.7 Congestion management and frequency control

Congestion has been discussed in §3.3.1. It was also the original driver for this PhD. In the north of West-Flanders, Belgium, a high voltage line was congested due to the installation of offshore wind turbine parks in the North Sea. As a result, since 2011 no more decentralised production was allowed in the whole region until a new high voltage line is built. Due to political tinkering, the start of construction of this replacement line could only start in the beginning of 2016. In this section, a potential interesting solution is presented. The proposed method is to focus downward activations within the congested area and release it in an other area. This contrasts with the traditional method whereas downward activations are equal all over the control area.

Many distributed generation (DG) units are installed within existing grids. As such, they are using mostly existing infrastructure wherein also consumption is present. As a result, they will reduce the power needed to be imported in a region. As most DG units are installed without any control options, the grid operators need to decide whether there is enough capacity on the grid to transport the energy generated. When generated power in an area minus consumption is larger than the rated transformer or line capacity to neighbouring regions, the protection will trip. To prevent this, grid operators do not allow more installed capacity (nominal power) in an area than the annual minimum consumption plus the rated transformer / line capacity. As the capacity and coincidence factors of renewable sources are seldom equal to one, the maximum share of RES connected to the grid is significantly limited. Only a few hours a year of insufficient grid capacity can prevent a larger share of renewables in the grid.

To cope with requests for more installed renewable energy, grid operators sometimes install a telecontrol to switch off the source if there is grid congestion. However, as this is a ‘favour’ provided by the grid operators to install more capacity than available by traditional grid codes, often, no remuneration is provided in case of shut down due to congestion. With more installed RES capacity, this will become even worse for investors in renewable energy.

3.7.1 Frequency restoration reserve

Frequency restoration reserve, also called secondary reserve (R2), is used to restore any frequency deviations after primary control actions [50]. To provide a stable grid, the grid operators buy reserve capacity from energy providers as needed. As this reserve is called upon dynamically, the providing generators must also be flexible. Large shares of this flexible generation capacity exists of (combined cycle) gas plants. However, as the spark spread, the price difference between the gas price and the electricity price, diminishes and the capacity factor of these installations becomes also lower, many of these installations are planned to be phased out. A main driver for the lowering of this spark spread is the lowering of the electricity price over the last years. The Y+1 energy price dropped from 55/MWh in 2011 till a little less than 30 in the beginning of 2015 [73].

This increases the price of the reserve capacity available, although not enough to keep the gas plants profitable. This results in large demand of the grid operators for (especially negative) frequency restoration reserves. However, the requirements to provide this service are quite stringent so not many installations can provide the capacity, security, and dynamic behavior required for this service.

3.7.2 VPP combining congestion management and frequency restoration reserve

As has been presented before in this dissertation, a Virtual Power Plant is a control concept to manage many small electrical units. A VPP is defined as a flexible representation of a portfolio of Distributed Energy Resources (DER). This flexibility will be used in this section to reallocate resources to other regions.

From the grid operator's perspective, the VPP behaves as a single unit. Hence, if requested to reduce power, where in the control region the VPP does this doesn't matter for the grid operator. Each time the VPP is requested to reduce power, it will do so in the region affected by congestion. Requests for power increase will be directed outside the congestion affected region.

3.7.3 Congestion management

System congestion can be considered on different levels. The most considered congestion is on the transformer and/or line level. When the generated power minus consumption is larger than the rated transformer and/or line capacity, the protection will trip. As has been explained in §3.3.1, grid operators do not allow more installed capacity on an access point than the annual minimum consumption plus the rated transformer and/or line capacity.

Another type of congestion induced by uncontrolled RES is system-wide congestion. If generated capacity on system level is larger than total demand, grid grid-wide congestion will follow. In [40], some scenarios are presented with low load and high RES capacity. If no intervention is possible, this will also result in system congestion and subsequently system instability. In May 2012, this happened on a small scale in the Belgian power system. Due to prediction errors of wind and solar capacity, excess power had to be sold to France at negative price levels. If the neighboring countries were not able to absorb the energy, a brown/black-out in the Belgian power system would have been the result. However, as the export capacity was marginally sufficient, no actual measures had to be taken to curtail some production.

A Virtual Power Plant can help the system operator to visualise distributed resources in the system. Moreover, the VPP can give switching commands to the individual units to trigger more consumption or shut down some renewable units as necessary. As a VPP is dynamically reconfigurable, the resources affected by the congestion management program can be changed to have the most effect with the minimum affected resources needed to solve the problem.

3.7.4 Frequency control

Due to the relatively small amount of DER capacity in Europe at this moment, the traditional reserve capacity is sufficient to support production fluctuations. However, different studies expect that a 20 % RES share is the limit with current capacity reserves. This implies that DER will need to provide reserve capacity themselves. As is shown in [74], this will result in larger balancing needs and rising balancing cost if no proper action is taken.

As has been shown in Fig.3.2, primary reserve is activated within miliseconds, secondary within minutes and tertiary reserve within tens of minutes. In this section, primary and secondary control are the most important. As has been stated in §3.4.1, these are automatically activated. Primary based on a local frequency measurement, secondary reserve on a signal send every few seconds by the TSO to all participants.

In this section, the flexibility will be used to change the classical behaveour of primary and secondary control. As has been stated in §3.4.1, in the classical situation all units contributing to these reserves receive the same signal. Frequency deviations are uniform for the grid and the control signal is send to the secondary reserve units without differentiation. However, the VPP can adapt the gain setting of primary control resources and send a different secondary control signal to every unit. As a result, the units will not behave uniform any-more.

Depending on the available resources, a VPP can deliver all kinds of frequency control. Parameters regarding the reaction time and droop function for primary control can be adjusted by the VPP. Although primary reserve is possible, secondary and tertiary control are more straightforward services to be delivered by a VPP.

3.7.5 VPP reliability

As Virtual Power Plants represent a large amount of individual DER, the reliability is not affected by the outage of a single unit. As a VPP is constituted of many (different) resources, the reliability and availability is larger than that of one single (kind of) resource. This is a necessary requirement for ancillary service procurement. Load aggregators are therefore potential users of the VPP concept as this will facilitate their operations and enable them to deliver also technical services to the grid operators, which are also highly valued but require high reliability and availability. Due to the portfolio effect and the larger available power, a VPP enables DER to deliver these services also and hence gain access to this revenues.

3.7.6 FRR and congestion management

As discussed above, a VPP can aggregate many sources like wind turbines, solar parks or combined heat and power installations to behave coordinated [75]. The individual resources might not meet the requirements to deliver a certain service,

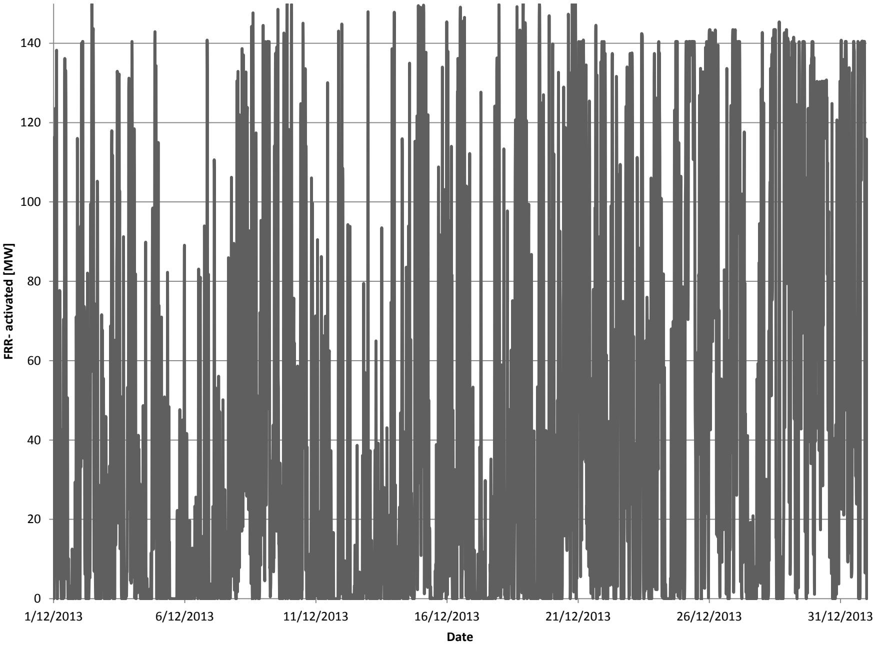

Figure 3.7: Activation of FRR- in Dec. 2013

but as a group, they can. In this section, a VPP is used to deliver negative secondary reserve. However, as a VPP is a flexible representation, this reserve can be provided from a region with production originated congestion if they occur simultaneously. As such, the VPP can provide two services at once: congestion management and negative frequency restoration reserve (FRR-). FRR- is a traditional service with a remuneration scheme already existing. As shut down due to congestion is often not paid for, combining these two services can alleviate the cost of congestion management. This however requires two prerequisites: simultaneity between FRR- and the congestion and a localized activation of the FRR-. In the next paragraph, the simultaneity of wind power and FRR- is investigated for a case in the Belgian power system.

3.7.7 Case study

As shown in Fig. 3.7, a large volume of frequency containment reserves is called upon for many hours a day. In this paragraph, it is investigated if this reserve capacity can be delivered by localised sources in case of local congestion problems.

As frequency restoration reserves are only geographically limited by the control area, it is not necessarily important which source delivers the service. A VPP can activate the negative reserve capacity depending on the available transfer capacity in a region to help reduce a congestion problem. The release of the FRR-

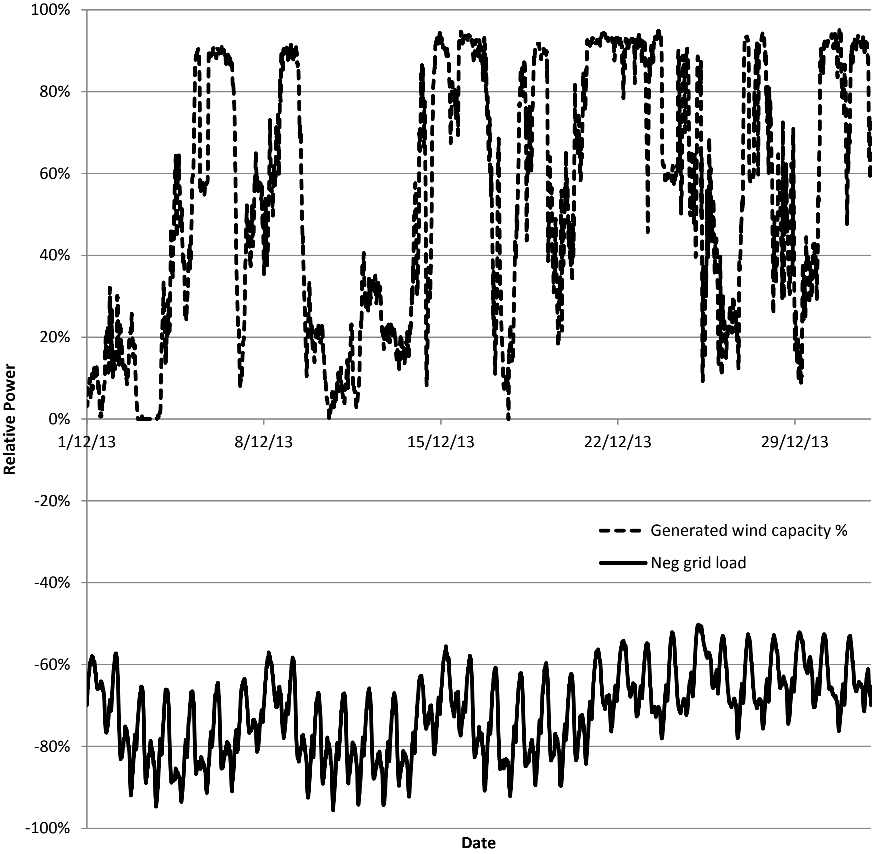

Figure 3.8: Power of wind farm and grid loading, relative to installed capacity (dec 2013)

capacity could be provided by other sources in a non-congested area. However, due to the delay between activation and release, slower units like combined heat and power can be fired up. Hence, a shift in localisation of the production is accomplished. The revenue gained from the FRR(-) services should be spread over the activated units. As such, a (small) revenue for the units affected by congestion problems can be gained.

In this case study, the potential gain of localised frequency restoration reserve is determined. Calculations are based on measured data from the Belgian power system. The total grid load, as measured by the transmission system operator Elia is rescaled to a peak load of 400 MW. This load is connected to a line with a maximum power rating of 500 MW. The yearly minimum load is 50 % of the maximum load (hence 200 MW). To this system, an offshore wind farm with variable installed power is connected. Data of the Belgian offshore wind farms as provided by Elia are used to simulate the power output. These data are rescaled to an installed capacity between 700 MW and 900 MW (Fig. 3.8).

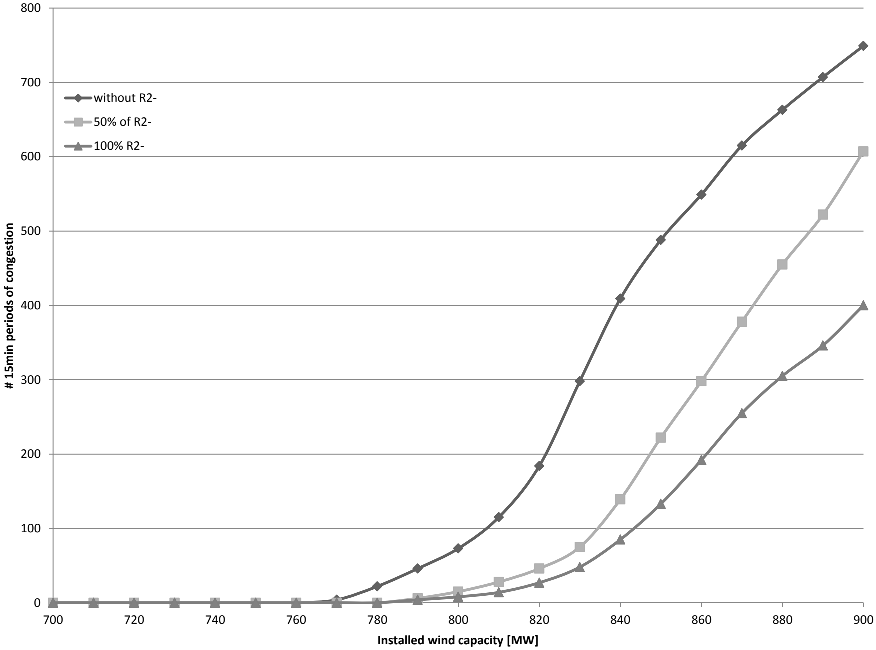

Figure 3.9: # quarters with congestion in function of installed wind power

As the minimum load is 200 MW and the grid can transport 500MW, an installed capacity of 700MW should not result in congestion. From this capacity, the installed power of the wind farm is increased. Based on data of December 2013, the installed power of the wind farm could be increased to 770 MW before any congestion occurred. In Fig. 3.9, the number of quarters in which the nominal line capacity is exceeded are shown. With increased installed wind power, the time the line is congested increases also. The simulations are executed to a maximum installed wind power of 900 MW. This resulted in 749 quarters with congestion or approximately 187h in one month.

Next, the wind turbines are used to deliver negative frequency restoration reserve (negative secondary reserve). First, only 50 % of the activated reserve is provided by the wind park. As a result, congestion only started to occur with 790 MW of installed wind power. This is an increase with 20 MW in comparison to the case no FRR- is delivered. If the installed wind power is further increased to 900MW, the number of quarters could be reduced to 607 quarters or 151 hours. This is a reduction of congestion time with nearly 20 % compared to the original case.

Next, all of the negative reserve is delivered by the wind farm (bottom curve of Fig 3.9). Congestion still occurred if the 790 MW wind power mark was reached. However, if the installed capacity is increased to 900 MW, only 400 quarters with congestion are counted. This is a reduction with nearly 50 % compared to the base case.

3.7.8 Conclusion congestion management and frequency control

This section demonstrates that localised activation of frequency restoration reserves in a congested area can reduce the congestion problem. However, as the amount of frequency containment reserve is limited, this method can not solve large congestion problems. Giving priority to units in congested areas in case FRR- is needed, can however reduce the amount of unpaid curtailment of renewable resources in congested areas. The research presented in §3.7 has been published in paper [15].

3.8 Positive balancing service by solar Virtual Power Plants

As photovoltaic solar plants have high dynamics due to the lack of moving parts, they could be used as fast acting resources to balance variations. In order to be able to increase power output, not the whole predicted power can be sold in the energy market to provide headroom in case power increase is necessary.

The last few years, photovoltaic solar (PV) power was seen as an attractive technology to produce environmental friendly electricity [30]. The government offered an abundant financial support scheme to investors, which resulted in a large expansion of the installed capacity. Due to the green and clean label of PV power, the government awarded this (and other renewable energy sources) a privileged status. Renewable energy sources are largely excluded from balancing obligation and market participation. This resulted in a situation where most of the revenue of PV installations came from governmental subsidies (green power certificates) and not from the selling of energy. As investigated in [11], in the former subsidy scheme in Flanders (Belgium) the balance between commodity value and subsidy income makes it not feasible for PV owners to participate in wholesale market operation. The potential extra revenue is not up to the added risk of a volatile and uncertain market. However, due to the quick decline of the GPC price, for new installations it can become economically profitable to act in the wholesale market as average day ahead market price is generally higher than the fixed price offered by suppliers. However, the variability and the unpredictability of PV power makes it very hard to determine the available power to trade. As the best way to trade is the day ahead market, production should be predicted. As mismatch between prediction and effective production is penalised, trading the entire PV production is not without risk. In previous research (§2.8), it has been proved that often the imbalance market can be more profitable than the day ahead market. In this section, a case study is presented whether it could be profitable to omit the day ahead market entirely and provide only positive balancing services. This is verified by real data of 2013, provided by the Belgian transmission system operator Elia.

3.8.1 Need for new trading strategies

During recent years, abundant financial support was provided for renewable energy sources. In Flanders for example, abundant green power certificates were awarded to e.g. wind and solar installations. However, today, new PV installations do not receive these high subsidies any more. They are however still offered a protected market position, but for how long? To make the financial model of these technologies future proof, they need to be incorporated in the existing energy market and compete with traditional power plants.

As has been shown in [11], PV energy alone is hard to aggregate and sell on wholesale markets due to prediction errors [35]. Wind power is better predictable, but also suffers from weather dependence. Thermal plants may lack the dynamic capabilities of power electronic interfaced units like PV and wind, but are more predictable and stable. Dynamic loads may have a large impact on user comfort and storage is expensive. However, by combining the benefits of different sources within a single VPP, the drawbacks of a single source VPP might be (partially) mitigated.

Keeping solar power from direct market access enables this source to provide positive reserve capacity. As solar power has no moving parts, if sun is available, the power can be instantaneously available without any start-up delay. Hence, PV power could be an attractive source for balancing services. In this section, the economic viability of providing positive balancing services with an aggregated PV park is investigated.

3.8.2 Providing balancing power

Balancing services have a crucial role in the stability of the electrical system. As Balance Responsible Parties (ARPs) should predict there production and consumption, their will always be some real time imbalance. As a consequence, the demand for balancing services is very volatile. As a result, the price of balancing energy can vary from just a few Euro per MWh to several hundreds Euro per MWh in just a couple of minutes (Fig. 3.12). In [13], the relation between the price obtained on the day ahead market and the balancing services is examined. It was concluded that often the monthly average of the balancing prices is often higher than the average price of the day ahead market. This could open an opportunity for solar power. As a solar plant has very high dynamics, it could be a very interesting provider of balancing services. However, as one can never be sure of solar power for a certain time in advance, balancing services are somewhat difficult.

