



Research Plan Proposal

“Adapting Energy Markets in Europe to Integrate Industrial Demand Response”

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Abstract

Demand Response has been considered over the last years as one of the possible solutions to further integrate variable renewable energy sources in future energy markets and to reduce the costs of the system. An easy way to capture most of the existing flexibility without negotiating with all the electricity consumers is to focus on industrial consumers. This group of consumers is rather limited and typically covers between 20% and 50% of the total electricity demand in most member states of the EU (except for Iceland and Cyprus). Within this group of industrial consumers, a number of industries and processes were identified that can provide the most flexibility to the system. The next step is to activate this flexibility within the current regulatory framework. The electricity markets were analysed for three European countries and this analysis pointed out what the main barriers are that limit demand-side participation. The last step is to design a model to evaluate those different types of flexibility under different regulatory frameworks.

This work provides the objectives of the study we will conduct, the methodology that will be followed and the motivation why this topic was chosen. The latter is directly related with the results of the literature, as we found that there are no existing models that capture the complexity of the industrial processes and the different markets designs in Europe.

The main objective of this thesis therefore to estimate the value of industrial demand response under different European market designs. This will be done by developing a model that is able to capture different market designs for energy and ancillary services. From the results of this model, some policy recommendations will be formulated on how future markets should be designed.

Research Plan Proposal

"Adapting Energy Markets in Europe to Integrate Industrial Demand Response"

1 Introduction

The interest for demand response (DR) has increased significantly over the last years. Although DR is one of the most straightforward and oldest ways of providing certain ancillary services, the majority of its potential has remained unused. Originally DR was only considered as a last-resource reserve that could be used in the occurrence of a black out. However, more recently the technological developments (smart meters, automated activation, ...) have reduced the costs of demand offering ancillary services to the system, which has created a playfield to unlock the full potential of DR (Hurley, Peterson, and Whited 2013).

Together these developments, the public awareness of environmental issues has grown. The change in the public opinion has led to a movement in which policy makers have invested in programs to reduce carbon emissions. Typically, this is done by installed generation capacity based on renewable energy sources that have a more variable output than conventional thermal generators. A second reason to explore alternative solutions is the need for security of supply to deal with this variability. Also here, demand response can contribute to reduce the system costs by flexibility when needed (Shoreh et al. 2016).

The focus of this work is to analyse how European energy markets should be adapted to facilitate the integration of industrial demand response. Therefore, the next chapter explains what is considered as demand response, followed by a description of the most relevant industries that have to be considered when studying the potential for demand response, an analysis of the regulatory framework in the three target countries (Belgium, Spain and the UK) and an overview of different mathematical models that exist in the literature to evaluate the value of demand response in different markets. At the end, also some preliminary conclusions drawn from the literature review will be presented.

The rest of this research proposal explains the motivation, the research questions and the objectives of the thesis. The motivation for this topic comes from the research gap that was identified during the literature review, which resulted as well in the most important research question: *what is the value of demand response under different market designs?*

This proposal ends with the methodology that will be followed during this thesis and of which tasks this thesis will consist.

2 State of the art

2.1 Demand Response

To define clearly what is covered in this literature review, it is necessary to define demand response. First, it is important to make a distinction between “Demand Response” (DR) and “Demand-side Management” (DSM). In the literature demand-side management generally includes the technologies, actions and programmes “behind the meter” that manage or decrease energy consumption in order to fulfil some system wide objectives. These objectives can be reducing the total system expenditure, emissions reduction, balancing supply and demand or other objectives (Warren 2014). Demand response on the other hand, is part of demand-side management and can be defined as the deviation in customers’ electricity usage from their normal load pattern as a response to the conditions of the system.

From both definitions we can conclude that DSM includes DR and “Energy Efficiency” programs (EE) (Building Efficiency Initiative 2012). The distinctions between both DR typically optimizes a given set of resources for a given short time period, while EE tries to change the characteristics such that the same processes can be done with a lower amount of energy. While demand-side management could reduce the peak demand consumption in the US with 7.5% through DR and EE, the potential of energy reduction (in the US) is estimated to be around 5.5% which is mainly achieved through EE (Gellings, Wikler, and Ghosh 2006). However, both components of DSM can also be counterproductive, which explains the need for a joint optimization of both objectives (York and Kushler 2005).

EE programs might reduce the energy needed for the same process, which might make this process more interesting to use. This can lead to an increase in the usage of this process that might lead to an increase in total energy usage. When this increase in usage happens during the peaks hours of the day, this might even increase the total expenditure of the system on energy. This is known as the rebound effect (Steve Sorrell 2007).

Similarly, the opposite effect can also occur. DR programs can lead to a reduction in energy efficiency, although the outcome for the system might be considered as better (Goldman et al. 2010). This can happen for example when a production process has to shut down during the peak hours (to reduce the system peak) and the process has to restart afterwards (and therefore it will consume more energy).

2.1.1 Different ways to provide demand response

Demand response typically can be monetised by doing energy arbitrage, providing ancillary services, providing congestion management or by offering firm capacity to the system. Consumers providing a service to the system can be rewarded based on bilateral contracts (between the consumer and an aggregator for example), an organised market (in which the TSO pays the demand for providing the service) or through a reward/penalty system (when demand is helping or harming the system). The activation

of these reserves provided through demand response can be done manually or automatically (Samad and Kiliccote 2012).

The ancillary services can be grouped into several generic services (IndustRE 2016):

- Frequency Containment Reserves (FCR): these are operating reserves for constant containment of frequency deviations, or fluctuations, from nominal value in order to constantly maintain the power balance in the whole synchronously interconnected system.
- Frequency Restoration Reserves (FRR): these reserves are used to restore frequency to the nominal value and power balance to the scheduled value after sudden system imbalance occurrence.
- Replacement Reserves (RR): these reserves are used to restore the required level of operational reserves to be prepared for a further system imbalance.
- Other ancillary services
 - Voltage Control
 - Black Start-up

The exact products that are requested by the system operator or that are traded in the market are different in every country. Notwithstanding these differences, they can all be assigned to one of the categories mentioned above. In principle, demand response cannot offer the last-mentioned service as this service requires specific capabilities. Nevertheless, there is a possible contribution of DR in the occurrence of an outage as disconnecting demand lowers the need for additional generation capacity (Bessler, Hovie, and Jung 2016).

The actual participation of the demand-side also depends on the definition of the different service (Shen et al. 2014). To attract the full potential, it is necessary to create for every service a market in which both generation and demand are allowed to compete. Despite the fact that the potential of participation is high, the role of demand response in electricity markets remains small (Ma et al. 2013).

2.2 Demand Response in energy intensive industries

The previous section showed that although the potential benefits of demand-side participation are significant, the actual activation might be problematic as small individual consumers might not be willing to give up their freedom. In this section, we will focus on different energy intensive industries for which the individual benefits might be significant enough to activate their full potential.

Each industry has its own technical features that determine the potential to participate in ancillary services. Not only the adaptability of the industrial process but also the reaction time and the maximum duration are some of the technical features should be taken into account when analysing the possibility for an industry to provide demand response (Alkadi, Starke, and Ma 2013).

These features show that treating industrial demand as one big load, will lead to over-simplifications and wrong conclusions. On the other hand it would be too complex to

evaluate each industrial process individually and therefore it is necessary to cluster the industrial processes (Khan et al. 2016). A solution here would be to identify some reference models for different industrial processes that can be used to represent the essential complexity without analysing each individual process.

2.2.1 Potential for providing DR of different types of industries

The rest of this section will describe the demand-response potential of the most relevant industries in the countries under study in this work (see Figure 1). The selection of the industries is based on (Samad and Kiliccote 2012; Eurostat 2014).