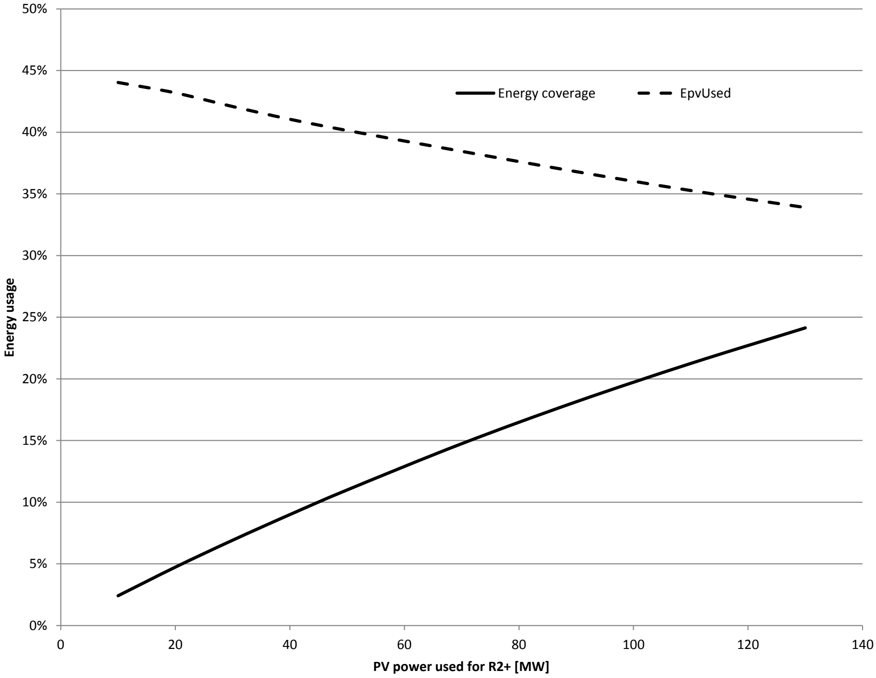

Figure 3.10: Coverage of R2+ energy by solar power in function of reserved solar capacity

In this section, it is investigated if it could be profitable not to sell solar energy on the day ahead market, but keep it as quick deployable positive balancing power. As such, solar plants can cover some of the balancing services covered formerly by gas turbines. However, this is only valid as long as there is enough solar power available. Also, a producer should nominate the available reserve power a day before possible activation. This further increases the difficulty of providing positive balancing power with a single renewable source.

As a result of keeping reserve power, a lot of energy will be curtailed. This will result in waste of renewable energy, but can save on natural gas or other primary sources as the must run time of gas fired plants can be reduced. However, due to the intermittency, solar power will never be able to replace controllable sources like gas turbines. As is shown in Fig. 3.10, even in a sunny month like June, only 40 % of the R2+ energy can be delivered by solar power.

As Fig. 3.11 shows, requested upwards regulation power is a discontinuous function (grey line). The dashed line shows the available power of three consecutive days in May 2013. It can be clearly seen that many requests of R2+ power are larger or fall completely outside the available PV power. The reserved solar power consisted of an aggregated PV park of 130 MWp spread all over Belgium. This spread minimised the short term variability typically seen on PV power curves. It should also be noted that although 130 MWp solar power was installed, this peak

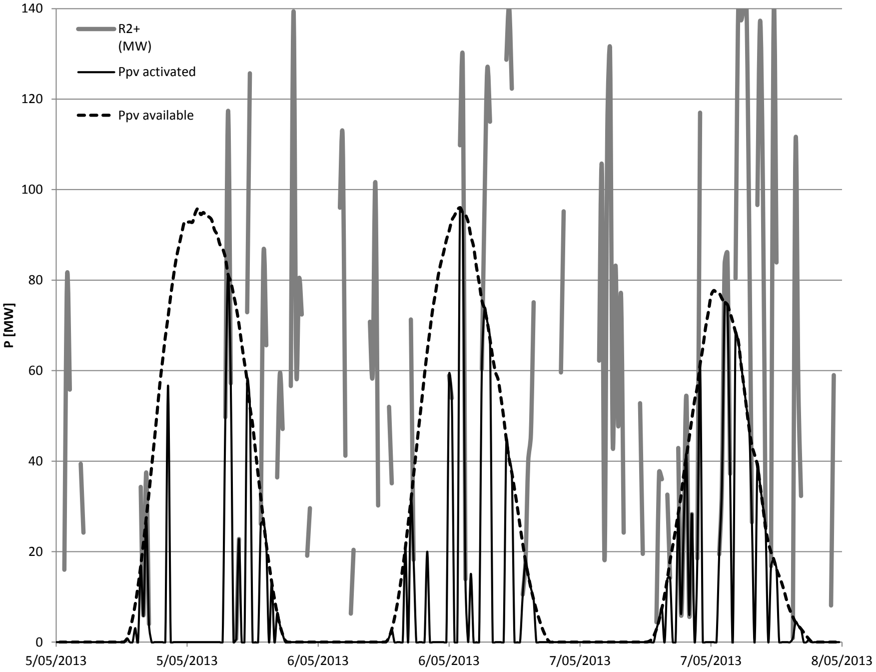

Figure 3.11: Requested R2+ power, Available PV power and activated PV power

power was never reached.

3.8.3 Price of positive balancing power

As has been presented in [13], Fig. 2.13 depicts the average price of the day ahead market, positive balancing service and negative balancing service. However, these are only average values. It is more important the price is high at the times much solar power is available and positive balancing power is requested for.

According to the market rules, the price for reserve power is determined by merit order [76]. The supplier is paid (or need to pay) the bid price. However, in the data published by the TSO, only the price of the largest selected order is shown. As a result, only the supplier with the highest selected bid will receive the reported price. The other selected suppliers will receive a lower price according to their bid. As a remark, the BRPs who need to buy balancing services to compensate for their imbalance pay all the highest bid with an added premium.

Figure 2.13 shows an excerpt of prices offered for energy. The double black line shows the Belpex DAM price. This is the price of the day ahead wholesale market. The grey line is the price the BRPs get for having a positive imbalance. The black line shows the price offered by the grid operator for R2+ (positive frequency restoration reserve). The operation of this service is covered in §3.4.3. As

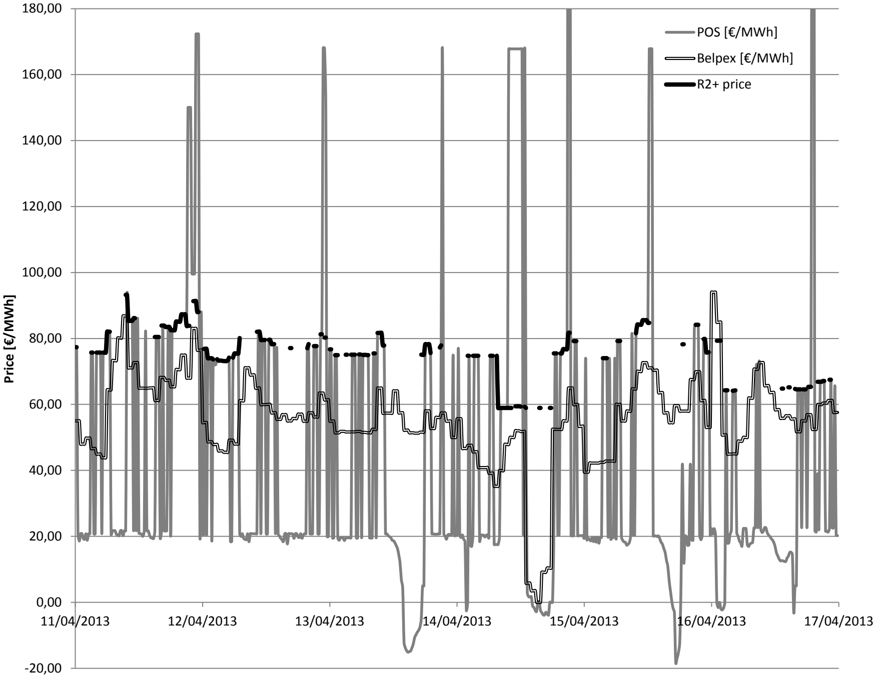

Figure 3.12: Price of R2+, Positive imbalance and Belpex DAM

not for every fifteen minutes positive regulation power is requested, there is not always a price fixed, hence this is not a continuous line. This graph shows the price of R2+ is almost always above the DAM price by a considerable margin. This should encourage suppliers to keep some headroom and provide upward regulation if the system requests for it (large suppliers are obliged to keep headroom and need to provide this service in order to get grid access).

The most flexible price is the price of the positive imbalance settlement. It fluctuates considerably between very low values (20 €/MWh and quite high values (80 €/MWh). This price sometimes even gets negative or sky-rockets to extreme prices of 180 €/MWh and more.

Figure 3.13 shows the average price of both positive imbalance power and R2+ for the quarters R2+ is requested. It can be seen the positive imbalance settlement price is higher than the R2+ price. If compared to Fig. 3.12, this could be attributed to the high price spikes paid for positive imbalances.

3.8.4 Case study

In this section, it is investigated how much financial gain or loss a cluster of PV power would have if used solely for upward balancing. This means no power is sold to the market and all the power from the VPP is sold as upward regulation

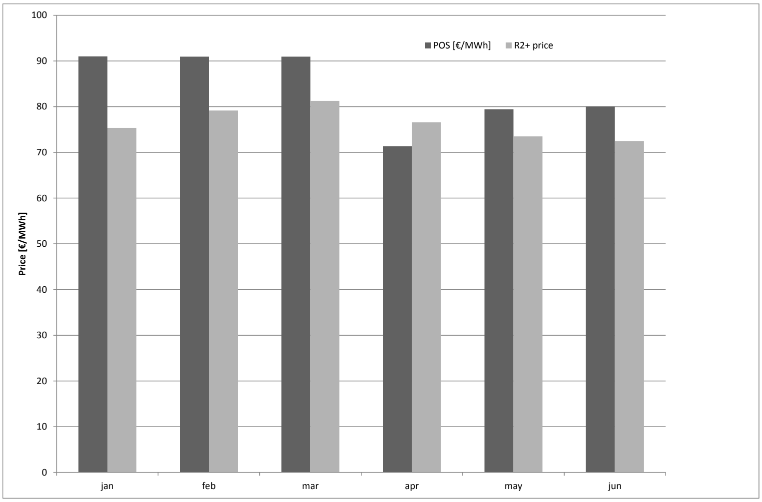

Figure 3.13: Average price of R2+ compared to positve imbalance price per month (2013)

power. The VPP used for this case study consists of many smaller PV plants spread all over Belgium to reduce short therm variability (cloud cover). The total installed power is set to 10 MWp and is solely used for upward regulation.

Figure 3.14 shows the relative financial result of trading solar energy as upward regulation power. The reference used is the revenue obtained if the power was perfectly predicted and sold to the day ahead prices.

Each left bar (dark grey) shows the relative result if the solar power was not taken into account by predicting the market position. All produced power is so sold at the positive imbalance price. Although the price is often significantly higher than the day ahead price, large portions of the time an upwards imbalance is offered only a very low price. This results in a significant loss in all months investigated.

The second bar (light grey) shows the relative result of selling the PV power as frequency restoration reserve (R2+). The results are somewhat mixed, but on average about the same result of positive imbalance is obtained. Generally, a significant loss is obtained compared to selling to the day ahead market.

The third bar (middle grey) of Fig. 3.14 shows the relative result if first power is sold to the TSO as R2+. The remainder of the energy is sold as positive imbalance. For the first months, this still results in a loss compared to DAM trading. However, in June a positive result is obtained using this method. It should be noted however that according to Fig. 2.13, the average day ahead price was quite low compared to the earlier months of 2013. This could indicate it is only interesting to sell PV

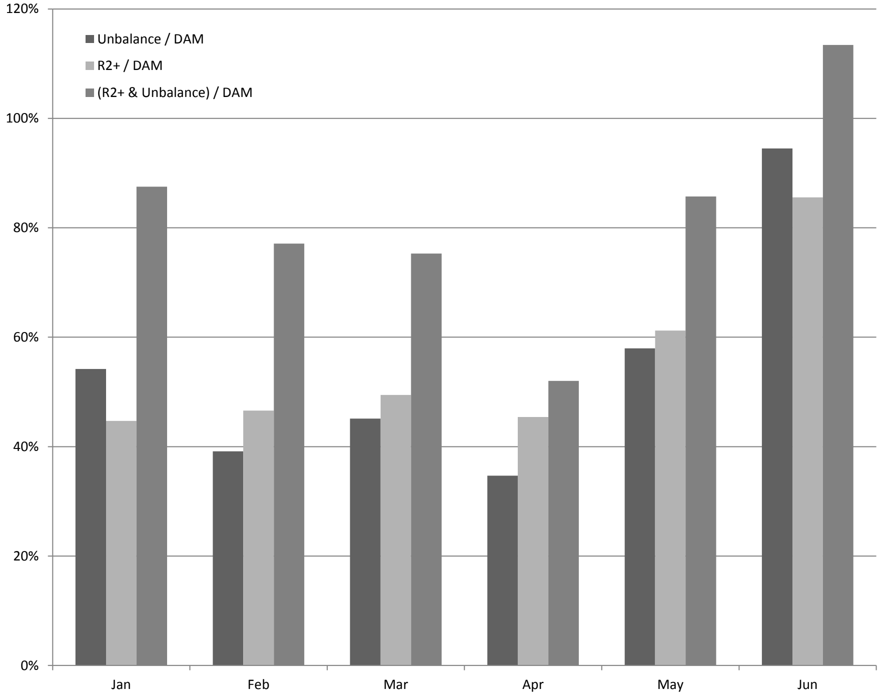

Figure 3.14: The relative margin of upwards power to wholesale (day ahead) trading

power as reserve power if the average DAM price is quite low.

The second aspect studied is the energetic efficiency. As stated above, keeping PV power in reserve to provide balancing services will result in a net energy loss. As positive balancing power is not always needed, the PV power should be curtailed if not sold as positive balancing power. Fig. 3.15 represents the effective produced energy per month relative to unrestricted production. It can be seen only about 40 % of the available energy is actually produced to deliver R2+ power. This is a loss of 60 % of energy compared to normal operation of the same PV park. If R2+ service is provided, the remainder can be curtailed or can be sold as positive imbalance. As indicated above, it is financially less negative to sell the remainder as positive imbalance instead of curtailing it. Also, this will result in less or no curtailed energy.

3.8.5 Conclusion combining balancing and congestion management

Trading solar power in the existing wholesale markets is not straight forward. Even if a VPP can aggregate enough power to meet the minimum requirements to participate in the markets or to deliver ancillary services, it should be decided how to trade the power. However, it seems to be preferable to combine solar power with

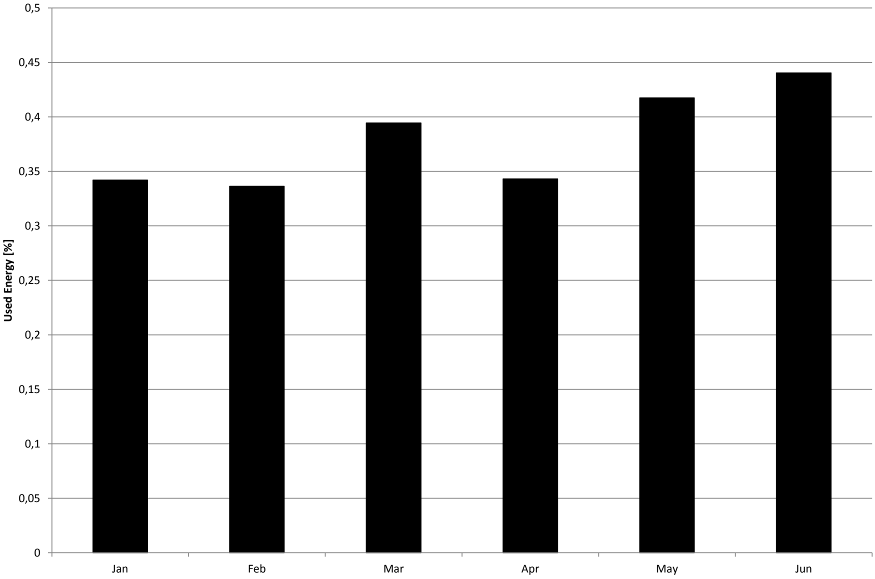

Figure 3.15: Part of PV power used to deliver R2+ relative to potential available PV energy per month

other technologies to mitigate the uncertainties.

The case study performed suggest keeping PV power in reserve to deliver positive frequency restoration reserves is nor economically nor energetically profitable. Although previous research suggested that due to the on average higher price of positive imbalance compared to day ahead trading, it could be viable to keep PV power in reserve, this study shows this is not always true. Further research should indicate if combining this methodology with switchable loads would be more interesting.

The work in §3.8 has been published as an article [14].

3.9 Opportunities for residential load reduction as emergency measure

Countries and utilities deploy smart meters today. Many of them have solid reasons to deploy smart meters. In Italy for example, fraud was a major driver to install smart meters. However, in other regions, the cost of working meter replacement is still too high. In Belgium for example, the grid operators are hesitating to begin a large rollout of smart meters due to concerns about cost and reliability.

In the winter of 2014, due to the loss of three nuclear reactors in Belgium, the system may not have enough production capacity to cope with all demand. At the end of the summer in 2014, plans were made to cut power to entire cities

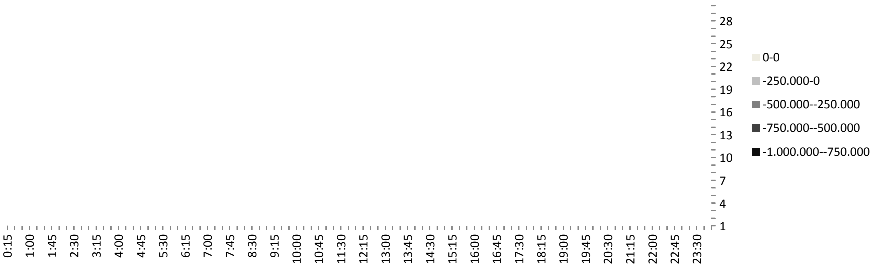

Figure 3.16: Capacity shortage (negative operations reserve) in Belgium, November 2014. Peaks show hours with expected shortage

to prevent a system collapse. As the grid operators have no direct possibilities to control consumption as of today, the last resort to decrease demand is to shut down distribution transformers and cut power to a whole region. Fig. 3.16 shows a graph of excess power demand in November 2014, showing a serious risk of shortage during weekday evenings. This figure is based on consumption data of Belgium in November 2013 and the available production capacity predicted for November 2014 [36]. The 'mountains' are the hours during which energy shortage is expected based on production and consumption data.

This analysis is also supported by the ENTSO-E winter outlook, stating Belgium is at risk of loss of load for every week of winter 2014/15. In severe winter conditions, France has also a serious risk of loss of load [77]. February 2013 was an exceptionally cold month, occurring on average once in 6 years according to the Belgian meteorological institute. The peaks show the periods in which demand exceeds Belgian production capacity. However, due to a warmer autumn and winter than usual, shortage did not occur. The relatively high temperature reduced the demand in Belgium and France, while the Netherlands had enough capacity to export. The average production capacity in Belgium was 11.2 GW while the peak power was 13.5 GW. The remainder had to be imported. The situation was especially precarious during the outage of the nuclear power plant Tihange 3 (30/11/2014 - 2/12/2014), with a capacity of 1 GW. Only import saved Belgium from emergency situations. Almost the entire import capacity of 3.7 GW was needed to cover consumption during this period [36].

As more power plants are considered or planned for mothballing or closing and no new production capacity is planned in the short term, only load reduction is left to cope with the current situation in Belgium and France. This should not be useless, as demand side management can be considered as a valuable resource in the future [78]. A highly decentralised energy system can benefit from demand side management (DSM) to reduce costs and to balance supply and demand. In [79], it is also shown that emergency demand response can have a positive impact on the cost of spinning reserve, the excessive energy and loss of load.

A positive impact can be expected from the smart grid on both technical, social and economical points of view [80]. To provide an intermediate, transitional, solution towards the smart(er) grid, in this section, it is suggested to expand the use of the ripple control system already available in many distribution networks. While smart meters can have certainly their use cases, they might be too complex (and expensive) to replace all meters. In many cases, simpler alternatives might be more economical to implement. This might be especially true for emergency demand response, which is only activated only a couple times a year.

Many households and industrial customers are already reached by ripple control signals. Many smart grid applications can already be implemented by further utilising the (one way) communication provided by the existing ripple control infrastructure, hence alleviating the immediate need to invest in expensive smart metering infrastructure and management. The possibilities of this infrastructure are obviously limited as only binary switching of 3-5 channels is possible, although many control schemes could be implemented with only a limited amount of communication. The use of ripple control for load shaping was already mentioned by [81].

The section is structured as follows: in §3.9.1, the existing ripple control infrastructure will be discussed. Next, in §3.9.2, extended or modified pricing options are discussed and in §3.9.4, direct load control options are discussed. Every method is described, arguments pro and contra are posed and the influence of each method is estimated according to the number of households in Belgium [82] (based on the data of 2011). Next, §3.9.7, discusses options to control distributed generation (DG).

In §3.9.8, a direct load control strategy based on spare outputs of existing ripple control receivers is investigated in detail. The benefits of this system are compared to the current proposed strategy of regional curtailment in Belgium. It is investigated if selective curtailment of residential customers can provide emergency (downward) reserve to prevent a total black out in case of production shortage during peak consumption hours.