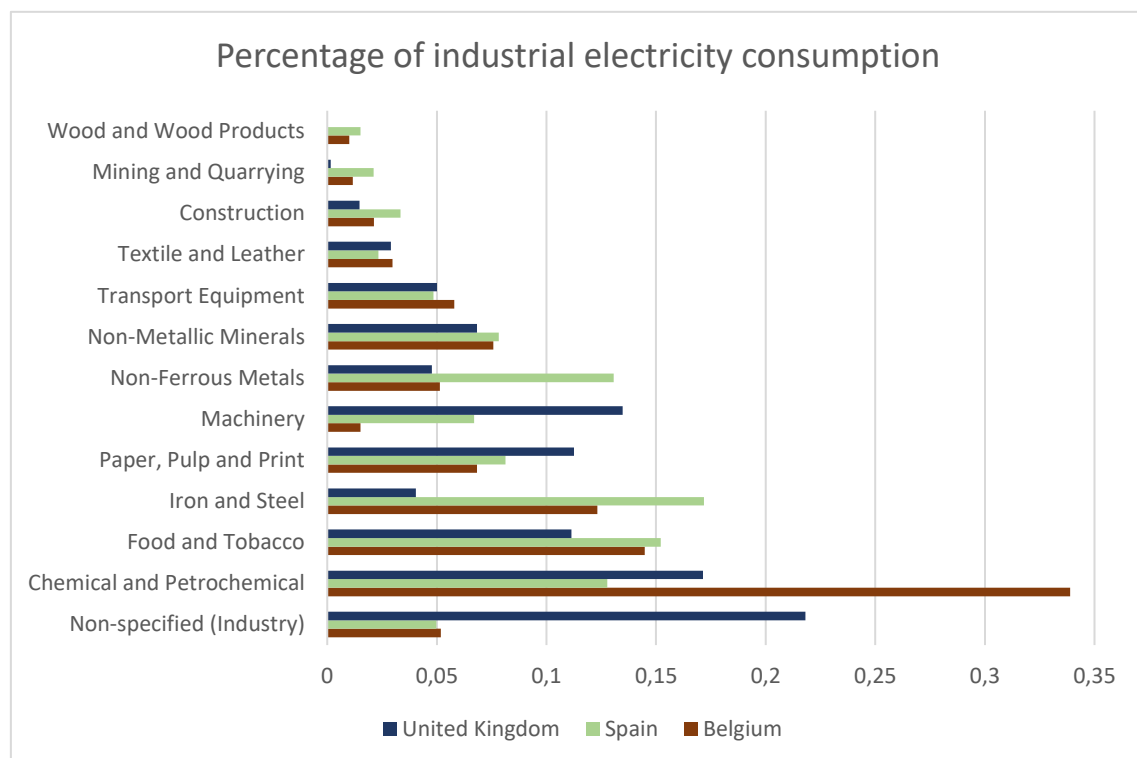


Figure 1: Industrial electricity consumption as a percentage of the total industrial electricity consumption in Spain, Belgium and the UK

a. Paper Industry

The paper industry is characterised by high electricity consumption and by a certain amount of flexibility in its production process. With a share of 6% in the world's total energy consumption, the paper industry was the fourth largest industry in the world in 2005 (Laurijssen, Faaij, and Worrell 2012).

The general configuration of a paper plant contains three parts: a pulp plant, a paper plant and a recovery plant (Furlan et al. 2015). The pulping process can be mechanical or chemical, with a limited potential for the latter one (Lindberg et al. 2014). The exact configuration among the paper industries can differ significantly.

As stated before, it is important to distinguish the difference between changes in energy consumption through demand response on one hand, and changes through energy efficiency improvements. Demand response could lead to savings between 5-10%

because the pulp production has typically a larger capacity than the paper production. However, in practise the potential might be limited due to the limited potential of load shifting for the paper machine (Lindberg et al. 2014). On the other hand, there is a potential for a 15% reduction of overall energy usage through energy efficiency (Laurijssen, Faaij, and Worrell 2012). Through aggregation, paper plants can also offer ancillary services to the system. However, no public data are yet available to quantify the real potential of this service.

b. Cement Industry

One of the most energy intensive industries is the non-metallic mineral industry and more specifically the cement industry. Typically, the share of the cement industry in the total electricity usage of the different industries is situated between 4% and 10% (Spanish Ministry of Industry, Energy and Tourism 2012; Eryilmaz et al. 2014). Moreover, when the total energy consumption is taking into account, the cement industry can be considered as the most energy intensive of all manufacturing industries (U.S. Energy Information Administration 2010).

In Germany the cement industry has an installed capacity of 314 MW (compared to a peak demand of 84 GW in 2014) with an average utilization level of around 80% (Agora 2015; Paulus and Borggreffe 2011). However, due to limited storage capacity, the potential for Demand Response is rather small, even though technically the plants would be able to ramp up or down in a couple of minutes. The potential is not only limited due to the limited storage capacity in the quarry, but also because the kiln process operates close to 100%. (Lindberg et al. 2014)

c. Aluminium Industry

Aluminium smelting is based on an electrolytic process that transforms alumina into aluminium. In this process, a pot line can consume up to hundreds of MWs as the electrolytic process uses a DC electric current to separate the aluminium from the oxygen. This process is operated at a very high current (several hundred thousand amps) but at a very low voltage (10 volts). One aluminium smelter can have several pot lines and therefore the smelting process accounts for almost half of the energy consumed by an aluminium smelter (Shoreh et al. 2016; Zhang and Hug 2015).

The technical features of the electrolytic process make the aluminium industry an excellent candidate to provide ancillary services. Alcoa, a major electricity consumer, has been providing up to 70 MWs of ancillary services in the Midwest ISO (MISO, USA) in the past, which shows that the potential of this industry is significant (Samad and Kiliccote 2012).

Finding the right balance between offering its capacity for ancillary services and selling energy is often hard. Typically, an aluminium smelter will dedicate most of its capacity to the market where the prices are the highest. Therefore, it could happen that a plant is willing to offering a peak capacity in primary reserves at valley hours while selling energy at peak hours (Zhang and Hug 2015). To use the full potential of the aluminium industry, the ancillary services should be designed flexible enough such that a plant can

provided a high instantaneous capacity without being activated too often. In other words, demand response becomes more interesting for aluminium plants when they do not need to provide a high amount of energy throughout the day.

d. Steel Industry

The technical features of the steel production process indicate that this industry has a great potential to participate in demand response programs. Theoretically, DR could help saving around 12% of electricity costs in the case of a high utilization of the furnace. These savings could increase to up to 52% in case of a lower utilization (Castro, Sun, and Harjunoski 2013).

One should be careful from drawing conclusions based on these numbers. The typically melting process reaches a utilization level of 75%. This is due to the fact that during an one-hour melting cycle, the furnace can only be on for 45 minutes and the other 15 minutes are used to empty and refill the furnace. As this process is not very flexible, unless the process is completely stopped, the steel industry does not seem to be a very suitable candidate to participate in a demand-response program. In case of the interruption of the process, long start up and shut down times should also be taken into account. (Lindberg et al. 2014; Paulus and Borggreffe 2011)

e. Chemical Industry

The chemical and petrochemical industry is another major sector when it comes to electricity consumption. Looking at the aggregated electricity consumption for all the members of the European Union, the chemical and petrochemical industry tops the ranking of most energy intensive industry (with even 50% more electricity used than the second most intensive industry) (Eurostat 2014).

The flexibility of the industrial consumers in this sector depends strongly on the specific processes that they are performing. In the case of a simplified refinery for example, the manufacturing plant would be able to reduce its electricity bill with 30% by only demand shifting (Mendoza-Serrano and Chmielewski 2013). However, because of its complexity, a real refinery will never be able to save this amount of money as adding constraints will always worsen the solution. Therefore, this percentage can only be seen as an upper limit to the potential savings.

Not only the complexity of the process, but also the price variability determines the possible savings. Moreover, to accurately estimate the possible savings, some stochastic component should be added to the model to take into account the uncertainty of the price levels. Together with implementing a more realistic model of the manufacturing plant, this leads potential savings of only 5% in the case of an air compressing plant (Zhu, Legg, and Laird 2011). The cost reduction will be higher when the price variability increases. Furthermore, consumers will have more incentives to use their flexibility when exposed to hourly electricity prices compared to fixed prices or Time-Of-Use contracts (Xenos et al. 2016).

2.2.2 Conclusions

In general terms the aluminium industry is the most attractive industry to participate in a demand response program. This is mainly due to the high electricity consumption and the electrolytic process whose schedule is rather easily adjustable.

The paper and cement industry are also excellent candidates to provide flexibility to the system, but mainly due to the limited buffer space between processes most of its potential has remained unexplored.

Despite their high electricity consumption, the chemical and steel industry both are not the most appropriate candidates to be involved in demand-response programs. This is due to the high complexity of their process and the high utilization rates of the machine on the continuous processes.

2.3 Demand Response in European Markets

The first step to activate the potential of demand response is to harmonise the European markets (Verzijlbergh et al. 2016). In reality, the services that demand can provide differ among all countries in Europe. This makes that demand can be rewarded differently depending on where it can offer its service, purely based on the definition of the service. To illustrate the differences among different industries and countries, we will analyse the current situation of demand response programs in three different European countries: Spain, the UK and Belgium.

This chapter is organised as follows. First, we describe how the different markets are organised in these countries. The second section describes the energy mix of the different countries and the need for demand flexibility that is a result of this energy mix. This chapter ends with a description of the different products that are traded or procured by TSOs in each country.

2.3.1 Belgium

2.3.1.1 The market (situation in January 2017)

The Belgian electricity markets comprise the Belpex day-ahead and the intraday markets. Although Belpex mentions a third market in its website, namely the strategic reserve market (Belpex 2016), in practise this is not a market in the strict sense. In the case that Elia expects that additional reserves could be needed, it could decide to activate these reserves in this market based on the bids that were provided during the tendering process (typically several months to one year before).

The day-ahead market opens 14 days before delivery and closes at 12:00 p.m. the day before real time as shown in Figure 2. The market operator has around one hour to publish the contracts after which market agents can still adjust their schedules in the intraday market. This market is a continuous market that opens at 2 p.m. the day before delivery and closes at 5 minutes before real time (Belpex 2016).