To finish, in §3.9.12, a conclusion is drawn.

3.9.1 Existing telecontrol infrastructure

As stated in the §3.9, this section draws upon existing ripple control infrastructure. This paragraph discusses the infrastructure and its abilities.

3.9.1.1 Basic operation

Ripple control signals are currently widely used for simplex communication from the grid operator to customers. Example uses are tariff switching and street light control. Signals are superimposed on the fundamental frequency of the grid. The superimposed signals have a frequency between 110Hz and 3000Hz. Receivers in the client metering cabinet use these signals to switch their output. Commands are repeated several times to prevent data loss due to signal loss. Clients need to ensure their impedance for the applicable frequency is high enough to prevent signal loss, e.g. in capacitor banks.

3.9.1.2 Grid operator infrastructure

At the grid operators side, the main infrastructure is the ripple control transmitter. This transmitter injects a signal voltage on top of the supply voltage. In Belgium, most of this signal injection is done at distribution level. Most of these grids have a voltage between 11 kV and 15 kV.

3.9.1.3 Client infrastructure

Almost every household is equipped with a ripple control receiver. These receivers switch their output if the appropriate signal is received. Most receivers have 3-5 relays outputs and are programmable trough an optical connection. The first output in residential installations is mostly used to control the meter selection. This leaves 2-4 outputs unused, available for other purposes.

3.9.2 Pricing variations

Pricing variations are a 'soft' demand response signal. No direct intervention to the user processes is applied. Instead, the user keeps the freedom to respond to the price or not. This method is used for decades in many countries (day/night tariff). In Fig. 3.18, the G1.4 graph (light line) shows a peak after 23h, the start of the night tariff period in most regions in Belgium. It should be noted however, that many of these loads are automatically switched due to the night only metering circuit. So although the user has the freedom to choose the time of use, the largest power swing is automated.

3.9.2.1 Changing On/Off-Peak pricing schedules

Traditionally, On/Off-Peak price switching is done on fixed times. These times depend on the local grid operator. Often, peak price is charged between 7h and 22h on weekdays. The other hours and weekends are Off-Peak price. Without any changes on the consumer side, this fixed schedules could be adapted. For example, the low price could be in effect when much solar or wind power is available. During expected energy shortages, the high price should be maintained. Extra relais outputs could be used to warn the user of a tariff change. The effect of this method is highly dependant of the awareness of the user of the pricing changes or the amount of automatically switched consumers, e.g. domestic hot water heaters. In [83], a method is described to evaluate the potential effect of changing the tariff switching moment. No changes are necessarily to be made on the electrical system of the user. However, an effective method of informing the user of the pricing schedule is necessary. This can keep the cost relatively low. The positive effect of this method is its simplicity. As proven in [84], the re-assignment of off-peak tariff can lead to a significant reduction of curtailed solar energy in domestic installations. As a negative point, this method heavily depends on price sensitivity and awareness of the user. Without both, this method would have limited impact on total consumption. Secondary, the risk exists the user would get tired of checking the pricing schedule, further reducing the impact.

3.9.3 Introducing additional pricing levels

Most users now have only single or double pricing. Increasing the number of pricing levels is possible by introducing extra energy counters. With three binary outputs, theoretically eight prices could be communicated. A more practical method would be introducing one very high price and possible a very low price.

An intermediate solution with a simple smart meter could also ease the applicability of this solution. A digital meter can register time of use and tariff switching commands and store the data to a memory card. The (content of the) memory card can be sent to the supplier and the price applied retrospectively. Just as the previous method, this method is highly dependant on user awareness and price sensitivity. If not enough of the process is automated, the risk is high the user will not change his behaviour. Implementing this method would require the installation of extra energy counters in the meter cabinet. As an energy meter is a quite expensive component, this would require a significant investment in equipment. As a positive point, price aware consumers could be influenced and further steered to use energy when it is abundant. The price and complexity of installing, maintaining and registering many extra meters would be very high. Also, without a flexible timing as in the previous method, the effect would be very limited. Complex pricing strategies would only be practical if combined with a smart meter and an extensive communication network to automate the whole process.

3.9.4 Direct load control strategies

As opposed to pricing variations, which rely on the price sensitivity and awareness of the user, direct load control strategies directly influence the consumption. As the user is less involved, the reaction to a command is much more predictable. This lend direct load control schemes better for reaction to emergency situations. An emergency event can directly trigger load shedding [85].

However, the possibility of the user to decide when to use energy is more limited. This method hence lends itself more as an emergency strategy or for appliances without direct user interaction. The effect of different DSM methods in Hungary is discussed in [86]. This section also acknowledges the need of direct load control methods (as opposed to 'soft' DSM methods like dynamic tariff switching) to react fast and reliable to sudden situations.

3.9.4.1 Interruptible load

Many households already have circuits powered on off-peak hours only. This could be enhanced by adding a separate circuit, connected to the off peak energy counter and controlled by an extra channel of the ripple control receiver. Grid users can use this low(er) priced energy for non essential interruptible loads. This could for example be the garden or hallway lightning, pool filter pumps or even electric stoves. Preferably, this should be circuits with hard wired appliances to prevent users of simply using an other, non interrupted, wall outlet if the curtailment is activated. The effect is highly dependant on the user price awareness. Users can reduce their bill by rewiring uncritical loads to interruptible circuits. However, as user action is involved to pay for an electrician to rewire their distribution cabinet, the effect could be limited.

Implementing this method requires some rewiring in the distribution board of the user. This can be time consuming and hence costly. However, only a power contactor and an extra output relay for the ripple control receiver are needed, so installation cost for the utility is limited. Rewiring of the distribution board can be left to the electrician of the consumer, as it is the consumer who decides which circuits are eligible for interruption.

The main cost of this method would be the reduced price of the energy to the consumer. As the user selects more circuits to be interruptible, a larger share of the total bill will be shifted to the low tariff counter. The cost could however be reduced by interrupting the loads during high price periods on the wholesale or imbalance markets. This strategy can be implemented easily in the electrical distribution cabinet of the user. It requires only installation of an extra relay output in the ripple control receiver, a power contactor in the distribution board and rewiring of selected circuits. Most of the work can be done by any electrical technician. Only the power contactor and the extra output of the receiver need to be installed by the grid operator in the sealed part of the customer distribution board. If only this part is carried out by the DSO, the installation cost for the DSO can be very limited.

Many large household users have a separate circuit already. As 'wet' appliances like washing machine, tumble drier, water pumps are required to be supplied by a dedicated circuit, rewiring should be an easy task. If wall outlets are controlled by this method, the user can simply use an other outlet and thus mitigate the effect within seconds to minutes of activation. Many large consumers are connected by wall outlets and are hence less favourable: washing machines, tumble driers, microwave ovens,. . . This could minimise the effect of this system. However, switching to other outlets results in higher priced energy.

As this method would require switching some circuits to the low tariff counter, a larger share of the total bill would be sold at a lower price. This could reduce the income of energy suppliers.

The effect of this method heavily depends on the time of activation and is only usable as downward regulation. Many of the appliances are only active for a relatively short time, hence the effect could be low. However, during typical peak hours, when downward regulation could be very valuable, many of the household appliances could be active. This could compensate for the limited availability (and predictability) of the service.

3.9.5 Power reduction

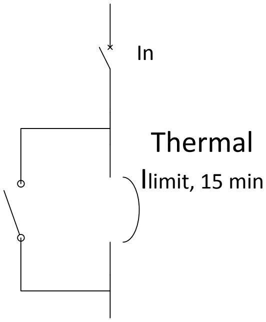

Figure 3.17: Power reduction shematic

Instead of the complete curtailment of the load, a different strategy could be implemented. A secondary circuit breaker with a lower current rating could be installed in series with the existing breaker (Fig. 3.17). As long as no load reduction is needed, this breaker should be bridged by a power contactor. As a result, during normal operation, the user has all the contracted capacity available. If power reduction is needed, the contactor should be opened. The lower rated circuit breaker is now in series with the consumer, effectively reducing the available capacity.

The effect depends on the choice of power reduction ratio, the type of user and the time of use. As can be seen in Fig. 3.18, the average consumption of a private (home) consumer triples or quadruples on an average winter evening. Limiting this rise by reducing the available power can have a significant effect if used on this hours.

The cost of this method per installation could probably be very low. Only three components are needed: a circuit breaker, a power contactor and one extra relays output for the ripple control receiver. All three components are common and relatively cheap. Installation of those components and reprogramming of the ripple control receiver could be done in a very limited amount of time. As a rough estimate, the installation time will be 30 minutes. However, to have a significant impact, many households should be altered, hence increasing the cost.

The main benefit of this strategy is that the user is never left without power. This is a major benefit over a rolling black-out strategy where many users are completely cut off from power supply. As a result, the effective impact on the society will be much less than the black out strategy while maintaining a reliable power reduction. As the available capacity to the user is effectively controlled, this is a reliable solution. Tampering is almost impossible and at the same level as tampering with the meter itself.

Implementation of this strategy is also very simple. It only requires an extra circuit breaker, a power contactor and an extra relays in the ripple control receiver. All of this equipment can be located in the sealed meter cabinet, hence preventing tampering. Also, as no modification to the rest of the installation is required, this could be done in a very short time per installation.

If the user overloads the circuit breaker, all power will be lost. This requires the user to manually reset the breaker to restore power. Managing power consumption manually will be necessary for the user to prevent frequent tripping of the breaker. This could be tricky as most energy meters have no direct indication of power. This could be mitigated by installing a cheap current meter in the cabinet, but this would increase the cost of the retrofit. Also, the users should be warned well in advance of the power reduction to give them a chance of voluntary load reduction to prevent tripping of the breaker.

3.9.6 Thermostatically controlled loads

Many household consumers are thermostatically controlled: refrigerator, freezer, heat pump,... These can be used to respond to dynamic grid situations. Different implementation methods exist: changing deadband, changing setpoint, synchronising behaviour, etc These algorithms can rely on local information, for example the grid voltage. However, to be able to react to grid-wide circumstances, communication is essential. Almost every household has one or more thermostatically controlled loads. In western Europe, the most prevalent are refrigerators and freezers. These are relative small consumers regarding power consumption. However, they are 24/7 available. If a single combination unit (refrigerator and freezer) has a power rating of 160 W and an estimated energy consumption of 204 kWh per year, the average power consumption is 23 W. This also means the duty ratio is on average 15 % on time. Belgium has 4.5 million homes. This can be translated in 108 MW permanent consumption. Requesting all units to switch off, this power can be made available to the system. If however all units are directed to the on state, a power surge of 612 MW can be demanded.

The potential with electrical water heaters, heat pumps or other larger loads is much higher. However, their relative low penetration level translates in a lower potential. Even with a large penetration degree, these appliances are harder to utilise, as their usage and consumption pattern is much more variable. The viability of this method is highly limited by the cost of implementation. This method would require the thermostatically controlled loads to be equipped with extra inputs to signal the preferred direction. Also, extra equipment or cabling is required to connect every load to the ripple control receiver.

As this method utilises the dead band of thermostatically controlled loads, the effect on user comfort can be neglected. Large loads controlled by an intelligent and reconfigurable controller (e.g. a programmable logic controller) makes this an easy method to implement in large cold stores. Although the effect is limited, it could provide a reliable way of activating available flexible capacity.

As this method relies on the thermal capacity of the loads, the effective time this method can be used consecutively is limited. Combined with the high cost of installation and limited effect, the applicability to many small installations is quite low.

3.9.7 Distributed generation control

In many situations, Distributed Generation (DG) suffers from limited injection capacity of distribution grids. Traditionally, distribution transformer tap changers are set a little bit above nominal voltage to compensate for voltage drop in the distribution grid. If power flow reverses during sunny hours with low consumption, over-voltages occur along the line. These over-voltages trips the grid protection in the inverter and power production of the plant is automatically curtailed. This could result in oscillations and unpredictable curtailment along the line. Some users will experience more over-voltages and hence production curtailment than others. This could be regarded as an undesirable effect.

Also, at certain moments, typically during windy and sunny spring weekend days, a system wide overproduction of renewable energy can occur. As a large share of the energy is delivered by renewable sources, traditional sources are shut down. However, ancillary services are only delivered by some of those traditional plants, so they cannot be shut down.

The spare outputs of the RC could be used to instruct (partial) DG curtailment. Many commercial inverters have the option to limit power to a certain percentage of their nominal capacity. Systems with a high penetration rate of renewable energy risk of producing more energy than is consumed. Export to neighbouring systems could then be an option. However, this is not always an option, hence curtailment is necessary then. In [87], it is described how renewable energy curtailment can increase the hosting capacity of the grid. Installation cost can be very low. Only a spare contact is needed if the RES has an option to be externally controlled. In case the RES source lacks this input, connecting to a separate power contactor controlled by the RC is also an option. Direct control over (some of) distributed production could allow grid operators to be more flexible in grid management. Hence, the rules to obtain grid access for new DG units could be eased, allowing more DG units to be connected to the grid. As a result, a larger share of the energy can be produced by renewable sources.

Compared to the voltage based droop method [88], this method has the advantage it is directly manageable by the grid operator. The droop control is designed to alleviate local problems, but the coordinated solution can also reducing more remote congestions. European legislation forbids the curtailment of renewable energy sources for non safety reasons [89]. This significantly limits the current applicability of this method. However, the priority dispatch obligation will not be uphold in the future if instantaneous renewable production exceeds more often the demand.

Curtailment of renewable sources will reduce the profitability of certain installations. Some installations which are currently not curtailed due to their favourable position on the cable, will also be curtailed if they adopt this control. As a result, it would be difficult to oblige this strategy to existing installations.

Most DER units operate at a fixed power factor. However, many electronically (inverter) coupled units have the possibility to control their power factor. This can be useful to control the voltage in the grid. Having the possibility to control the power factor of DER units could enhance the voltage control in the grid. However, as the resistance in distribution grids is often much higher than the reactance, the effect will be limited and the losses will rise significantly. Installation cost for the grid operator could be very limited. Only a couple of digital outputs need to be brought out of the sealed metering cabinet. Connection to the inverter can/should be done by the end customer. Many inverters already have the possibility to connect some digital inputs to control some settings. For some models, these connections are present directly on the meter itself, for other systems a separate module should be installed. Voltage control in grids often requires expensive equipment like variable tap transformers, synchronous condensers or large capacitor banks. By utilising already present capabilities of power electronic inverters, the investments in those technologies can be reduced. Due to the increased current, the losses in mostly resistive low and medium voltage grids will increase. This method could only work in locations where the need for reactive power is high and enough current capacity is available.

3.9.8 Case study

Of all above opportunities, the power reduction mentioned in §3.9.5, seems to be the most applicable in Belgium. As described in the introduction, due to the closing of several nuclear power plants, a power shortage could become real. As a solution, the government and the grid operators have designed a scheme for a rolling blackout. In case this scheme should be activated, the impact on society and industry will be very high. Six zones of 500 MW each are selected to be curtailed in case of shortage. As a very low degree of automation is available in the grid, the curtailment will be carried out on a high level in the grid. The result is that not only non-priority consumers are curtailed, but also hospitals, large industrial sites, traffic lights, gas substations, ... A selective curtailment would be much more desirable in such a case. Two of the above mentioned methods seem feasible to implement with a reasonable cost: complete curtailment and power reduction. In this section, the potential effect of these measures will be quantified.

3.9.8.1 Assumptions

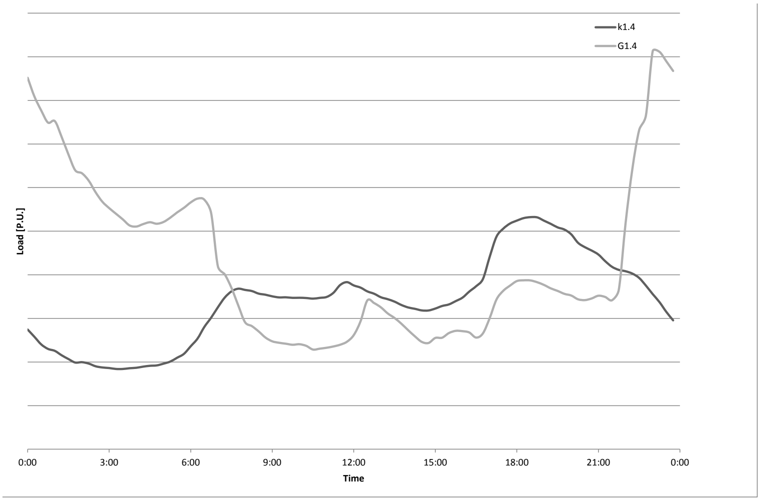

Figure 3.18: Residential load profiles, the basis for residential power and energy predictions

According to the Flemish energy regulator, an average household consumes about 3500 kWh per year. However, not every household consumes electricity in the same way or at the same time. To predict the average household consumption for every 15 minutes, synthetic load profiles are designed. Two shapes, k1.4 and G1.4, are in use for residential customers (fig.3.18). A division is made between consumers with a single energy counter or a night/day consumption rate smaller than 1.4 (k1.4) and consumers with a night/day consumption rate higher than 1.4 (G1.4). In this study, half the consumers are nominated according profile k1.4 and half according to profile G1.4. This division is based on empirical data.

These profiles are used by suppliers to buy and nominate the needed energy in the markets. In these profiles, the total annual consumption is split in fractions for every quarter hour. So by multiplying the fraction with the annual consumption, the average power for one consumer is known. To estimate the total demand, this 15 minute average power is multiplied with the number of households. In Belgium, there are 4.5 million households.

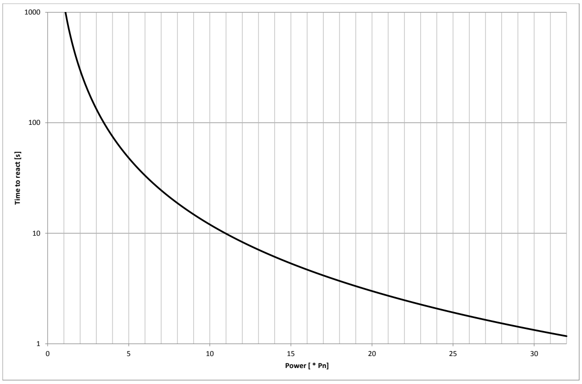

Figure 3.19: Reaction time of thermal circuit breaker in function of nominal power

To place numbers in perspective, the total electricity consumption in Belgium varies between 7 GW and 14 GW, depending on the time of day and day of year. From this total consumption, residential consumption varies between 162 MW and 1.2 GW.

3.9.9 Implementation

The purpose of the strategy is to limit the consumption by residential customers, without interrupting service completely. Due to the high number of customers, only the average consumption is important. As a result, it is not necessary to use traditional circuit breakers with a very short reaction time. A softer characteristic like the I/t curve of a motor protection would be more appropriate. With this implementation, consumers can still use more power than the limit for a short time, but the 15 minute average is limited. This reduces the risk of tripping the circuit breaker due to a short energy burst. In this way, it is still possible to use the microwave oven to heat something for a couple of minutes, but it is not possible to use washing machines or electric water heaters. Hence, the 15-minute average load is effectively reduced to the desired level without compromising user comfort to much. This thermal protection relay is bridged by contactor in the normal situation. In case the curtailment is active, the contactor opens and the thermal protection relay is in series with the load.

The values in this section are based on synthetic load profiles, and are hence averages. The peak power of the profiles is 836 W (k1.4) and 1322 W (G1.4). It may be clear that many consumers have a peak consumption far higher than these values. The difference between the load profiles and individual consumption is due to the simultaneity and duty cycles of loads. The use of slow (thermal) circuit breakers with a 15 minute time constant will effectively enforce the maximum load without tripping due to small and/or short power levels above the desired power level (Fig. 3.19).