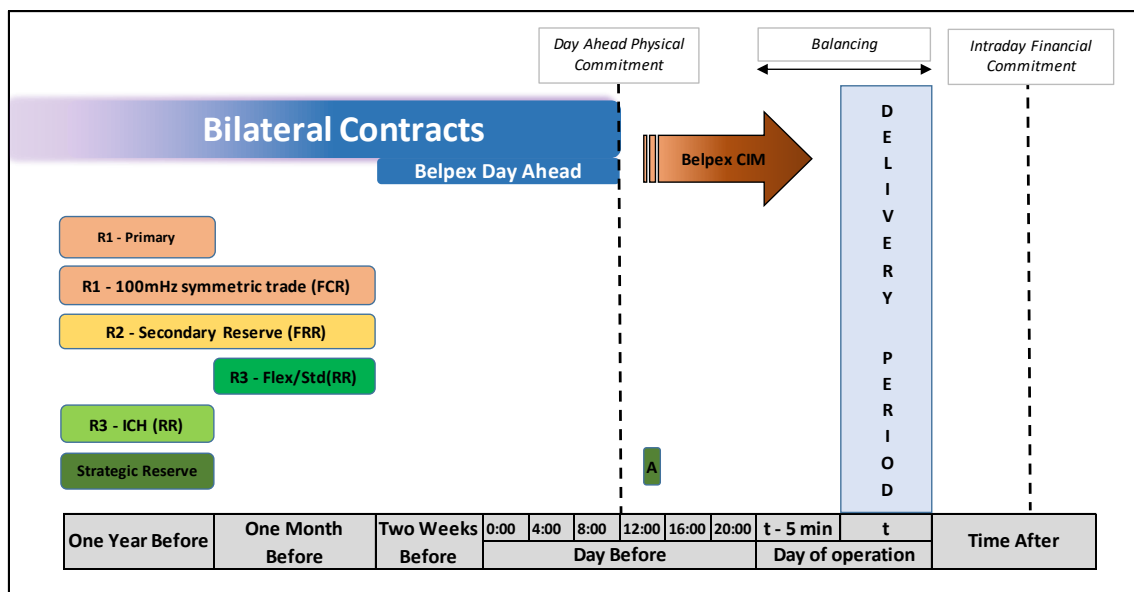


Figure 2: Schematic representation of the Belgian electricity markets in the beginning of 2017

Similar to the strategic reserve, other reserves are contracted on yearly basis through tenders organised by Elia. Only for the primary reserve (100mHz symmetric) and secondary reserve a month-ahead tender is organised (Elia 2016a). Until the end of 2016, the tertiary reserves consisted of R3-PROD, R3-DP and R3-ICH. The last two products and primary reserve were open for demand-side participation and the technical information about all the reserves can be found in Appendix 1.

In the beginning of 2017, several products were redefined to broaden the participation. R3 DP and R3 PROD stopped existing and R3 ICH will also disappear at the end of 2017. Two new products were introduced with a similar functioning: R3 Standard and R3 Flex. Both products are open for generation units and the demand side to participate and will be contracted on monthly basis as shown in Figure 3. At the moment of this literature study, Elia has not published any technical information on those products and this work only contains the information for Belgium which was valid until the end of 2016.

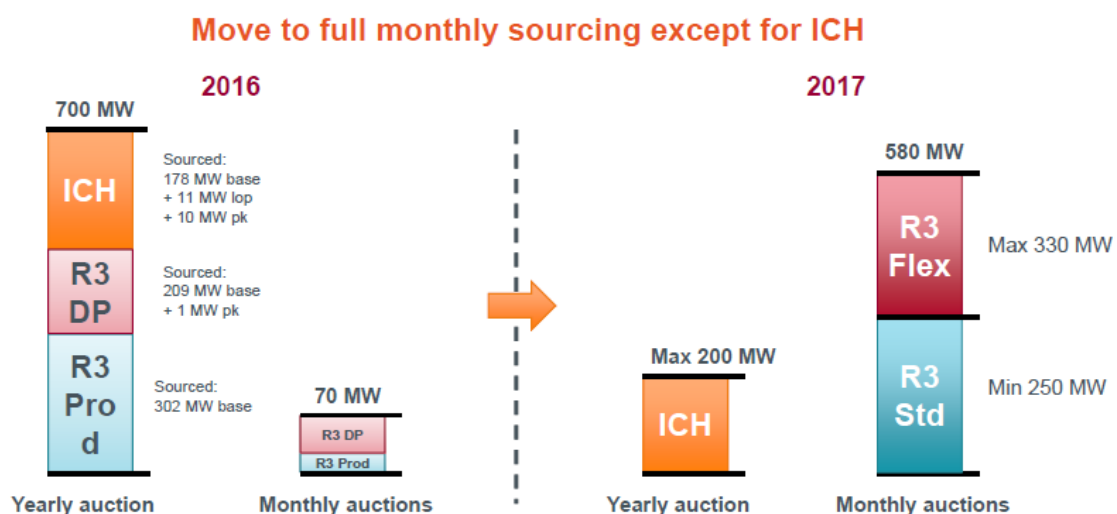


Figure 3: New tertiary reserve products in Belgium (Elia 2016b)

2.3.1.2 The installed capacity

The Belgian power system relies strongly on nuclear power (30%) and conventional thermal generation (30%, mostly gas) (as shown in Figure 4). The winter peak load has reached over the last years a level that is very close to the installed capacity. The availability of the nuclear power plants has led to the creation of new products (e.g. Strategic reserves) (ENTSOE 2017; Valles, Gómez, and Frías 2015). With an installed capacity of 19 324 MW and a peak demand around 14 000 MW, Belgium has faced some risks for the security of supply (ENTSOE 2017).

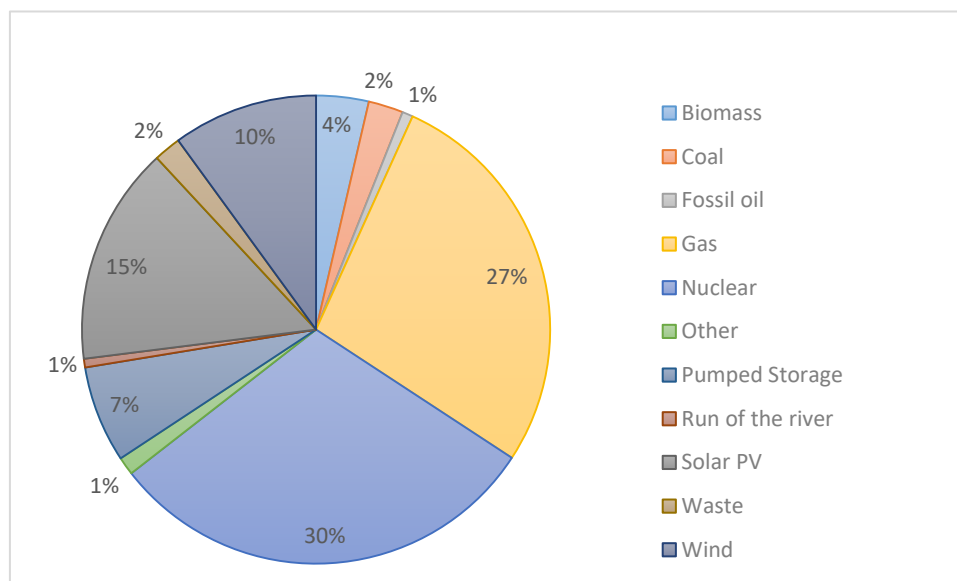


Figure 4: Installed Capacity in Belgium per Production Type (ENTSOE 2016)

2.3.1.3 Industrial Demand Response

All of this has put the market under pressure and regulatory boards have started to create a playfield that enables demand to participate in the market. Despite all of the recent efforts, load participation remains low and the secondary reserve market is still not open for demand response. Therefore, Belgium has to take some steps to facilitate access to the market such that also small customers can participate. The fact that aggregators have to sign an agreement with the supplier/BRP of the customer who wants to participate in DR is probably the most restrictive barrier in the market nowadays. So far, only a few large industrial consumers (such as steel or chemical industries) have been able overcome this barrier (Smart Energy Demand Coalition 2017).

According to the industry, the main barriers are commercial and legal constraints (ownership, exposure to prices...), system constraints (minimum size, duration, frequency,...), grid codes and tariffs (rebound effect) and transparency (real-time metering data is missing) (IFIEC Europe 2016). They also stated that demand side flexibility cannot replace investments and cannot provide any long term solution.

A special regime is applied in the case of the activation of the strategic reserves provided by demand (SDR) or the interruptible contracts (R3 ICH). The curtailed energy is added back to the portfolio of the BRP (Smart Energy Demand Coalition 2017).

Most of the ancillary services that can be provided by demand only receive capacity payments. The only exception here is R3 ICH, which receives also an activation payment that is linked to the bid prices for the R3 Production reserves. R3 ICH reserves are provided by industrial consumers connected to the transmission grid of which the majority is active in the steel industry, electrometallurgy, pulp and paper industry, cement industry and agro-food industry. (Energy Pool, 2014)

In 2014 the R3 Dynamic Profile (DP) was launched to attract new demand participation. Before its launch, a pilot was run in cooperation with the REstore, a Belgian aggregator. The idea of this project is to attract new industrial customers, connected to the distribution grid. However, the participation is not exclusive for industrial customers connected to the distribution network, but to also to the customers connected to the transmission grid. This means that even the ones which are already participating in the R3 ICH program can participate. Elia originally contracted 50 MW R3 DP with three parties: REstore, EDF Belgium and Actility Benelux. While Restore and Actility Benelux are both aggregators, EDF Belgium focusses on using the back-up generators located at the sites of industrial customers (Engineeringnet.be 2014; Van Isterdael 2014).