3.9.10 Results

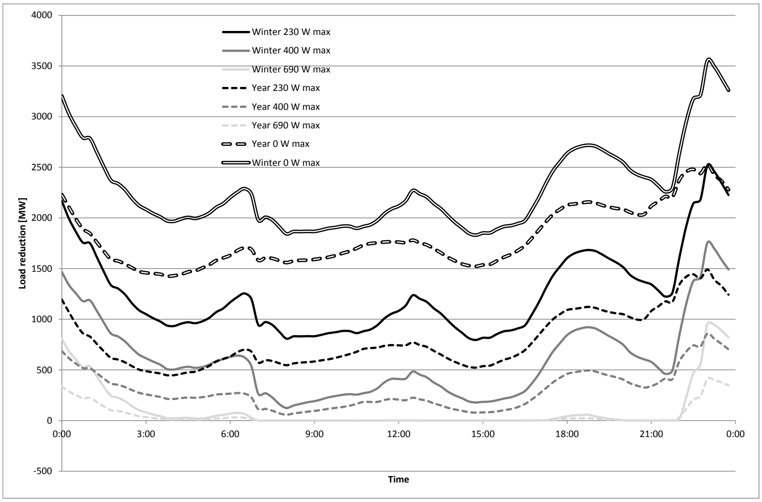

Figure 3.20: Possible load reduction based on residential curtailment

As the need for curtailment will be highest during the winter months, the results are displayed as annual average and winter average. November through March are considered as winter months. Based on the above assumptions, three curtailment levels have been applied; 230 W (1 A), 400 W (the average consumption) and 690 W (3P, 1 A).

The possible load reduction in megawatt per 15 minutes is shown in Fig. 3.20. The graph shows clearly the load reduction potential is highly dependant on the time of day. The time of the year has also a large influence as the difference between the winter and whole year curves indicates. This is not necessarily a problem, as the grid load and hence the need for curtailment in Belgium are the largest during the winter months.

It is also important to note that these values are averages over several months and types of days. The load profile of a normal working day is different than that of a weekend day or a holiday. To exploit this load reduction potential, an estimation per day should be made to nominate the capacity in the balancing markets. These estimations should be no big challenge, as only the synthetic load profiles are

	Residual power		
Total power	0 W	230 W	400 W
100 MW	170 k	278	524 k
250 MW	425 k	696 k	1309 k
500 MW	849 k	1392 k	2619 k
1000 MW	1700 k	2784 k	5237 k

Table 3.1: Necessary number of participants for different curtailment levels (average between 17h and 20h

needed to calculate the potential. Hence, the same relative error will be expected. If only a 99 % certainty band is nominated as reserve, the same firmness can be reached as with traditional methods.

If the power is reduced to only 230 W, roughly 500 MW is minimum available during a whole year at any time of the day. However, during the peak load period (17 h - 20 h), more than 1000 MW is available. During the winter months, 700 MW - 1000 MW is available during the day. During peak hours, more than 1500 MW can be curtailed. Compared to the current curtailment plan, this equals 3 regions simultaneously.

If the minimum allowed power is raised to 400 W, the availability is significantly reduced. During the day hours, the power reduction potential drops to only 250 MW. However, during the peak load period, 500 MW - 750 MW is available. The all year average is significantly lower, peaking at 500 MW on 19h. Limiting the power to 690 W per household diminishes the potential effect of the intervention almost entirely. Only night consumption could be affected significantly. However, the necessity of curtailment during night hours is negligible.

If the load reduction to 200 W is compared to the total curtailment of residential customers, the effect is about halved. However, the customers still have basic power to fulfil basic needs like central heating, refrigerator, communication and basic lighting. The social impact will be significantly reduced. At the same time, the implementation cost is not significantly higher as the only difference is a thermal breaker. However, compared to the current solution, power curtailment at transmission station level, the impact on society is significantly reduced. Essential safety infrastructure remains unaffected. As the effect is possibly large enough to reduce power enough in almost all cases except total system failure, industry can remain unaffected, even further reducing the economic impact of the method.

3.9.11 Costs and revenues

The cost of manual curtailment can also be estimated. Curtailment requires extra operational personnel in the grid operations centres. A reasonable number of extra operators is 10 for the Belgian control area. Curtailment requires also field personnel. Many of the distribution stations can only be manually operated. Once the substation is switched off, individual distribution cabins should be switched off before power to critical infrastructure can be restored. As there are about 70 substations involved in the curtailment plan, and one out of six is curtailed at once, there are on average 12 substations curtailed at once. Requiring two technicians per substation to switch distribution cabins, 24 technicians are required in the field. It is estimated that 10 days per winter, standby for curtailment will be needed. The people involved will be paid €50 per hour and for 7 hours a day. In total, the personnel cost adds up to €119.000 per winter.

The cost of a non-selective curtailment is estimated to 55 to 120 million Euro per hour curtailment [90]. A moderately problematic winter requiring 10 hours of curtailment hence results in about 550 million to 1.2 billion Euro. The residential cost of one hour curtailment is estimated to 7.1 million Euro and is included in the aforementioned total cost. As industrial curtailment can be evaded with the proposed selective curtailment and residential curtailment should not result in a complete loss of functionality, most of this cost can be evaded with the proposed method. It seems reasonable to reduce the cost of the selective curtailment to 50 to 100 million Euro per winter. This results in a relative yield of 450 million Euro to 1.1 billion Euro.

Selective curtailment can also be sold in the reserve markets. Based at the available power (Fig. 3.20) and a reserve power value of €3500/MWh, activation of this reserve can yield a revenue of up to €6.400.000 per hour. Based on 10 hours curtailment per year, a revenue between 4 million Euro (curtailment to 400 W) and 64 million Euro (based on 100 % curtailment) per year can be made. The value of this reserve power is based on the price cap on power contracts in the Belgian day ahead power market. This is currently 3500 Euro/MWh. As curtailment will be the last resort, it is reasonable to apply this price to the available volume. Next to this energy value, the system operator could award a standby reward for this emergency contract. Based on a minimum availability of 100 MW and a reward of 1 Euro / MW / hour, this could source 360.000 Euro per year with only 5 months availability. This brings the measurable yearly revenue up to 6.760.000 Euro based on 10 hours of insufficient supply.

Implementation of this method is not without cost. All residential meter cabinets should be equipped with new hardware and the ripple control infrastructure should be reprogrammed. In Belgium, there are about 4.5 million residential clients which would need an intervention in their cabinets. If installation costs can be kept low enough to yield a reasonable payback time, the solution might be worth considering.

Strategy
Pricing variations
On/Off-Peak pricing schedules Additional pricing levels
Direct load control
Interruptible load Power reduction
Distributed generation control
Production curtailment Reactive power control

Table 3.2: Overview of strategies

3.9.12 Conclusion residential curtailment

As a conclusion, it can be stated that many options are available based on the current infrastructure, without the need for immediate implementation of smart meters (Table 3.2). However, only few options are feasible to implement.

3.10 Conclusion TVPP

This chapter started with an introduction to technical VPPs. In contrast to CVPPs, a TVPP will actively support the electrical grid by selling flexibility. This flexibility can be used to deliver several ancillary services to the TSO or to other grid participants (ARPs).

Next, an overview of technical services required to operate the electrical grid was presented. This provides an overview of the possible services and the requirements of these services. As has been presented in §1.4.2, microgrids have been researched previously by Tine Vandoorn and could well be building blocks of a VPP.

Next, the role of storage in a VPP has been investigated. Storage will be absolutely necessary in order to reach the goals set by the European Comission for renewable energy. An overview of different storage technologies is presented and their applicability to the Belgian power system is investigated.

Next, a very interesting case has been developed. Original research showed that a VPP could relocate resources in order to relieve congestion. But the most interesting aspect of this research is that this system could reduce the cost of curtailment. Up till now, no remuneration is given to curtailed resources. The concept presented in §3.7 relocates some resources paid for frequency restoration to congestion management. As no extra expenses are required, this is a win-win both for the TSO and the facility affected by curtailment.

§3.8 presents a piece of research conducted with a less positive outcome. It was investigated if PV could be used as a fast reacting positive balancing resource. As no moving parts are involved and a large production park is already available, this would make technically sense. However, it was found that this is economically not viable under the current circumstances.

This chapter concludes with an investigation of residential curtailment capacity. In §3.9, the potential of residential curtailment is investigated. This original research has not yet been published, but will be (re)submitted soon. It proved that in an emergency, a large capacity could be released by curtailing residential customers. Depending on the level of curtailment and the time of the year and day, tens of megawatts up to three gigawatt could be released. Compared to the maximum load of the Belgian energy system of 14 GW this is significant.

As a final conclusion, a technical VPP could deliver a lot of services. However, the cost and technical capabilities of each flexible resource should be known in order to determine the viability of activation and to which cost.

4

Virtual Power Plants and thermal resources

4.1 Introduction

In many systems, thermal and electrical energy are converted from one into the other. Combined heat and power, steam turbines, heat pumps, electrical heaters, they all convert thermal to electrical energy or vice versa. In many current applications, these systems are designed and controlled by the thermal production or demand. The electrical production or consumption is dependant on the thermal requirements. In many situations, these thermo-electrical devices are among the bigger electrical devices in their (sub)system, making them ideal candidates to provide electrical flexibility. This requires the thermal side to become flexible as well. Due to the vast differences in time constants of thermal and electrical systems, in many situations, the shift in load makes no tremendous difference on the thermal side while offering enough flexibility to be valuable for the electrical grid. If the thermal side offers not enough flexibility inherently, thermal buffers can often be added with a much lower cost than the same electrical storage unit.

As has been detailed in the previous chapters, the electrical grid needs flexibility to maintain its stability. Especially if new intermittent sources like solar and wind energy are connected. However, traditional sources of flexibility are also under economical pressure. Gas turbines and steam and gas plants provide the majority of flexibility in the Belgian system. Due to a decreasing spark gap [73], these units become less profitable and are being closed.

During the last decade, many CHP units, heat pumps and other thermo-electric capacity has been installed. Also in the industry, due to energy efficiency reasons and environmental regulations, a lot of thermo-electric capacity has been installed. Examples are waste heat recuperation in waste incineration plants and steam expansion turbines in process industry. These units are however primarily designed and operated to meet thermal requirements. The operations are also planned based on the thermal profile needed. Electricity production (or consumption) is sent to (or taken from) the grid, without knowledge of the grid state.

This chapter is structured as following: §4.2 sets the boundaries of the available thermal energy. Next, in §4.3, the basic functions of thermal grids are discussed. In §4.4 the VPP concept and thermal grids are combined in a case study. The case study demonstrates the possibility of providing day ahead marked access for renewable energy sources by combining thermal grids, thermal storage units and wind or solar farms within a VPP. Next, in §4.5, several thermo-electric resources and their potential value for a VPP are discussed. To conclude, §4.6 and §4.8 asses the thermal potential in industry and for residential projects respectively.

4.2 Waste heat integration

As studied in [12] and [91], in the process industry, a large amount of waste heat is available. Many industrial companies have invested in heat recovery from one part of the process in another part. This is essential, as process integration ensures the total process is optimised first. This prevents the export of process inefficiencies to a thermal grid. However, in many installations, there is still a large amount of residual heat. This residual heat can come both in quality and or quantity. High temperature steam is much more useful than low temperature. Process integration also takes care of the preservation of exergy, next to energy. First using a high temperature source to produce electricity and then using the exhaust for low temperature heating may be more exergetically efficient than direct production of low temperature heat. many companies prefer to utilise the waste heat for electricity production. These waste heat recovery processes are thus mainly heat driven and do not care about the needs of the electrical grid.

The first goal therefore should be the identification of the true process needs. How much thermal energy is needed and available and at what temperature level. First, it should be investigated if a thermal stream tha should be cooled can be used to heat an other stream. This ensures that only true losses will be exported from the process.

Next, the utilities and their exergetical efficiency should be investigated. For example if natural gas is used to produce low pressure steam, it might be much more efficient to generate this steam by a CHP and produce electricity next to low temperature heat. Although the total gas consumption might be bigger, the total exergetical efficiency will be much higher.

4.3 Thermal grids

First, an overview of some available heat sources and their properties in the process industry is given. Second, an introduction to thermal grids is presented. These grids are used as a thermal sink if the electricity demand is low to preserve energy utilisation and vice versa.

4.3.1 Available heat sources

As mentioned in the §4.1, there is an enormous amount of waste heat available in the process industry. Basically, we can consider all the process streams that need to be cooled as energy sources [92]. First, as much as possible of the available heat should be recovered within the process itself. The remaining energy that cannot be used in the plant itself should be exported. Due to environmental constraints, venting to the environment is only the last possible solution. Therefore, many installations convert their residual heat to electricity.

Another very interesting use of heat is distribution into a district heating and cooling network. This is further explained in §4.3.2. Using waste heat provides a decrease in the use of fossil fuels (for space heating for instance) and thereby a decrease in CO_2 emissions and running cost reduction [93]. The amount of total available heat is determined as the total amount of heat available above the practical working temperature for district heating.

Waste heat is mainly coming from four types of industrial installations: chemical industry and refining, electrical power plants, CHP plants and waste incineration plants [94]. CHP provides heat and electricity simultaneously. Because the production of both cannot be adjusted independently, companies using CHPs are often faced with problems of using all the produced heat when the electricity demand is high [95]. Somtimes, Organic Rankine Cycle (ORC), is used as a conversion technology for low temperature (below 130 °C) heat. If this is not possible due to economical or other restraints, the introduction of extra heat sinks is necessary. Therefore a district heating network can function as heat sink. Temporary storage of heat is an important element of these networks.

4.3.2 Thermal grids and storage

District Heating (DH) and cooling networks are most spread in Northern and Eastern Europe. E.g. the share of citizens served by district heating in Denmark and Finland amounts 61% and 50% respectively [96]. In [97], the difference in energy efficiency between electricity networks and DH networks on natural gas CHP is shown. Although DH networks lose part of the energy input on heat losses and pumping energy, their overall efficiency is much higher. Moreover, when waste heat from industry is used, lower costs and less primary energy consumption and CO_2 emission can be taken into account.

The increase in the production of energy from renewable energy sources necessitates -due to the fluctuating nature of renewable energy [98] - more flexibility in the network [99]. This flexibility can be established by the use of energy storage. According to [100], energy storage is also required when there is a mismatch between the (thermal) energy supply and the (thermal) energy demand. This can occur for instance with the use of a CHP installation. The storage of heat enables the system to produce heat when the electricity prices or the electricity demand are high and reduce the production when the electricity prices or demand is low. Furthermore, the heat demand of a DH network can be predicted on short term by using an algorithm taking account of various parameters including outdoor temperature, hour of day, day of week, time of year, time lag, etc. [101].

In [102], it is show that thermal energy storage in CHP installations can improve the net reduction of CO_2 emission by factor of almost three. The main reason for this the increased continuous operation of the co-generation unit. In [103], the flexibility created by the combination of a district CHP unit with sensible heat storage is assessed. An interesting conclusion is the linear relation between the buffer size and the flexibility of the system. The power of the CHP installation on the other hand does not influence the flexibility. Moreover, [104] showed that the use of CHP systems reduces costs, primary energy consumption and CO_2 emission and that the addition of a thermal energy storage device generates even larger reduction of these factors providing the power-to-heat ratio of the buildings is low enough.

Thermal energy storage, further called heat storage, currently occurs in three main physical principles for heat storage: sensible heat storage, Phase Change Materials (PCM) and chemical reactions. With sensible heat storage, the heat is retained by a material with a certain storage capacity like water, ground, rock or ceramics at a wide range of temperatures. This technology is relatively cheap but has the disadvantage of low energy density and a gliding discharging temperature. PCMs store heat in the phase change and release this heat when the material is cooled down. The energy density of these phase changing (melting or vaporisation) processes is much higher than this of sensible heat. In [105], the benefits of PCM storage in micro-CHP applications are investigated. With storage by chemical reactions, heat is added to a compound to separate it in two components. When heat is needed, the elements are brought together providing heat by the exothermic reaction.

To provide electrical flexibility, there should also be thermal flexibility. This can be provided by thermal storage. To avoid high losses in the thermal storage, temperatures should be kept low. As a result, the available temperature in the storage is quite low, inhibiting the efficient conversion of this thermal energy to electricity. However, as thermal grids can operate at a lower temperature, these can be fed from the thermal storage. As such, high grade thermal energy is preferentially used to generate electricity. If no electricity is needed, the high grade heat can be used to top off the thermal storage and the remaining energy can be fed into the thermal grid.

4.4 Case study

As an application, balancing the day ahead forecast error of renewable sources with a VPP and thermal storage is demonstrated. The main objective of this VPP is to avoid imbalance. As renewable energy production, and especially solar power, is hard to predict on longer time scales, the CVPP should try to sell the energy as close as possible to the actual production time to reduce the needed prediction horizon. As has been clarified in [11], the Day Ahead Market (DAM) is the best option in Belgium.

4.4.1 Market operation

The DAM requires traders to submit their position before noon the day before delivery. But as delivery takes place trough the Elia Day Ahead Hub, the trader should also be granted network access from Elia (TSO). The TSO requires the BRP to nominate the required power (injection or off-take) on a fifteen minutes basis before 14h the day before delivery. This requires traders to have accurate fifteen minute average power predictions. This is however a very difficult task for renewable sources.

In the day ahead market, a price is formed for every hour of the next day. this price is dependant on the submitted positions (volumes and prices) of suppliers and customers. As can be seen in Fig. 2.12, this is highly volatile with prices ranging from €10 /MWh to €120 /MWh. Price differences of €60 /MWh within one day are no exceptions.

As has been explained in §2.8.3, once market positions are known, the traded volumes should be nominated to the TSO. The TSO will check if the balance between production and consumption will be met. The TSO will check on a fifteen minute basis if the nominations are effectively followed. If a BRP has an imbalance compared to its nomination, an imbalance fine will be applied.

As described in [11], the preferred market is a day ahead market. As such, the volumes are traded the day before actual delivery. Before 12h (in Belgium, rules of Belpex), a BRP needs to submit his position (price and volume) for every hour of the next day (from 0h00 till 23h59). As a result, the position is a prediction of production and consumption 12-36 h before actual delivery. Furthermore, after market clearing, the BRP needs to nominate its power ratings to the TSO for every fifteen minutes. If the actual power exchanged by the BRP is different to this nominated power, the BRP needs to pay a fine. This fine is determined by the TSO according to the price paid for regulation services, the direction of the imbalance of the BRP and the system imbalance (ref. §3.4.3.2.

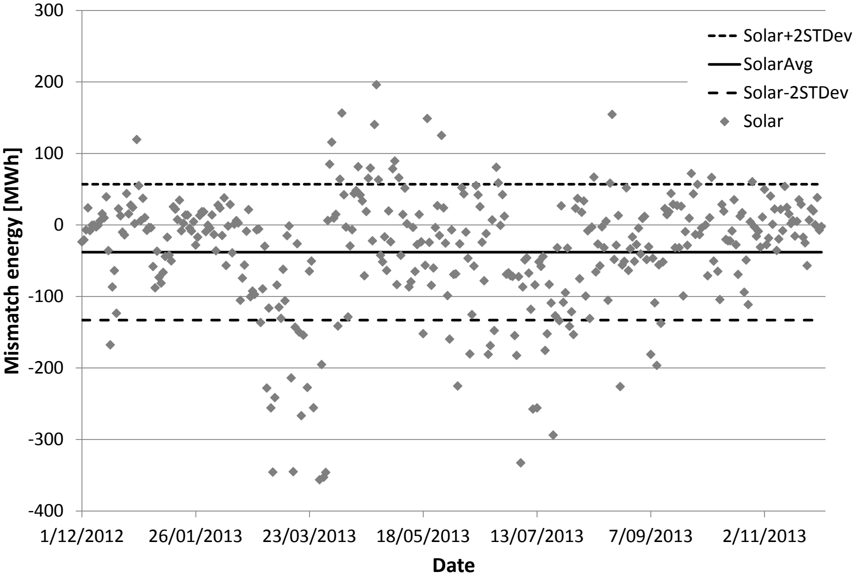

Figure 4.1: Daily cumulative miscast energy for photovoltaic energy in the Belgian coastal region

4.4.2 Variability needed for DA market operation

In this case study, thermal generation is used to offset prediction errors from renewable sources like solar photovoltaic and wind. The VPP communication infrastructure is used to measure the real time power of the RES sources and communicate a new setpoint to the thermal generators. As such, the thermal unit will produce a different amount of energy compared to its own prediction as to correct the production of the other sources in the VPP. This will result in a thermal imbalance. To offset this, thermal storage is added. In this section, the needed volume of a thermal buffer (hot water tank) will be determined.

In [35] different methods of forecasting PV power output are presented. As a conclusion, it is presented that day ahead forecasting accuracies range from 22 % to 33 % in clear and cloudy weather respectively. The data are obtained in the Belgian coastal area. [36]. In [106], the impact of the geographic spread of PV systems on the output variability is studied. One of the conclusions is that the variability of PV power can be reduced by geographically spreading the PV installations. A VPP naturally implements this as the concept is not geographically constrained. This is especially important for PV power and can be seen by comparing Fig. 4.1 and Fig. 4.2. Both show the 24 h difference between predicted and produced energy for PV and wind respectively. Although the capacity factor of PV is much lower (due to no production during night time) than the capacity factor of wind, the miscast energy of a 100 MW PV cluster is almost as big as

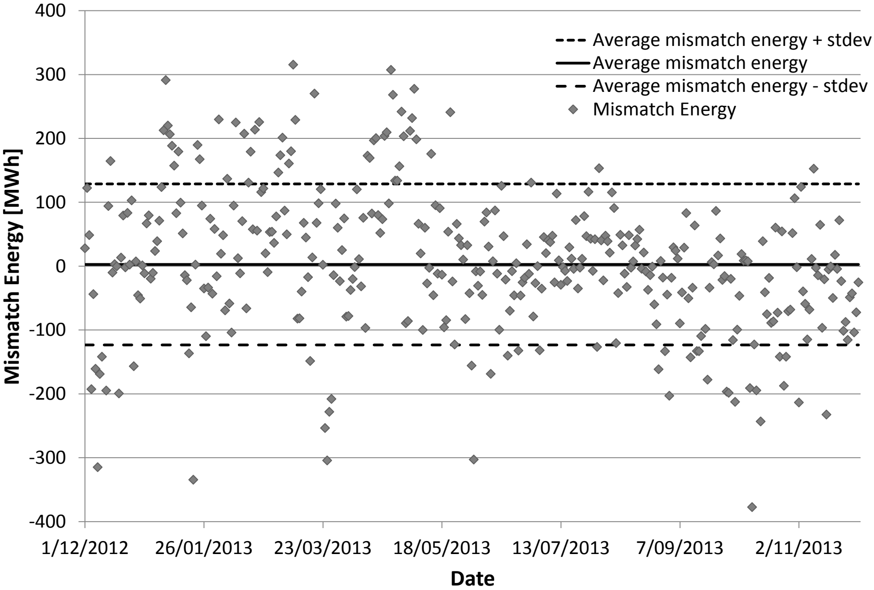

Figure 4.2: Daily cumulative miscast energy for wind energy in the Belgian coastal region

that of a 100 MW wind cluster. This is due to the difficulties of obtaining accurate day-ahead PV predictions.

Fig. 4.1 and Fig. 4.2 show next to the mismatch energy for PV and Wind power, also the average daily mismatch energy and the 68 % confidence interval. The miscast energy is defined as follows:

$$E_{\mathrm{miscast}} = \int_{12\mathrm{h}\,\mathrm{D}-1}^{12\mathrm{h}\,\mathrm{D}} P_{\mathrm{produced}} - P_{\mathrm{forecast}}\,\mathrm{d}t$$

As a result, if E_{miscast} is positive, the RES produced more energy than forecast and vice versa. Fig. 4.1 shows that on average, solar power is predicted 50 MWh/day too low. That would result in a 2 MW continuous compensation of the predicted thermal power for the next day. As seen in Fig. 4.2 the average daily miscast energy for wind is almost zero. Both energy resources have a 68 % confidence interval of about 200 MWh.

An overestimation of RES availability could lead to the activation of back-up power. In order to be able to start these units fast enough, they often need to be stand-by early enough. This requires an increase in the running reserve and hence cost and carbon (di)oxide emissions. These reserve units are also often open loop gas turbines, which have a low efficiency.

An underestimation of RES availability and hence an overproduction could also lead to instability. Traditional power plants are expected to be running. This units are often also the units providing ancillary services. If a major overproduction of RES is present, this can force these units out of the system in order to guarantee RES production. This could result in a drop-out of flexibility due to the rearrangement of the traditional plants. Automatic reduction of the power output of a gas turbine due to secondary reserve activation could force these units to their lower production limit, removing further downward activations and hence cause system instability.

To size the thermal storage, the mismatch between prediction and really produced energy needs to be calculated. In this section, this is done for solar energy and wind energy separate. Both comprise 100 MW uncontrollable (RES) sources and thermal power. For the thermal power, a conversion efficiency to electricity of 50 % is utilised.

As the goal of the thermal plant is to sell all of its available energy, either as thermal or as electrical power, the required thermal consumption should be determined day ahead. The remaining capacity can be converted and sold in the day ahead market. But as the thermal generators are called upon to correct prediction errors of other sources, thermal buffering should be applied. The steps involved can be listed as follows:

1. predict thermal consumption
2. predict RES production
3. calculate thermal buffer restoration
4. sell RES power
5. sell electrical energy from remaining thermal capacity
6. adjust thermal power according to real time RES output

As a result, if the thermal buffer is higher than normal, more thermal power will be available to convert to electricity and to be sold on the day ahead market. If the thermal buffer is nearly depleted, part of the thermal energy should be reserved to replenish the buffer and hence can not be converted to electricity or sold as thermal power.

Based on the 2 * standard deviation confidence interval (see Fig. 4.1 and Fig. 4.2, 200 MWh per day is needed to compensate the difference between predicted and actually produced renewable power in 68 % of the time. This can be averaged as 8.5 MW continuous power for one day. However, as the forecast error is a dynamic value, the instantaneous power needed can be much higher. As the VPP does not aim at compensating all deviations, the maximum up or downward power variation is chosen slightly larger, at 12 $\mathrm{MW_e}$. This results in the requirement the thermal unit can adjust its output power by 24 $\mathrm{MW_e}$.

4.4.3 Sizing storage

As calculated above, 100 $\mathrm{MW_e}$ installed power RES need about 200 $\mathrm{MWh_e}$/day electrical storage to compensate for prediction errors. If a 50 % conversion efficiency of thermal to electrical power is assumed, this results in a thermal buffer of about 400 $\mathrm{MWh_{th}}$.

To size the thermal buffer, the operating temperatures should also be known. As input for the thermal grid a temperature somewhere in the range of 90-110 °C is mostly chosen. To be able to convert thermal energy efficiently to electricity, the higher the temperature is, the more efficient the process can be. However, as the primary purpose is to use waste heat, this temperature can not be taken to high. As a compromise 130 °C is chosen. This results in a maximum temperature difference of 40 K. As the thermal capacity of water is about $4.184\ \frac{\mathrm{MJ}}{\mathrm{m^3K}}$ or $1.162 * 10^{-3}\ \frac{\mathrm{MWh}}{\mathrm{m^3K}}$, the needed storage volume is 8600 $\mathrm{m^3}$. If the storage tank is designed as a sphere, this results in a tank of 25 m diameter. If phase change materials (PCM) are utilised in the tank, the size and potentially the costs can be significantly reduced [107]. However, PCM storage tanks are still in research phase.

4.5 Other technologies

Many technologies exist which have a direct relationship between thermal and electrical power. Co-generation or Combined Heat and Power (CHP) utilises the wast heat of electricity production. In this systems, there is a direct relation between the amount of electrical and thermal power generated, most often utilising a chemical energy source. Waste heat recovery converts thermal energy to electrical energy. This is done on a commercial basis by steam turbines and organic rankine cycles, depending on the temperature of the waste heat. Next, heat pumps are used to transfer thermal energy from a low temperature environment to a high temperature area. Heat pumps are either used as a heating solution, replacing gas or fuel heaters, or as a cooling device in freezers, refrigerators or buildings. Depending on their application, they displace double to four times the thermal power compared to their electrical power, depending on the Coefficient Of Performance (COP). The final technology covered is power to heat. This is direct conversion of electrical power to thermal power. This is often used as peak power or backup of a heat pump.

4.5.1 Combined heat and power

A CHP produces electricity trough combustion of a fuel. The waste heat of electricity production is then also used as a resource, instead of vented as in traditional electricity production. CHP systems could play a major role in a VPP. They are manageable, reliable, predictable and often have a significant power.

4.5.1.1 Economical aspects

In Flanders, many CHP systems are installed due to the favourable support scheme. To gain financial support, minimum criteria need to be met. Due to this regulations, many CHPs where designed to run as many hours per year as possible. Due to the changes in many ghosting processes and higher fuel costs, many CHPs now run much less than their design targets. This frees up flexibility, as units are not running 24 hours a day but (much) less.

4.5.1.2 Technical aspects

As stated in the previous paragraph, most CHPs are designed to run as much hours as possible. As a result, electricity is regarded as a by-product. However, due to changing conditions, a lot of CHPs are not working as much hours as designed for. This opens the opportunity to control them from the electrical side. Sometimes, this would require the investment in a thermal buffer, but the same approach could be taken as studied in §4.4. By providing flexibility, the CHP owner can receive more for the electricity than the normally offered price by suppliers.

4.5.2 Heat pumps

Heat pumps transfer thermal energy from a low temperature to a higher temperature. Typical applications are refrigerators, freezers and building heating. These units are most of the time controlled by an independent thermostat. As a result, they turn on and of independently of the grid state. By synchronising the consumption of heat pumps to the needs of the grid, an enormous flexible capacity could be accomplished [108].

4.5.2.1 Economical aspects

Heat pumps are today already economically combined in a form of a VPP. Restore, among others, groups many cold stores together and offers an interruptibility contract to the grid. In case there is a large demand for energy, the company can remotely reduce the consumption of its contracted heat pumps. This is however done on a modest scale and a lot of expansion is still possible.

4.5.2.2 Technical aspects

Heat pumps can be considered as a flexible resource in a VPP. However, as they rely on thermodynamic systems, they are also limited in their dynamic behaviour. Once the compressor is started, it must keep running until the medium becomes in a known state within the cycle. After compressor shut down, a minimal time is required before restarting. This impacts the flexibility of a single unit, but diminishes when many units are combined.

An extra benefit of heat pumps can be obtained by the thermal demand of cooling processes and solar production. Coordinating cooling units with solar production could be an interesting case [109].

4.6 Industrial potential

It is difficult to quantitatively assess the amount of thermal flexibility in industrial processes. It can however be expected to be of significant scale. An study carried out to investigate the potential of a thermal grid in Ostend [110] showed several hundreds of MW of thermal power available in the Ostend harbour area. Similar studies in Bruges [111] and Genk [112] presented also large quantities of thermal potential.

Many industrial processes have residual heat available. This heat is often converted to electricity. However, this electricity production is mostly driven by the availability of residual or waste heat. As a result, these sources don't actively support the electricity grid. In [12] and [91], it was proven that combining thermal sources and a district heating system can create flexibility for the electricity production. As a result, the waste heat recovery system can actively provide ancillary services to the grid.

As mentioned in §4.3, there is an enormous amount of waste heat available in the process industry. Basically, we can consider all the streams of the process that need to be cooled as energy sources [92]. Next, these streams need to be narrowed down. Firstly, a part of the heat is used for other streams in the same process to increase the temperature or cause a phase change. In process engineering, pinch technology is applied to explore these heat streams. Briefly, the calculation of the overall heat requirement and the thermal loads of the hot streams are plotted into respectively a cold composite curve and a hot composite curve (Fig 4.3).

As marked on Fig. 4.3, there is a (optimal) heat integration inside the process where the temperature difference between the curves is minimal. This point is called the pinch point. No heat should be transferred across the pinch temperature, except with ORC-systems. An Organic Rankine Cycle can convert heat into electricity at temperatures which do not include the pinch point.

Another very interesting use of heat is distribution into a district heating and cooling network. This is further explained in §4.3.2 of this paragraph. Using waste heat provides a decrease in the use of fossil fuels (for space heating for instance) and thereby a decrease in CO_2 emissions and possibly also a cost reduction [93]. Waste heat is mainly coming from four types of industrial installations: chemical industry and refinement, electrical power plants, CHP-plants and waste incineration plants [94]. Combined heat and power plants (or CHP plants) provide the generation of heat and electricity simultaneously. Because the production of both cannot be adjusted independently, companies using CHP's are often faced with problems of using all the produced heat when the electricity demand is high [95].

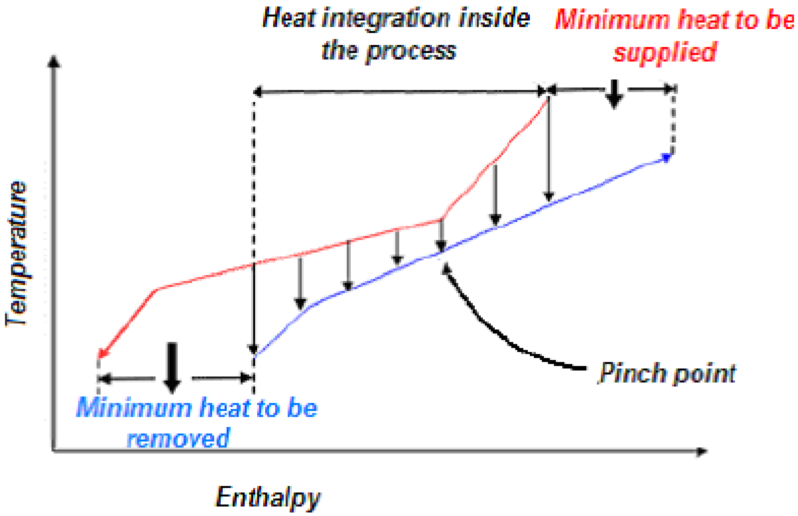

Figure 4.3: Thermal composite curve

Therefore the introduction of extra heat sinks is necessary. A district heating network can play this role as heat sink. Temporary storage of heat is an important element of these networks [93].

4.7 Load-shifting of Electrical Heat Pumps

Electrical heating is still widely used in the process industry. While the use of immersion heaters for the production of hot water or steam is declining, the adoption rate of electrical heat pumps is increasing rapidly. Heat pumps show great flexibility and potential for energy savings, e.g. through low temperature waste heat recuperation. In combination with thermal storage they also allow for load shifting. Because their main power source is electricity, which up to now cannot be stored efficiently, heat pumps can transpose their thermal load shifting ability to the electrical grid. Today, more and more industrial electricity consumers are adopting energy supply contracts with variable pricing parameters strongly coupled to the energy trading market. Some large consumers even buy and sell on this market directly. In this section, it is proven that for customers with (hourly) variable electricity pricing, the use of electrical heat pumps can lead to additional cost savings without influencing the industrial process. The yield of the heat pumps can be increased during hours with low energy cost, with the thermal buffer absorbing the heat surplus. During hours with high energy cost the heat pump yield is lowered and stored heat is used by the industrial process.

Considering that heat can be stored much more efficiently than electricity, the load shifting ability of heat pumps can also be utilised to provide stability on electrical smart grids and to increase electrical selfconsumption on microgrids. This section will also explore the potential of thermal storage through heat pumps for these electrical smart grid applications.

4.7.1 Why load shifting could be interesting

Heating is a fundamental component in many industrial processes, especially in manufacturing. Depending on the type of process or application, different types of heating methods and fuel sources are used. Slow processes with a constant heat demand, e.g. dehumidification of wood, will require a different approach than short burst processes, e.g. plastic cap sealing.

According to the U.S. Department of Energy (2004), most key industrial processes requiring external heat are gas fired. Coal is used for processes requiring slow and constant heat such as calcining. Electricity is used in some metallurgical processes such as melting, or chemical processes like curing.

The performance of a heating process is typically based on its ability to deliver a certain product quality in a given time constraint. Most companies focus on these productivity related parameters because process output and product quality are economically important. With rising energy costs, the Industrial Heating Equipment Association (2001) demonstrates that companies are also starting to consider the ‘energy use per product’. More efficient heating systems can therefore lead to a competitive cost advantage. In some cases however, the heating system cannot easily be changed due to process constraints, or because of the most efficient heating system is already used.

An alternative way of achieving cost savings is by lowering the cost per energy unit. The liberalisation of the energy market has opened up perspectives for cost savings by exploiting variable energy prices. The market for electrical energy is especially interesting because of its significant price fluctuations, with sometimes only a few hours between peak and bottom price levels. This can make electrical heating attractive, e.g. as an addition to a conventional gas fired heater or by employing efficient heat pumps powered by available waste heat streams as shown by [113], even low temperature as demonstrated by [114]. It has been shown by [115] that heat pumps can be used in industrial processes, or in large scale residential and commercial applications [116, 117]. Research [118, 119] has already proven that heat pumps can offer potential for balancing (renewable) energy production, even in small scale applications such as described by [120, 121]. This section will expand those findings by using this potential to benefit from the price volatility on the wholesale energy markets.

The use of electrical heating, combined with sufficient thermal buffering, also offers opportunities for peak shaving or demand side management applications. Essentially, the thermal storage capacity of the buffer is transposed to the electrical grid with the electrical heat pump functioning as converter. This section will elaborate on the cost savings achievable in heating processes by buying energy directly from the market, and on the use of electrical heating for balancing applications on the electrical grid. The section is structured as follows. First the mechanism of wholesale energy trading is detailed, with the Belgian market as a study case. The following sections give some examples on how participating on this energy market can lead to cost savings. Finally, the conclusions and some considerations for further research are given.

4.7.2 Wholesale energy trading

In this paragraph, the process of wholesale gas trading is discussed. A detailed look is given on the wholesale trading platform for natural gas. The concerned platforms are Belgian, but are representative for other trading platforms elsewhere in Europe.

4.7.2.1 Electrical energy

4.7.2.2 Natural gas

Trading of natural gas is a relatively new phenomenon in Europe. Historically, natural gas was produced and consumed regionally and pricing was set by the local government and/or the state-owned utility company. Where gas transport grids were connected, regional pricing structures started to develop. Starting from the 1960s, Melling (2010) describes the coupling of natural gas pricing to the oil price index becoming the dominant market mechanism throughout much of the world.

However, in the United States, hub trading emerged as a competing market mechanism. In this mechanism, buyers and sellers form individual pricing arrangements and notify the gas hub to exchange the agreed upon volumes on agreed upon dates.

The European situation started to shift in the 1990s when the United Kingdom liberalized the natural gas market and utility companies started adopting the American market mechanisms. When the UK natural gas transport grid was connected through the Interconnector pipeline to Belgium in 1998, Interconnector UK (2014) states the hub trading mechanism gained a foothold in mainland Europe as well. The liberalization of European energy markets increased the popularity of the hub trading mechanism, but oil indexing still retains a not to be underestimated market share.

Natural gas trading is not as centralized or transparent as electrical energy trading discussed in the previous paragraph. The most important trading platform is hosted by the Dutch company ICE ENDEX. Parties can engage in futures or spot market trading, similar to the way electricity is traded. However, because of the greater flexibility of the natural gas transport grid provided by gas storage and flexible pipe pressure limits, the CIM is much more active. Nominations can be made up to one hour before delivery time.

Nonetheless, a lot of day-to-day natural gas trading in Europe happens in the form of OTC contracts and through brokers. Brokers are intermediate parties who receive buy or sell orders from their client portfolio and try to match them. They function similar to a trading platform, but provide no anonymity or clearing services. When a match between supply and demand is found, the broker arranges an OTC contract to be signed between the selling and buying party and informs the hub of the required volumes to be exchanged.

Because of the more decentralized nature of the natural gas market, it is less transparent and regional pricing differences exist. It is in some aspects similar to the electricity trading market before the establishment of the CWEMC interconnected zone.

4.7.3 Economics

In this section an example is given how participation on the energy trading market can result in lower energy costs without influencing the process the energy is delivered to. Only energy costs are discussed, A reference case is compared to two additional cases in which the process operator buys electrical energy at trading prices. The cost comparison is made between three set-ups:

- Heat delivered exclusively by gas fired boiler
- Heat delivered by gas fired boiler and electrical immersion heater
- Heat delivered by gas fired boiler and electrical heat pump

The process heat demand is identical and constant in each case. In the first case, the heat is delivered exclusively by the gas fired boiler resulting in an energy cost dependent on a gas price fixed on a monthly basis. In the second case, heat is delivered by a gas fired boiler combined with an electrical immersion heater, with the energy cost depending on the monthly gas price and hourly electricity price. The immersion heater is only activated during hours when producing heat with electricity has a lower energy cost than producing heat through the gas fired boiler. During these times, the boiler is shut down. The third case is similar to the second, but with the immersion heater replaced by an electrical heat pump. The immersion heater is considered to have an efficiency of 100 %. The heat pump is considered to have a constant COP, e.g. by connecting the evaporator to a waste heat stream.

The cost comparison is made for a period of one year. The hourly electricity prices are taken from the Belgian power exchange (Belpex) DAM of the year 2012, the corresponding natural gas prices are monthly averages from the Dutch ENDEX gas trading platform.