In 2013 a survey was conducted by Elia, Febeliec and EnergyVille to investigate the possible flexibility of demand. The consumers that responded represent 13.6% of the Belgian electricity consumption in 2012 and they stated that they have a total flexibility of 631 MW. However, already 497MW of this total flexibility has been used, which indicates that the additional potential for these consumers is limited (Elia, Febeliec, and EnergyVille 2013). The International Federation of Industrial Energy Consumers stated that demand response should always be “on a voluntary basis and must always be fairly remunerated”. Furthermore, they disagree with the suggestion that load will have to follow supply (IFIEC Europe 2016).

2.3.2 UK

2.3.2.1 The market

The electricity markets in the UK (shown in Figure 5) are organised very similar to the ones in Belgium. However, in spite of one single market operator, two companies operate the market: APX and N2EX. APX is owned by EPEX SPOT, exchange for the power spot markets in central Europe (EPEX 2017). N2EX, created by NASDAQ OMX Commodities and Nord Pool Spot, is the biggest market operator in the UK. Both market operators run a day-ahead market (“auction market”) and a continuous intraday market (“spot market”). The day-ahead markets open two weeks before the delivery period and close at 11 a.m. GMT on the day before delivery, at the same time as the other European day-ahead markets. In these markets, energy is traded by means of an auction for the 24 hours of the delivery day (N2EX 2016).

The continuous markets work slightly different in the UK from the one in Belgium. The opening of the continuous APX and N2EX markets in the UK depends on the products that are traded. For example, at all times there are 12 rolling 4 hour-block products open for trading. This means that the 4 hour-block intraday market opens two calendar days before it closes (APX 2014; N2EX 2016).

Besides the auction market and the spot market, APX also organises a prompt market and a UK half hour day-ahead market. Trading in the first market takes place up to 7 days ahead (14 days for the weekend base) of the delivery day while the second market has a limited trading period on the day before delivery (from 1 p.m. until 3.30 p.m.) (APX 2017a, 2017b).

Generators and suppliers are obliged to provide an initial physical notification at 11 a.m. on the day before delivery and a final schedule the hour before the actual delivery (National Audit Office 2016).

The market share of both organised markets remains rather low as only 3,8% of the electricity is traded through APX, while N2EX has a market share of 7,5%. This means that most of the trading is still done over-the-counter.