Fig. 4.4 shows the relation between heat pump COP and cost savings for different boiler efficiencies. For a plausible case with a boiler efficiency of 85% and

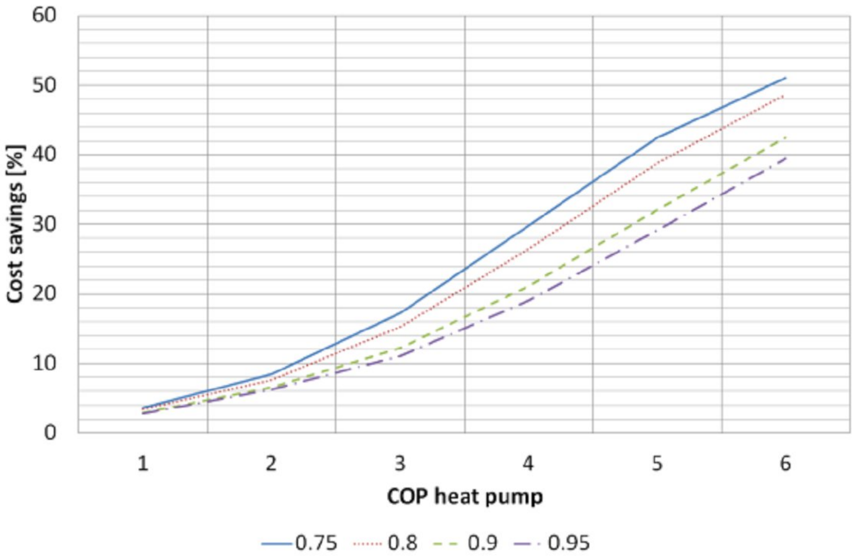

Figure 4.4: Cost savings related to heat pump COP for different boiler efficiencies

a heat pump COP of 3 a cost saving of 13.63% can be achieved if the heat pump is activated rather than the gas fired boiler during times when generating heat with the heat pump results in lower energy cost. When the COP of the heat pump is lowered to the minimum value of 1, the gain drops to 3.16%. This case is the same as when using the immersion heater. In the worst case, with a heat pump COP of 1 and a boiler efficiency of 95 %, the cost saving is 2.78%. In the best case, with a heat pump COP of 6 and a boiler efficiency of 75%, cost savings can be as high as 51.08%.

4.7.4 Energy balancing

Distributed Renewable Energy Systems (DRES) have known a rapid increase in both number of installations and combined power generating capability throughout Europe. In the case of Flanders, the northern part of Belgium, this was especially the case for photovoltaic (PV) installations. The main driver for this growth were the plentiful subsidies provided by the Flemish government combined with tax breaks from the federal Belgian government. According to data supplied by VREG (2008) this resulted in yearly increases of total installed PV power generating capacity as high as 488% (in 2007).

The number of PV installations in Flanders is more or less evenly divided between small installations ($P \leq 10$ kW) and large installation ($P \geq 10$ kW). Of the latter, around two-thirds are very large installations with more than 250 kW power. Again according to data supplied by VREG [122], as of 2012, PV power

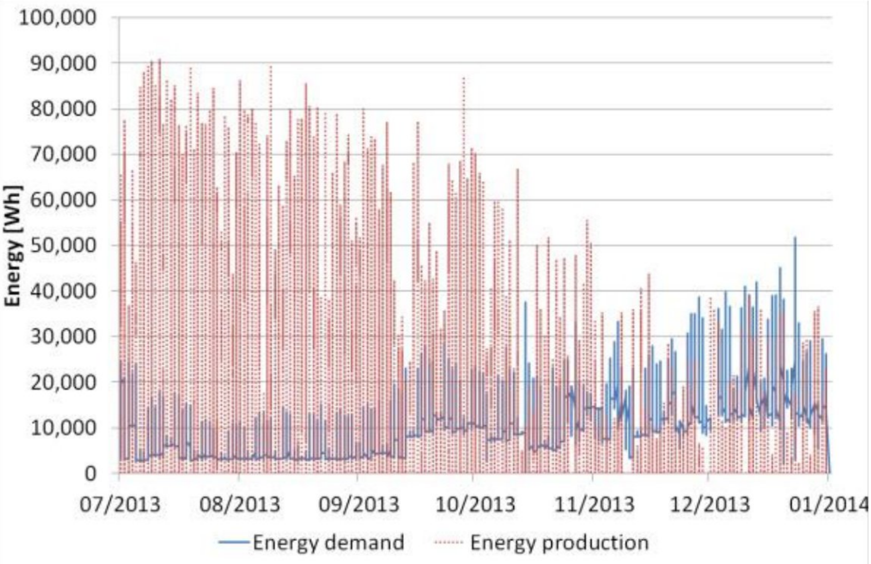

Figure 4.5: energy demand and production for July 2013 to December 2013

accounts for more than 33% of the total renewable energy production in Flanders. The large amount of DRES can cause balancing problems on the electrical grid. DRES power production is more unpredictable than conventional controlled power generation and, in Flanders, DRES have priority over conventional power plants. Grid operators are therefore promoting the increase of synchronism between local energy consumption and production. This is also reflected in the energy pricing: the buy price of electrical energy is higher than the sell price, encouraging the increase of synchronism.

Energy storage offers interesting perspectives for increasing synchronism between local energy consumption and production as described by [123, 124]. Electrical energy storage is however relatively expensive an often suffers from low efficiencies. In [125], it is stated that heat storage is often much more feasible. This paragraph explores the effect of thermal storage, e.g. of heat produced by electrical heat pumps on total energy cost of a process.

In Fig. 4.5 the measured energy consumption of an electrical heating system for the months July to December is depicted, together with the energy production of a PV installation on the same site. The average power demand of the heating system is 11.8 kW and the half-yearly energy demand totals 51 MWh. The PV installation is sized to cover the energy use of the heating process. In the considered months, the 90 kW PV installation produces 53 MWh. Energy is bought at hourly variable price, which is taken from the Belgian power exchange (Belpex) DAM of the second half of the year 2012. Surplus energy is sold at a fixed price of €35 /MWh.

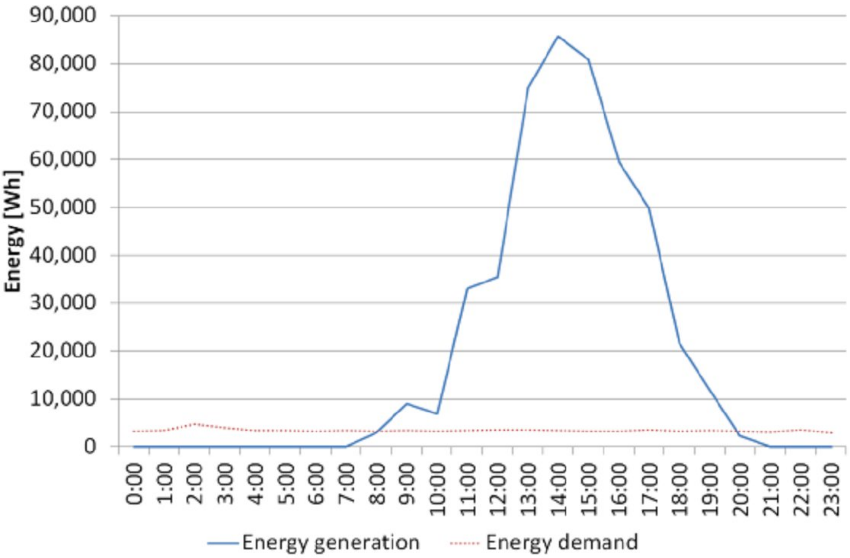

Figure 4.6: energy consumption and production for 20/08/2013

While the total energy production of the PV installation cancels out the total energy consumption of the heating process in the considered time frame, the energy demand profile seldom matches the energy generation profile. This lack of synchronism is depicted in Fig. 4.6, which shows the demand and generation profile of a single day in August. PV power generation peaks while energy demand from the heating process remains stable.

Increasing the synchronism between energy demand and energy production can result in additional cost savings. When there is a surplus in energy production, e.g. during noon, this surplus is sold on the grid for a price typically lower than the price at which energy is bought at market tariff when there is a shortage, e.g. during the night. If the energy surplus can be stored it (partly) removes the need for buying energy at market tariffs.

A simulation was made by adding a thermal buffer to the heating process. When there is a surplus of generated PV energy this is converted to heat, e.g. by raising the COP of the heat pump, and stored in the thermal buffer. When generation of PV energy falls below the energy demanded by the process, heat is taken from the buffer until it is empty or generated PV energy again rises above the energy demand. Fig. 4.7 shows the relationship the size of the thermal buffer, expressed relatively to the average energy demand of the process, and the calculated cost savings. When a thermal buffer the size of 25% of the average energy demand is used, the cost saving amounts to 8%. When the buffer size is doubled to 50%, the cost savings rise slowly to 8.6%. At 100% around 11% costs can be saved. Cost savings max out just below 18%, but this requires a thermal buffer of five

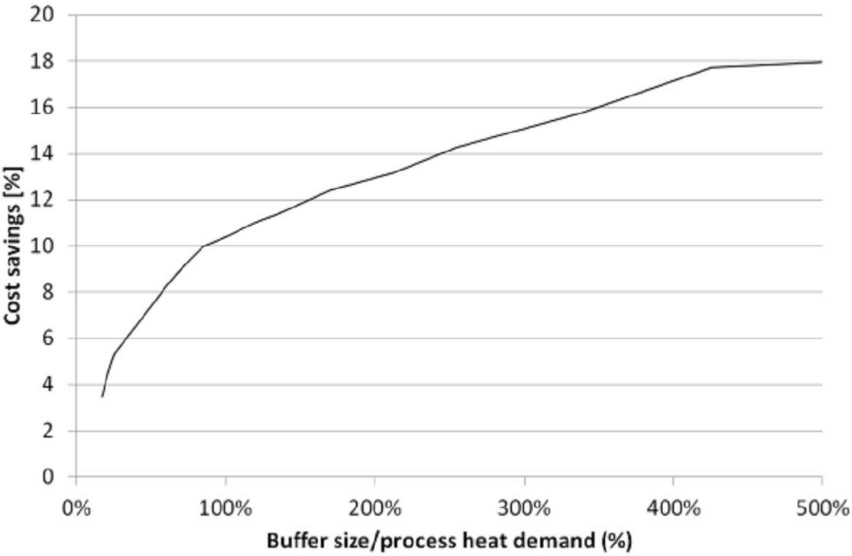

Figure 4.7: cost savings related to buffer size

times the average process energy demand.

4.7.5 Conclusions load shifting heat pumps

This section explored some practical opportunities for additional cost savings in electrical process heating by employing the hourly variable pricing options provided by wholesale energy trading platforms and flexible electrical heating systems such as heat pumps. First, a short overview of the technical aspects of heat pumps were given, and some previous research into the use of heat pumps for balancing and storing of energy consumption was presented. Then the energy trading markets were discussed, with some similarities but also some discrepancies highlighted. Finally, two simulations were presented showing how variable energy pricing can lead to cost savings without influencing the process.

Most energy savings are modest but can reach levels as high as 51.08 % when high performing electrical heating systems are used, e.g. heat pumps with a high COP. With an installation with more feasible parameters, such as a heat pump with a COP of 3, 15.3 % savings still represent an interesting opportunity.

In a second simulation it was shown how thermal storage can be used to balance local energy production and consumption. By bridging the spread between higher energy buying prices and lower selling prices additional cost savings can be achieved. In the considered heating process, up to 18 % cost savings could be realized.

This section only discussed potential energy cost savings. A complete economic analysis would also require hardware and installation cost. Also, electrical heating cannot be applied to all heating processes or process plants. E.g. for the sensible use of a heat pump, a waste heat stream is required. Additional research can be done into more optimal use of the thermal buffer. In the above simulation, heat was transferred from the buffer to the heating process when local energy production did not meet the heating process' energy demand, independent of current hourly energy price. Additional cost savings could be realized if the stored heat is released during hours with high energy price.

Paragraph 4.7 has been published as an article in chemical engineering transactions [16].

4.8 Residential potential for thermal VPPs

According to the Belgian government [82], between 1996 and 2014 on average 50,000 homes per year are built with a surface of 104 m^2. The maximum energy requirement for heating is 70 kWh/m^2 [122], resulting in an average requirement of 7280 kWh per home. To produce this required energy, a thermal capacity of 10 kW is needed, resulting in 728 h full power operation. This is 9 % of full load on yearly basis. Due to higher load during winter season, the loading will be much higher. However, in modern low energy buildings, a short interruption will not be disturbing the user comfort.

If this thermal load is covered by a heat pump with an average coefficient of performance of 4, the resulting electrical power is 2.5 kW. Multiplied with 50,000 newly built homes per year, 125 MW electrical capacity is theoretically installed every year. Even if only 25 % is effectively realised, this results in a capacity of 156 MW electrical capacity which could be controlled within reasonable limits.

It should be noted that modern buildings (Near Zero Energy Building (ZEB) and Zero Energy Building (ZEB) require less and less thermal energy. However, although space heating is significantly reduced in these new buildings, domestic hot water is still a significant energy consumer. These requirements could often be met with a correctly sized thermal solar system. However, these units are often equipped with a electrical back-up heater. This could lead to an extra increase in electrical consumption during longer periods without much sunlight, e.g. cold and dark winter weeks.

Also, the (N)ZEB concept is mostly reached for new buildings. However, a large potential of thermal VPPs lies within the renovation market. Many buildings are renovated, including building insulation. It is however much more difficult to reach NZEB in renovation than in newly constructed homes. In these situations, a larger thermal demand will still be required.

4.9 Conclusions thermal VPP

In this chapter, the possibilities of utilising industrial waste heat to compensate for the variability of renewable energy sources have been assessed. Although the needed storage is large, it still falls within reasonable dimensions. Coupling thermal and electrical grids can provide the needed flexibility to incorporate more renewable energy in the electrical grid.

However, much work is still needed to investigate the correct balance between different technologies within the VPP. This balance will depend on the available sources, the thermal demand, season, etc. Much more factors need to be taken into account to verify economic viability of this system, although this research proved at least day ahead balancing is technically feasible.

Due to the slower reactions of thermal systems, they are ideally suited to compensate some of the variability of electrical grids. The relatively slow reaction to changing input parameters results in a low(er) impact of a temporal interruption or increase of electrical energy. As a result, processes converting thermal to electrical energy or vice versa could contribute to the equilibrium of the electrical grid, which allows much shorter reaction times. By increasing the thermal storage capacity of a system, by a specially built buffer or by increasing the inherent thermal mass, the flexibility even further increases. Thermal storage is also much more economical if the storage time is limited to a few hours, compared to electrical storage.

The proposed strategy is designing the system for thermal requirements. This ensures the exergy in the fuel will be utilised to the best extend. Next, the operational planning should be carried out for the thermal side as well. Although thermal energy can be stored, time is also limited. The host process will have limited flexibility depending on design and operational limitations. This operational planning can be used to determine the electrical flexibility. The next step is then to sell this flexibility to the electrical grid. As a last phase in the process, the real time operation is driven by the short therm variations demanded by the electrical side, limited by the defined borders in the thermal planning phase.

If thermal and electrical production and consumption are coordinated, it has been shown that this could reduce the impact of the unpredictability of renewable electrical production. Even with limited storage or by addressing inherent thermal capacity, an enormous electrical flexibility could be created. As has been shown in earlier chapters, this flexibility is already remunerated on a large scale. The challenge for the near future will be to develop systems to remunerate and give incentives to small industrial prosumers to provide this flexibility. Most of the investments are already done or will be done anyway, but managing this capacity is an ideal task for a VPP.

5

Replacing a combined cycle gas plant

5.1 Introduction

Replacing a Combined Cycle Gas Turbines (CCGTs) could be a very well defined goal for a VPP. CCGTs are important units in the electricity system, as they are flexible in production and can adapt quickly to changing demand. However, many CCGTs are having difficulties due to decreasing profit and low load factors. Load factors decrease due to many factors. First, gas powered units have a relatively high marginal cost compared to other resources. Therefore, they often come in last in the merit order based on their price.

Secondly, nuclear power in Belgium is designed and operated as base load. As these nuclear power plants have a major share in the Belgian power market, they push other units with higher marginal costs out of the low demand hours.

A third factor is renewable energy. Due to the priority dispatch of renewable energy, the grid operators should give priority to energy coming from these resources. This places an extra burden on CCGTs. As a result, CCGTs are only profitable during peak demand with low renewable energy production. The load factor of all Belgian gas fired plants, mostly CCGTs, for december 2015 for example was only 48%.

As a result, many gas fired units are expected to close. This incorporates all aforementioned aspects. First of all, a gas fired power station trades electricity, so the replacement should be a CVPP. But as gas plants are among the most flexible plants currently in use, they deliver also a large share of ancillary services like frequency control and imbalance settlement. Replacing this type of installation with a collection of distributed resources is therefore the second challenge and requires a TVPP. Managing the resources in real time is therefore essential to mimic the behaviour of a traditional gas plant.

In this chapter, a decision tree to replace a traditional CCGT of 300 MW with a VPP is proposed. The data are based on the Belgian power system, provided by Elia, the Belgian TSO and Belpex, the Belgian DAM. Although a model is proposed, this chapter is not meant to be a thorough studied portfolio proposal. It should be regarded as a basis for further discussion and as an overview of the decision process.

5.2 Requirements

To be able to replace a gas fired power station, the key aspects of this type of power plant need to be analysed. A one to one replacement is not necessarily required, as long as key aspects are respected.

The first key aspect is the energy production. Replacing a CCGT should be neutral in the energy balance. Based on a certain time period, the net energy production of the VPP should be the same. In Fig. 5.1, an overview is shown of the power of the total gas production park in Belgium. This graph shows the power produced by gas fired power plants. The maximum produced power is 4700 MW, the minimum 744 MW and the average power is 2124 MW. The daily average, shown in the dashed line, changes however considerably from day to day. A seasonal trend can be observed, as the average power is lower during summer months compared to the winter months. However, several peaks in power production can also be observed during July.

Secondly, CCGTs are important suppliers of ancillary services. Flexibility in production output is one of the main advantages of a CCGT. Therefore, the replacing VPP should be able to deliver these services as well.

5.2.1 Power and Energy

According to the list of available production plants in Belgium, published by Elia [36], there are 13 installations of the CCGT type in Belgium. There rated power ranges from 20 MW to 465 MW with an average power of 300 MW. Therefore, a replacement of an average unit of 300 MW will be proposed.

To select the resources, a strategy is required. In this case, the goal is to replace as much fossil fuel by renewable resources without exceeding storage requirements. Therefore, renewable resources are selected first. In Fig. 5.2, the daily power output of the Belgian wind power park in 2015 is shown. Comparing this graph to Fig. 5.1 reveals directly these do not match. The difference in daily energy output is shown in Fig. 5.3.

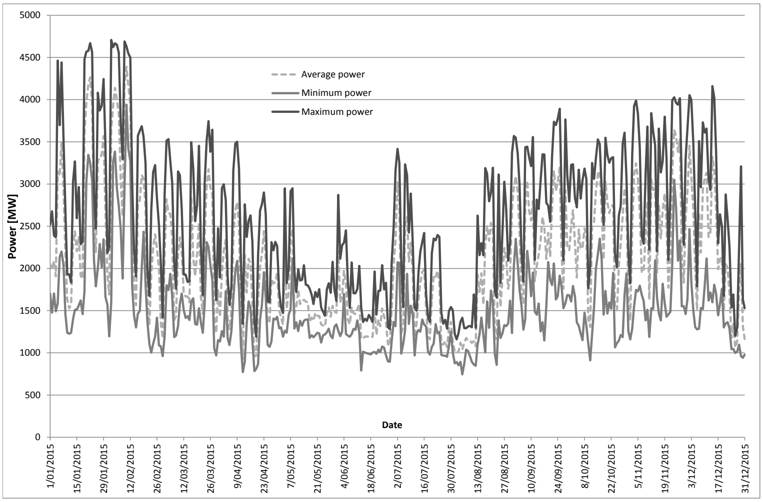

Figure 5.1: Daily average, minimum and maximum power of the Belgian gas power plants

5.3 Determining necessary portfolio

Mimicking a gas plant with a collection of distributed resources will require a balanced portfolio of assets. A VPP will need to carefully chose the incorporated assets to be able to mimic a traditional power plant as closely as possible. Exact replacement of the power profile is however not necessary, as a VPP can also control loads and use storage. As has been shown in 4, thermal storage can full fill a major role. Other storage technologies can also be taken into account 3.6. Except for hydro storage in the Coo power plant, no large scale energy storage is currently present on the Belgian grid.

5.3.1 Economic aspects

To be able to trade like a CCGT, the VPP needs to have enough energy available. As a traditional CCGT plant is almost continuously available to the market. Based on the load factor of the Belgian CCGTs in 2015, the load factor is 45 %. The replacing VPP should be able to do this also. As a result, a certain amount of controllable resources like CHP or heat recovery systems are necessary. To determine the minimum amount of controllable resources, the minimum available capacity of the rest of the portfolio needs to be known.

5.3.2 Technical aspects

Due to their flexibility, CCGTs deliver a lot of ancillary services. As these ancillary services are more dynamic in nature than traditional market operation requires, this places additional requirements on the VPP delivering these services.

5.3.2.1 Controllability

The dynamic nature of many services requires the VPP to have a very reliable control over the constituent DER. This means in the first place a reliable connection to the different units. As has been mentioned in 3.4.3, the Frequency Restoration Reserve (FRR) requires activation of the contracted power to be activated within 30 seconds. The setpoint is updated automatically every 10 seconds and distributed to the BRP.

5.4 Case study: replacing 300 MW CCGT in Belgium

In this paragraph, a quick overview of a portfolio selection process will be shown. As has been explained in the beginning of this chapter, the purpose is not to produce a complete business model, but provide an insight in the possibilities and decision making.

5.4.1 Selecting resources: RES priority

5.4.1.1 Wind

The first resource selected in the portfolio is wind. Based on the load factor of the total Belgian wind power production park, it can easily be determined how much installed capacity is needed to deliver enough wind energy to cover the total output of the CCGT to be replaced. To deliver as much energy throughout the year as a gas fired plant in 2015, 364 MW of wind power is required. This would result in 169 days where enough wind energy is produced to cover the production requirement of the same day. As the wind energy is not necessarily evenly distributed over the day, the loads will need to follow the wind profile during the day. As 169 days are fully covered or more, 196 days will have not enough wind energy available to cope with the intraday demand. However, if enough storage capacity would be available, the energy demand throughout the year would be covered. Fig. 5.2 shows the available relative wind energy per day in Belgium.

In Fig. 5.3, the daily energy difference between wind production and the output of the gas fired plant to be replaced is shown. Positive values indicate the gas plant produced more energy than wind, negative numbers indicate more wind energy was available during that day than required to replace the gas unit.

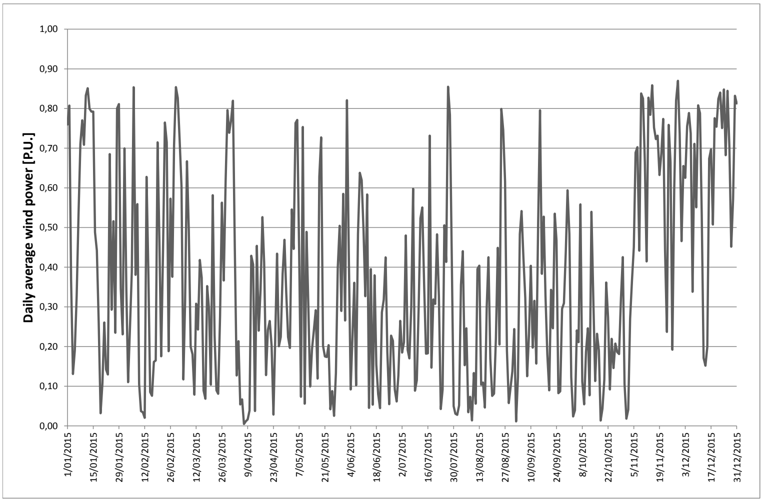

Figure 5.2: Daily average wind output in 2015 in Belgium

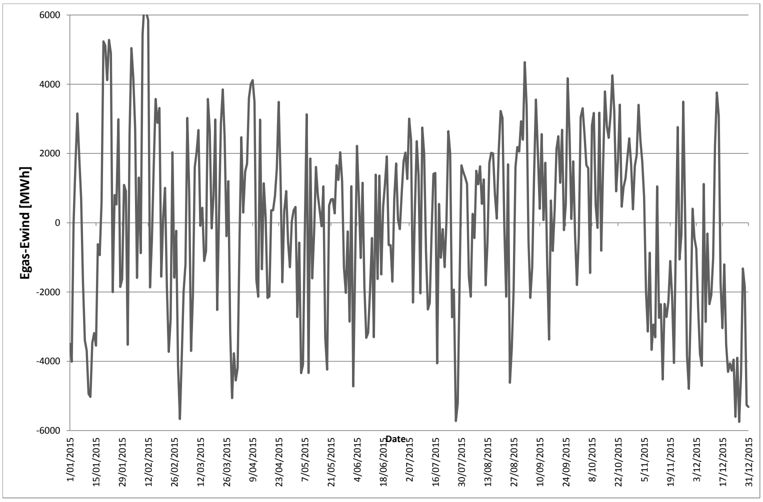

Figure 5.3: Daily energy difference between gas power plants and wind turbines

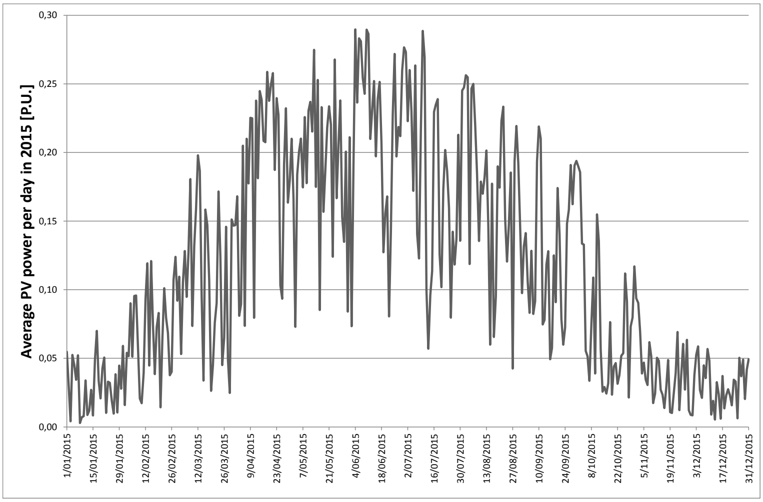

Figure 5.4: Daily average PV output in 2015 in Belgium

5.4.1.2 PV

The next logical step is to add PV power. Solar energy will have a different profile than wind (Fig. 5.4). Therefore, it can help to reduce the number of days renewable energy is not able to cover the intraday demand.

However, each MWh solar energy which is added to the wind capacity added in the previous paragraph, will result in a surplus at the end of the year. If the wind capacity is 364 MW and the same amount of PV power is added, the number of days where energy demand is not met drops from 196 days to 130 days. The largest shortage on a single day is then 6239 MWh, only 150 MWh less than with only wind power. The resulting daily energy is shown in graph 5.5.

Increasing the PV power to 580 MW results in a reduction of the days with energy shortage to 98. However, the largest shortage remains about 6150 MWh and therefore makes not much difference. The VPP would in this case produce 65% more energy than is required. This excess energy is entirely atributable to the PV capacity, as wind capacity was designed to cover yearly energy demand by itself. If no storage is applied, even more renewable energy is not used to cover the required load. This energy could be curtailed. Another option would be to convert it to natural gas and use it later to power CHPs or other appliances.

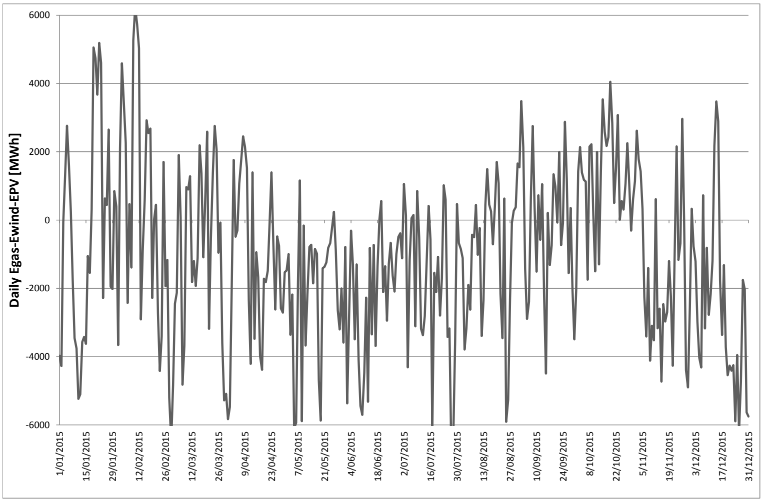

Figure 5.5: Daily energy difference VPP with 364 MW wind and PV vs CCGT

5.4.1.3 Firm capacity

In the previous paragraphs, it was shown that in order to cover the daily energy demand with wind or PV alone, huge amounts of installed capacity would be needed. During a lot of days, excess energy would be available, while at other days shortages still remain. These shortages will need to be solved by either curtailing load or controllable production capacity.

The first option is to assure enough firm capacity to cover the worst day. This would require 260 MW of other sources at full load to make up. These other sources could be CHPs, emergency gensets or any other controllable resource. As the purpose is to replace a 300 MW power plant, this makes not much difference regarding installed fossil fuel power. However, the capacity factor for the fossil fuel would drop from 45% for 300 MW to 9% for 260 MW, resulting in an enormous drop in fuel cost and carbon dioxide emissions.

If Fig. 5.5 is investigated more carefully, one can see the daily energy shortage differs highly for the days where wind and solar energy can not cover the daily demand. Therefore, it might not be necessary to cover the worst case scenario with firm capacity. Table 5.1 shows the number of days in function of reduced firm capacity. It can be seen that reducing the power of firm capacity, the number of days where the energy demand is not met increases. However, the load factor of this smaller capacity will increase. As a result, the revenue will also increase.

A combination of resources could also be made. The bottom end can be made

Firm capacity power MW	# days curtailment	load factor firm capacity %
250	1	10
200	6	12
150	11	15
100	32	20
50	69	27

Table 5.1: The number of days firm capacity is sufficient as function of installed power

of efficient CHPs, whereas the low load top end consists of less efficient gas motors (e.g. backup generators). This provides the CHPs with more running hours and prevents low efficiency gas motors to run to much.

The required firm capacity could be further lowered if it is allowed to transfer surplus energy from one day to the following if shortage is present. This might be achieved by increasing the temperature setpoint of a thermal buffer of a heat pump or starting to charge a cars battery earlier. Buffers might also be depleted further than normal, risking user discomfort. This inter-day energy transfer is not always possible as sometimes several consecutive days with energy shortage occur. These consecutive days are however quite scarce, so curtailment and sacrificing some comfort might be cheaper than investing in a large energy buffer which will see only limited use.

5.4.1.4 Storage

Storage can also be used to reduce the amount of curtailed energy. Most of the days with energy shortage come in short clusters of a few consecutive days (1-5 consecutive days). This presents the opportunity for the storage device to replenish its reserve within a couple of days. Also, to bridge most of these days, a relative small storage capacity is required. In the previous case, a VPP with 365 MW wind, 365 MW PV and 100 MW of firm capacity, the buffer needs to contain 14000 MWh of energy. That is the equivalent of 2.1 million Tesla power walls with a capacity of 6.4 kWh. This would mean less than one out of two households in Belgium should be equipped with an energy storage device.

Allowing some days with curtailment, the storage requirements could be lowered drastically. Reducing the buffer size by a factor of 2 to 7000 MWh would result in 4 days which require curtailment, compared to 32 days without storage. As table 5.2 indicates, further reduction in storage size increases the number of days with less energy production than with a 300 MW CCGT.

5.4.1.5 Selection process decisions

Which approach is taken for the selection process depends entirely on the VPP. If the main goal is to produce as much renewable energy, the approach of 5.4.1.1 -

Storage capacity [MWh]	days with curtailment
14000	0
7000	4
6000	6
5000	7
4000	18
3000	24
2000	27
1000	32
0	32

Table 5.2: Days with energy curtailment in function of storage capacity

5.4.1.3 could be taken. This could be an interesting approach if already a lot of renewable energy sources are under contract with the VPP. Hundreds of scenarios are possible, so it is not feasible to present them all. The aforementioned approach is only one scenario, with the main goal of producing as much renewable energy as possible.

An different approach could be to increase the load factor of the CHPs in the system. Producing a baseload capacity with CHPs could significantly reduce the required wind power capacity. Providing a baseload CHP capacity of 100 MW would only require 170 MW of wind power to supply the remaining energy. This would also reduce the load following capacity required, as the CHPs could deliver a stable base load.

5.4.2 Availability

The requirements in this chapter have been based on the total gas fired power plant portfolio. However, individual units have minimum load requirements, different cost structures and maintenance periods. Operators therefore will shut down some plants and operate others at full load. As a result, ancillary services could only be delivered during this running time. The VPP should be able to do better. In the first place, this means the system should be up and running during at least 7500 hours per year. This is however a requirement for the Supervisory Control And Data Acquisition (SCADA), not for the individual unit. This should be no large issue, as this is extremely low compared to the availability of standard industrial SCADA systems. As a matter of fact, all major SCADA suppliers offer the possibility to duplicate the critical components and therefore removing single points of failure.

Individual units could become unavailable due to different reasons. However, as the power of a typical unit in a VPP is most likely much smaller than the total VPP power, this can be catered for without much problems. Unavailability of a certain unit can be due to several reasons:

1. Connection problems

  - Availability: 99.95 %
  - Mean Time To Repair (MTTR) 8 hours [126]

2. Controller breakdown

3. Unit breakdown

4. Primary energy unavailable

All these sources of failure have only effect on an individual resource. A careful designed portfolio should therefore be able to replace a faulty unit with an other one which is operational.

5.4.3 Designing for primary reserve

Primary reserve provision is a very challenging requirement. As reaction time is only in the order of seconds, delays in communication could be fatal. Therefore, a local controller should be available. This has been discussed in §3.5 and published in [9]. Restore, a company providing ancillary services with distributed resources, works in a similar way [59, 60]. A local controller is responsible for the primary frequency control, whereas state information and settings are communicated at a much slower pace.

5.4.4 Reserve provision

A VPP with a lot of renewable sources will require also a lot of manageable load in order to utilise as much of the resources as possible. Storage is also an option, however, up till the present this is very expensive and for a lot of technologies still in a experimental phase. As a result, the total amount of installed power of a VPP will be much larger than the installed power of a traditional system in order to cope with the variability of renewable sources.

This spare capacity can be made available in order to deliver services to other grid partners. However, the VPP will need to determine the best value for its assets. Normally, internal goals need to be fulfilled first. However, depending on the value offered by third parties, be it the grid operator, an other VPP via the intraday market or a supplier, the VPP can decide to offer flexibility to these external parties. Knowing the state of all resources and the value of energy in each time interval is therefore of extreme importance to the VPP operator. Without this information, the VPP will not create the maximum added value possible.

5.4.5 VPP suggestion

Table 5.3 gives an overview of a possible portfolio of a VPP getting its energy mainly from renewable resources. This collection largely outperforms the requirement set to replace the functionality of a 300 MW CCGT. Much more energy is produced than required. This energy could be curtailed, as it is sometimes available when there is no demand. The same trade-off as with backup will need to be made: how much capacity will need to be installed to harvest the last bit of energy, or should some part be curtailed in order to reduce storage requirements. The proposed capacities will produce 1743 GWh of energy (without the emergency backup generators), whereas the CCGT only required 1186 GWh. The amount of RES could be reduced if the CHP is used more. Now the load factor of these units is only 20%, which might be to low to be profitable.

Type	Installed power MW	Energy GWh	Remark
Wind	365	1186	Main energy resource
PV	365	379	Complementary energy resource
Controllable load	250	1186	Production following
CHP	100	178	Main backup
Emergency group	100	38	Emergency backup
Curtailable load	100		Emergency backup

Table 5.3: 300 MW VPP portfolio requirement

5.5 Conclusion

Replacing a CCGT by a Virtual Power Plant might be an achievable goal, depending on how close the behaviour needs to be mimicked. However, without storage, a large amount of controllable loads is required. These loads are required as renewable sources are limited in controllability. Curtailment is always possible, but if the primary energy source, e.g. wind or sun, is not available, no electricity will be produced. These loads therefore should be able to move their consumption to the time the primary resource is available, making use of their internal storage capability. This load shifting is however not unlimited. In this chapter, it is assumed loads can not be shifted over the border of the day. This seams reasonable, as most processes and use patterns are also taking place in this intervals. However, in practice, energy could well be transferred from one day to the next.

Controllable loads could be heat pumps but also electrical vehicles. These loads have the advantage of having high power and some form of energy storage. This storage can be used to implement load following techniques and reducing the need for purposely build storage. As has been detailed in chapter 4, thermo-electric appliances are ideal candidates to deliver electrical flexibility.

It should also be noted that traditional units used as a backup will have an additional cost associated with them. As their capacity factor reduced, the fixed costs will need to be covered by a much lower amount of sold energy. Therefore, these units become more expensive if they are used less. This could be covered by using emergency generators. However, then the risk is that these have a much lower efficiency than traditional large gas fired power plants. This could increase the carbon footprint if they are used to much.

As a final conclusion, §5.4 showed that replacing traditional resources entirely by renewable resources is impossible within Belgium without additional measures. Even if energy requirements are to be met on a 24h basis, not enough primary resources are always available. Therefore, significant backup has to be foreseen. This backup can be fulfilled in many ways, either by storage or by controllable sources. However, in terms of power, this backup should be almost as big as the required power of the VPP. The energy delivered by this backup is however very low compared to the total amount delivered. Also, a large amount of RES is available which could be used for other purposes like power to gas.

6

Overall Conclusion

6.1 Why Virtual Power Plants

In this dissertation, an overview is presented on how Virtual Power Plants could be part of the solution to the current challenges on the electricity market. Virtual Power Plants are a means to activate smaller energy consumers and producers. Smaller in this case means all units which do not operate under CIPU contracts, thus smaller than 25 MW. Traditionally, a unit larger than 25 MW is considered as an important participant of the grid and is enforced to actively contribute to the grid. However, many units are (much) smaller and are not obliged to actively cooperate.

These units, smaller than 25 MW, could be considered as Distributed Energy Resources (DER). Distributed, as they are much smaller than the traditional power plants which range from 25 MW to more than 1 GW. The second part of the term, Energy Resources, states that these units could be both producer and/or consumer.

Historically, all production consists of large power plants and small loads dispersed throughout the system. As a result, the operation of the grid was designed based on controlling the few large power stations. The power production followed the consumption pattern. All adjustments on power levels was done on the few large production plants and the loads remained largely free to decide their consumption pattern.

However, Europe decided to incorporate much more renewable energy sources (RES) in the system. Most renewable energy production systems are much smaller than the traditional power plants. To add to the difficulty, two major kinds of RES, Photo-Voltaic (PV) and wind are very difficult to predict. As the penetration level of these sources in the electrical grid increases, it becomes harder to maintain a stable grid. Especially as most of this renewable distributed generation is not taking part in the grid operations, this becomes challenging at least.

A VPP can be helpful in this context. A VPP can collect data from these small units, clustering all individual power requirements and present this to the grid as one single unit. This unit becomes then an addressable and accountable partner for the electrical grid operators.

6.2 Implementation strategy

A decent and flexible strategy is very important to develop a VPP. As has been shown in chapter 2 and 3, to be profitable, a minimum size will be necessary. This minimal capacity will depend on the type of resource, the flexibility, the market conditions and the implementation cost.

Before actually incorporating a certain resource in a VPP, the techno-economic characteristics of this resource needs to be known. A thorough understanding of the predictability, flexibility and associated costs of the resource is required before incorporation in the VPP. As a result of this initial investigation, a detailed overview of the resource should be made. This overview will indicate the aforementioned parameters in order to determine the minimal revenue required to activate the resource. Next, the resource should be fitted within a VPP. For some resources or cases, this will be a simple CVPP with optimised run times or profiles, others will generate more profit if used in a TVPP to deliver ancillary services.

As mentioned by the Fenix project [53] and the Umbrella project [127], implementation of VPP technology in real world test cases is not straightforward. Legal, political, regulatory and practical challenges limit the fast deployment of large demonstration projects. This will however be necessary to gain experience and have real-life results to base further research on. However, since the end of these projects and the beginning of this research, a lot has changed. Several companies have started building actual VPPs. However, testimonies identified the struggle to implement the technology and develop appropriate business models. In several cases, the legal framework had to be adapted in cooperation between authorities and industry.

Worth to mention is the ENTSO-E research and development roadmap [128]. In this document, the strategic goals of the European transmission system operators are described. Six main innovation clusters are set forward:

- Grid architecture
- Power technologies
- Network operation
- Market designs

- Asset management
- Joint TSO/DSO R&D activities

Virtual Power Plants can be fitted in different clusters: power technologies, network operation, market design and joint TSO/DSO activities are all possible project scopes. Hence, developing and implementing a VPP is a multidisciplinary project, and cooperation with many different specialists will be key to succeed. Developing VPPs will require joint effort of many different disciplines, incorporating legal, economical, spatial, technical and social skills.

6.3 Drivers and Bottlenecks

As has been mentioned in the previous paragraph, VPPs require a multidisciplinary approach. This might be one of the biggest challenges in itself. Specialists of several domains will need to cooperate to implement this technology. As has been remarked several times during the course of this PhD research, energy specialists of the different domains do not necessary have the same opinion on the same topic, nor do they understand the challenges present in the other fields.

Therefore, an integrated approach will be required, combining knowledge of Legal, Economic, Spatial, Technical and Social (LESTS) domains. Experts and companies will need to cooperate in order to realise a working VPP. Clustering and symbiosis is the essence of a VPP. Challenges and opportunities of industrial symbiosis are well understood [129], but will need to be adapted to the specifics of VPPs.

Next to challenges, there are also drivers which are advancing the implementation of VPPs. As has been mentioned in §1.1, European ambition to become a leading region in energy efficiency might be the biggest push towards the adoption of new technologies.

6.3.1 Legal

The liberalisation of the energy market in Europe created in theory a level playing field. However, more than ten years after the opening of the markets, the results are not what were hoped for. Large companies still dominate the system and small players are struggling to gain market share. The switching between suppliers is still low (Fig. 6.1). This shows the dominance of the traditional market players. Even with very competitive prices, new companies struggle to encourage clients to participate in an active market.

But the energy market is not only the only one dominated by large traditional players. Grid codes still favour large participants to deliver ancillary services. Gaining access to these revenue streams will be crucial to the success of TVPPs. Small changes are however observed, but not without large effort from early adopters of the technology.

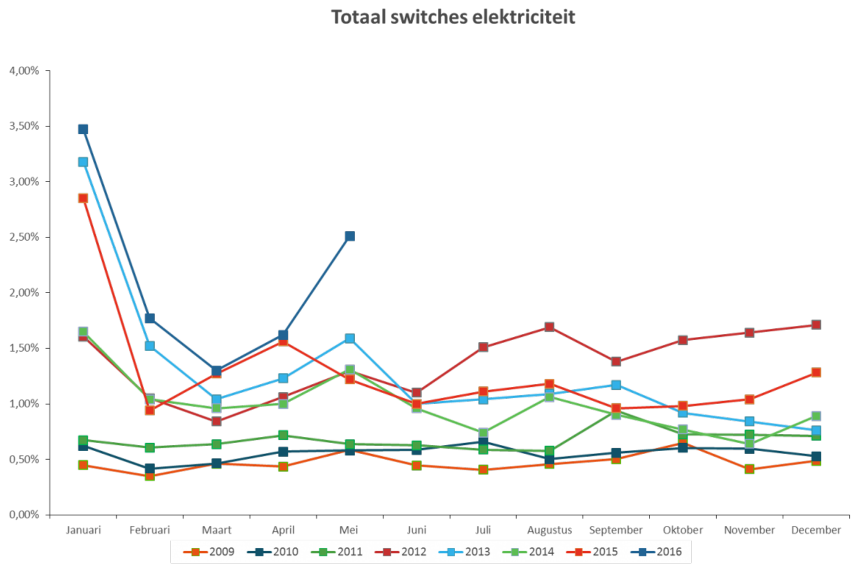

Figure 6.1: Supplier changes in the Belgian energy Market

A potential pitfall of RES integration is the priority dispatch requirement. The priority dispatch guarantees renewable sources access to the market, before any other technology. As a result, even during overproduction, renewable sources may not be curtailed. Only in case the safe operation of the grid is endangered, the RES can be curtailed. This creates sometimes adverse situations.

First, in some regions, installation of more RES is prohibited due to congestion during only a few hours a year. As the grid operators cannot guarantee the safe operation of the grid at all times, the connection is refused altogether, reducing the installed RES capacity and production in the long term. As has been indicated in §3.7, a VPP could reallocate resources and control RES. In these situations, a VPP could make a difference, allowing more RES while maintaining control over the congestion.

The second adverse effect is negative prices. At certain times, the energy market prices became negative. As the TSO had to give priority access to renewable sources, during low demand periods with high RES availability, the market could become saturated. However, other resources like nuclear power can not react to these situations as dynamically as required in these situations. This could create an excess of energy, forcing the prices to go negative. This should not be dramatic if occurring only a few hours a year. However, if negative prices become regular, this could impede energy efficiency.

However, the energy system is in constant evolution. The situation changed dramatically during the last five years. Changes in the legal framework have impacted the energy sector very deep on several fields.

First, the opening of the intraday market creates new opportunities. During the research phase of the solar CVPP [11], this market was only accessible as an emergency market, in order to alleviate sudden changes. The utilisation was limited to three consecutive days and five days per month. This has been changed in the meanwhile. However, the grid operators still require the grid participants to predict their position as precise as possible and abuse will still be punished.

Next, the legal framework of the nuclear power plants in Belgium has been changed frequently during the last decade. This creates a very unstable investment climate which also impacts the development of VPPs. Decisions made regarding the nuclear power plants are clearly reflected in energy market prices. Uncertainty about the future of nuclear power within Belgium also impedes uncertainty on the energy prices. This creates an unfavourable environment to invest in new and challenging technology.

Finally, residential customers are excluded from VPP participation as long as no smart meter programme is decided upon. Up till today, no legal framework for residential smart meters exists in Belgium. As the first metering for residential customers is mostly on the connection point between the distribution and transmission grid, many suppliers share one access point. As a result, imbalances can not be allocated to a single supplier and are hence socialised according to market participation on the access point. This holds back suppliers to invest in better technology to introduce active participation schemes from residential clients.

6.3.2 Economical

Current evolutions in market design make it somewhat more profitable for small scale energy producers to trade on the energy markets. The opening created in the intraday market can make a large difference for example. However, this is only true for the largest and most predictable DER technologies like CHP or large wind farms. To cope with the power variations of RES on a technical level, only basic level of the theoretical control and management possibilities are available. System operators still mostly rely on grid reinforcement to cope with large DER penetration. Activating and aligning all parties involved, from RES producers over grid operators and energy consumers will be key to succeed. Sharing the profits in a satisfying way, without impeding the profit or even the operational viability of the others will be essential.

The increasing price volatility presents an opportunity for flexible resources. Consumers who are willing to adapt their profile to better fit with renewable energy production will be able to take optimal advantage of the cheaper energy. For example electric cars for example can benefit from price volatility as they are connected to the grid for a large portion of the time. Users will need to select whether they prefer to charge fast, at a potential high price, or profit to the maximum by waiting until cheap(er) energy becomes available.

Industrial resources might also benefit from price volatility on the electrical grid. Managing electricity consumption and on-site production can reduce the electricity bill. This requires however a thorough understanding of electricity flows within the industrial plant. Knowing the relationship between energy consumption and process operations will be key to manage the energy cost. As has been detailed in §2.1, ignorance of the energy profile will increase the margin on the electricity price taken by the supplier, further increasing the energy bill.

To be able to acquire the necessary knowledge and managing financial risks, a gradual approach starting with the largest DER installations and gradually incorporating smaller installations will lower the cost and ensure profitability right from the beginning. The first steps are already taken by some companies like Powerhouse [130] and Restore [131]. Some offer only CVPP services like wholesale market access, while others also incorporate ancillary services. The CVPP operators rely on the economic reason of the participants to react to price signals. However, for many companies this is not appealing enough as the economical and perceived benefits are quite low. As has been mentioned before, a major bottleneck here is the unavailability of detailed energy profiles. Companies have often not enough knowledge of the impact of operational decisions on their energy profile. Reducing peak consumption can sometimes be as simple as a staggered start-up after a production break (e.g. in the morning or after lunch). Allocating energy resource to production decisions will increase the predictability of the electricity profile. This can be the basis for negotiations to obtain a better energy price from a supplier.

Most of the markets today are operating in one hour or longer product intervals. Additionally, most markets require participants to submit their position at least twelve to thirty-six hours in advance of actual delivery, although the intraday market has been gradually opened during the last year before this publication. This imposes the day ahead weather prediction is of crucial importance to the market outcome. In low load conditions combined with high wind power, a small error in wind speed prediction can have a large impact on the market price settling. Market operators have conceded to the market participants by the (strictly limited) intraday market and by introducing the imbalance market. However, further segmentation within a market area is not possible. Market segmentation can be desirable when technical limits restrict the normal unified market operation. Today, this is already the case in the international power market in central Europe. When cross-border transmission capacity is insufficient to sustain market coupling, the market is split on the limiting border and two or more separate price zones are formed [132, 133]. However, in certain cases, and especially for distribution grid operators, a more localised price adaptation could be beneficial.

As described in [134], traditional power plants ensure their future revenues against extreme price volatility by selling in forward contracts. The traders rely on market analysis for longterm price determination. Statistical models are present to predict seasonal renewable power production. However, on shorttherm (a few days to a few hours), price prediction is much more difficult due to the very local nature of available RES power. This imposes not only technical challenges, but economic dispatch of existing plants is also affected. Reference [135] describes an algorithm to dispatch power in multi-source systems with RES and thermal units together with storage. However, the high cost of storage and the uncertainty of renewable sources reduces the applicability of the method.

As a final remark, the very fast evolution in markets and the many influencing factors make it very difficult for small companies to compete. An individual company will struggle hard to maintain enough knowledge to individually compete in the energy markets. Individual market access exposes the trader to enormous risks as has been defined in §2.8. This is a problem which could be solved by the VPP. The resource owner needs to determine the cost of the flexibility and then the VPP operator can decide to activate this resource or not. The VPP operator can aggregate enough capacity to maintain a constant market analysis team in order to reduce trading risks.

6.3.3 Spatial

Renewable energy has a high spatial impact. Wind turbines require an unobstructed wind flow, solar panels require a large unshaded surface, biomass can impact agricultural acreage available for food...

The integration of renewable energy resources in the Flemish, Belgian or even European space is no evidence. Especially in Flanders, one of the most populated regions of the world, this poses often conflicts of interests. For example wind turbines pose large challenges. Due to their hight, wind turbines affect a large area around them. Neighbours can be affected by noise or visual pollution, but can also be affected by vibrations transmitted through the ground. Another, less obvious but very important spacial impact are the radar reflections from the moving blades. Aeroplanes use radar systems to navigate and land. These systems can be negatively affected by wind turbines in the vicinity of aeroports.

Other technologies pose also spatial challenges: solar panels can affect the visual impact of historical buildings, high value energy crops can replace less profitable food crops, (tidal) dams impact the water flow in rivers,...

A major spatial concern is also the impact of energy transmission: high voltage lines are not a popular neighbour. As has been presented in §1.1 and §3.7, congestion can be introduced if large amounts of energy needs to be transported from one region to an other. As has been explained in §3.7, a VPP can help to reduce congestion, large structural congestion will require new high voltage lines in order to connect producers, consumers and storage.

This leads to the next spatial challenge: storage. As has been explained in §3.6.4, some storage technologies depend on geological formations, e.g. mountains for pumped hydro or caves for compressed air.

Spatial aspects might not only present bottlenecks, but can also become a driver for technologies. The close proximity of functional clusters can be advantageous to some technologies. As many industrial clusters in Flanders exists in close proximity to residential or commercial areas, thermal grids require less distance in order to utilise waste heat. Combined with thermal storage, thermal grids can become an important supplier of flexibility to the electrical grid (chapter 4).

As has been presented in §3.6.4.6, Flanders possesses already an extensive hydrogen network. This network could be augmented to be used as an important storage buffer for energy in the form of hydrogen gas. Connecting this extensive hydrogen network to the electrical grid by fuel cells and electrolysers is an unique opportunity available in Flanders.

6.3.4 Technical

Most current VPPs are designed to operate within the current grid limitations. To make the transition to very high DER penetration as required by the European Commission, more active grid participation of DER will be necessary. Hence, current limitations need to be superseded. To meet these goals, DER will need to deliver ancillary services to maintain grid stability.

As such, large opportunities are left for research and large scale implementation of a mixed-asset VPP to deliver reliable services to the grid. During the last years, a slow improvement can be noticed. Several companies market and sell products using VPP technology. However, the market adoption is slow and many hurdles will need to be taken.

As is shown in chapter 5, a mixed-asset VPP takes advantage of many different technologies in its portfolio. The technical capabilities of DER can vary significantly. RES are largely constrained by the primary energy availability, whereas CHP systems need to take into account the heat demand. Also the dynamics of these sources have an enormous spread. Solar systems can ramp up or down in milliseconds, large wind turbines need tens of seconds to several minutes to change the power output and large-scale CHP systems can only vary their output on even longer time scales. Combining all these dynamic aspects to deliver reliable grid support services will be key to meet the set goals.

By combining these properties, a VPP can deliver advanced services to the grid. Solar capacity can be very responsive to grid demands. After the intervention of the solar panels, wind turbines can restore the depleted control margins of the solar panels. CHP systems in turn can restore the margins of the wind turbines on an even longer time scale. As a result, the VPP can deliver very fast changing services and large volumes due to the nature of the combined resources, thereby exceeding the limits of individual resources.

Due to the use of the renewables as reserve capacity, their capacity factor will decrease. But if thoughtfully integrated, this can result in a larger allowed installed capacity of renewables into the existing grid infrastructure. Hence, renewables can provide a larger share of the electricity production. So, although the yield of an individual installation will be lower, the total RES yield in the system can be drastically improved due to the larger allowed installed capacity.

6.3.5 Social

Implementing a VPP almost always will require changing operational parameters of certain processes. Except for very simple CVPPs which only communicate a consumption pattern to their supplier (the VPP), all other cases will require interaction with the process. Often this will impact the work regime of personnel operating the asset. The operation of the VPP should take this into account. Changing working schedules to match weather conditions is not an acceptable way of working for most people.

Next to the real impact a VPP could have on operations, also other social aspects should be taken into account. Companies already selling flexible energy contracts or buying flexibility from industry testify each time how difficult it is to convince potential clients of the possibilities. It requires a behavioural change of companies to actively change their energy profile. Users have become accustomed to an always available, very stable grid.

Knowledge of their energy consumption will be the first step for many consumers. It is observed during many contacts with industry that the electricity consumption is seldom known, let alone the energy profile. Awareness of the operation of the energy market, the way prices are set and the value of predictability and flexibility should be the next step. These insights could then lead to sensitivity to a more volatile prices scheme, as the opportunities become clear.

6.4 Final conclusion of the work presented

In this thesis, an overview is presented on how Virtual Power Plants could be part of the solution to the current problems on the quickly evolving electricity system. The massive adoption of renewable sources during the last decade and the ambition to incorporate much more of these volatile resources require a different approach. Also the demand side is changing. Heat pumps and electric vehicles are two challenges on the demand side the grid will need to cope with. The traditional control structures will not be able to cope with all these new resources, especially as most of these resources are not managed.

Virtual Power Plants are a means to manage smaller energy consumers and producers. Smaller in this case means all units which do not operate under CIPU contracts, thus smaller than 25 MW. Most of the renewable resources fall within this category. Traditionally, a unit larger than 25 MW is considered as an important participant of the grid and is enforced to actively contribute to the grid. However, many units are (much) smaller and are not obliged to actively cooperate to keep the grid safe and stable.

A VPP can be utilised in several ways to help these resources to actively participate to the grid. First, economic integration. Several well established electricity markets already exists. The large difference between power and energy levels of the traditional market and the individual requirements of a single customer are immense. This imposes difficulties for small units to directly participate to these markets. A VPP can be the perfect mediator between the wholesale market and the individual unit. This can offer the benefits of the wholesale market like dynamic pricing to the individual company. As such, the VPP can further increase the market dynamics as intended by the European energy market liberalisation. This has been detailed in chapter 2. First, the operation of the different energy markets have been studied in §2.2. First, in §2.7, it was investigated if a VPP consisting of only solar energy would benefit from wholesale selling its energy. As no rescheduling or direct consumption was applied, it turned out the benefit would be very low. Shifting consumption in order to benefit from low market prices could however be much more profitable.

Next, in §2.8, the imbalance market has been studied in detail. Trading with active use of the imbalance market can have a tremendous impact on profit. Taking the wrong decisions and the costs could double. However, if the right decisions are made, large profits can also be obtained. It should however be noted that using the imbalance market requires the correct procedures to be followed. Deliberately nominating a wrong schedule is illegal and can endanger the system stability. The results show however that one who is willing to offer flexibility can benefit from the increased price volatility on the imbalance market.

Next, a TVPP can collect and coordinate flexibility of individual resources in order to maintain grid stability. Grid support services are up till now mainly provided by large gas fired power plants. VPPs can offer the control structure to enable these small units to deliver these services without requiring the same reliability for every individual unit. Responsibilities can be shared between VPP participants to meet the required service level no single unit can guarantee on its own. This ensures that small units can also contribute to the stability of the system as a whole and eases the burden on the traditional production park. This ensures especially the safe and future proof integration of renewable energy within the electrical system. This was elaborated in chapter 3. First, in §3.3, ancillary services have been discussed. These form the second pillar of revenue for VPPs. A TVPP can sell its flexibility as ancillary services in order to help maintain the stability of the grid. Selling these services can be very profitable. However, in order to be able to sell flexibility, a company or plant will need the impact of the flexibility on the production process and plant operation. Integrating the TVPP concept in companies will require much more detailed research. A research proposal to integrate VPPs within chemical process industry has been submitted.

In §3.6, an overview of electrical energy storage has been presented and the potential impact and applicability to the Belgian grid has been presented. As is further presented in §5.4.1.4, storage will be crucial in the transition to renewable energy. Combining renewable resources, storage and flexible demand will be crucial to make the transition. VPPs are an instrument to ease this integration, based on the current grid system and energy markets.

In §3.7, an application of a TVPP is presented in order to reduce congestion induced by wind energy production in a region. It is proven that the flexibility of a VPP can be utilised in order to reallocate resources to other regions. Allocating downward reserve activations within the congestion affected region and upward activations outside the affected region can alleviate the problem. Further, the revenue from the reserve service provision can be used to partially remunerate the congestion management, which is in itself an unpaid service.

Paragraph 3.9 discusses an option to enable secure emergency curtailment on residential level. As system peak power consumption often coincides with peak residential consumption, curtailing residential consumption can be a solution to cover the last peak power. It is proven that up to 3 GW can be curtailed during winter peaks from residential consumers. This would have a lesser impact than the currently used method of curtailing entire zones of the country. Even limiting residential power during critical moments can make a huge difference on system scale, without impacting basic comfort.

Chapter 4 elaborates on the large potential role for thermal energy in VPPs. Many technologies convert thermal energy to electrical energy or the other way around. Due to the large differences in time constants between the electrical grid and most thermal systems, these can provide a large share of the required flexibility. Heat pump operation for example can be shifted a couple of hours in time without significantly affecting user satisfaction or requiring significant increases in thermal storage. Harvesting thermal flexibility to provide electrical flexibility can reduce the need to invest in large electrical storage, without significantly increasing the thermal investments.

In chapter 5, a replacement of a CCGT by renewable energy is investigated. Production data of CCGTs and renewable sources is compared on a day-by-day basis. It is assumed that enough flexible consumers are available to follow RES production within a frame of 24 h. It is calculated that in order to replace a 300 MW CCGT, 365 MW of installed wind power is needed. However, the energy is not always produced within the required time frame. Augmenting the portfolio with solar power and firm capacity can reduce the day-by-day energy mismatch, but some gaps in energy coverage will remain. Therefore, energy storage on a large scale will be required in order to avoid curtailment.

6.5 Further work

It has been proven in this thesis that VPPs can offer many benefits to the Belgian power system. However, a stable and open legal framework will be necessary to develop this technology to its full potential. The market will need a stable investment environment with enough freedom to incorporate new technologies and further develop new business models. Continuing the work on new legislation will be required to create a framework in order to make the energy transition happen. A lot of technology is available, but requires legal changes in order to thrive.

A second big challenge is the lack of knowledge of energy profiles and electricity consumption in particular. The society is not enough aware of the dynamics of electricity and the impact on its price. Not enough energy profiles are available in order to make a realistic prediction on potential flexibility, let alone determine the cost of this flexibility. Extensive (sub)metering will be required to couple industrial production planning to the corresponding energy profile. This can then be used to better predict the energy profile, based on the production planning. Rescheduling production can then provide (part of) the required electrical energy flexibility. This will however not be without a cost, as it will have an impact on operations, maintenance and personnel requirements.

In this dissertation, it has been proven the framework for VPPs is present. The next step will need to bridge the gap between theory and practice. The main challenge will be combining the knowledge of several domains; legal, economical, spatial, technical and social. During the last years, bottlenecks are slowly being removed. Many drivers for the change are present, in the first place the European desire to become world leader in energy efficiency and energy independence.

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