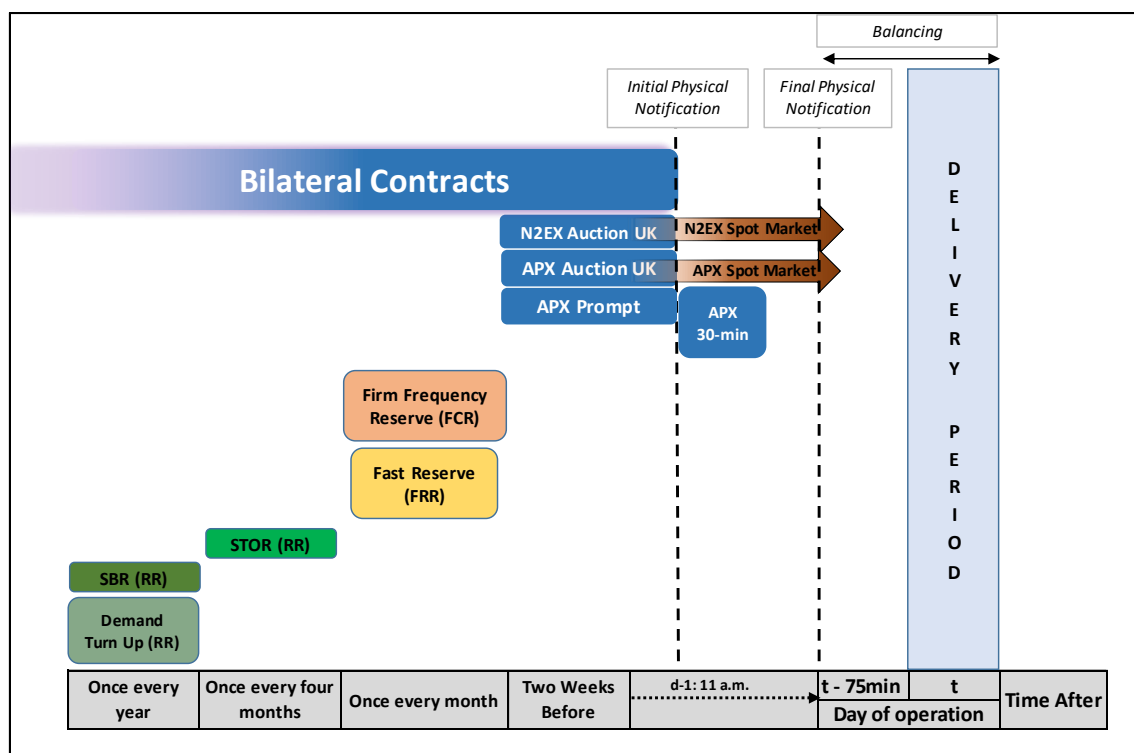


Figure 5: Schematic representation of the electricity markets in the UK

In June 2017, National Grid launched a consultation document with the intention to change the ancillary services in the future. This means that probably the current regulatory framework will change drastically ("Future of Balancing Services | National Grid" 2017).

2.3.2.2 The installed capacity

The share of fossil fuels in the installed capacity (shown in Figure 6) has decreased from 68% in 2012 to 52% in 2016. This is mainly because the share of renewable energy resources has increased to 24% and based on provisional data of 2017, the installed capacity of solar energy is expected to increase even more in the near future. With a peak demand of 55 765 MW between 2011 and 2016 and an installed capacity of around

91 000 MW, the UK has significant amount of spare capacity (ENTSOE 2017; National Grid 2017b)

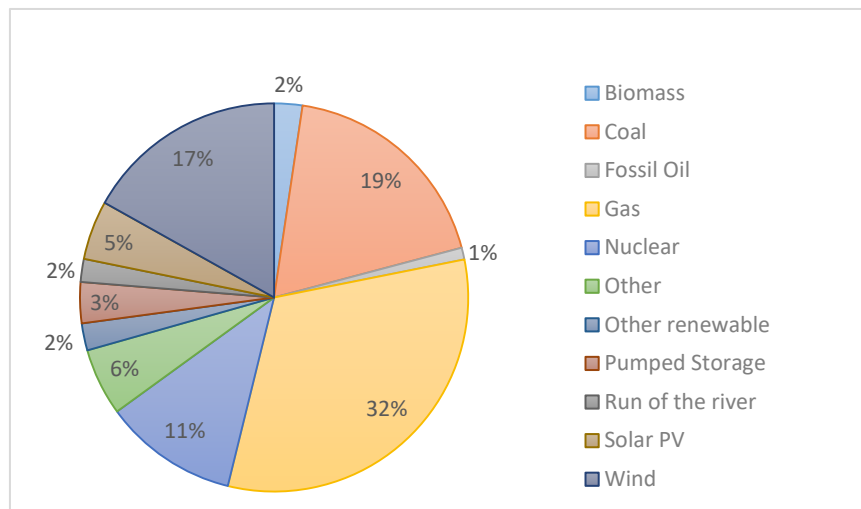


Figure 6: Installed Capacity in the UK per Production Type (ENTSOE 2016)

2.3.2.3 Industrial Demand Response

Primary reserve and secondary reserve (frequency response) and voltage regulation are mandatory services that have to be provided by large and medium sized generators, depending on the criteria mentioned in (National Grid 2016). Besides the mandatory provision, these services can also be provided through commercial balancing services. Typically, these products are acquired through monthly tenders and are remunerated based on availability fees and an energy based fee. The commercial balancing services only include upward reserves (National Grid 2017).

Tertiary reserves (RR) on the other hand are manually activated and in general contracted several months to one year upfront. Although National Grid is offering many different products, the most common used is the Short Term Operating Reserve (STOR). Furthermore, yearly tenders are held to contract Supplemental Balancing Reserves (SBR or DSBR for demand), Demand Turn Up and a number of other reserves (National Grid 2017). All of these services only provide upward reserve, except for the Demand Turn Up product. The technical characteristics of each of these products can be found in Appendix 1.

The STOR program has been relatively successful so far although the main contribution of the demand side comes from on-site back-up generation. In 2011-2012 only 10-15% of the 1.5 GW DSM capacity was offered by demand response. (Ward, Owen, and Pooley 2012) For the Firm Frequency Response a participation of around 8% was registered.

2.3.3 Spain

2.3.3.1 The market

Different from the previously described markets, most of the energy and balancing services are contracted one day before delivery. 80% of the electricity supplied in Spain and Portugal is traded through OMIE which means that the share of bilateral contracts

in the Spanish electricity market is significantly less than in the UK or in Belgium (OMIE 2016).

The Spanish day-ahead market opens at 10 a.m. on the day before delivery (although bids can be sent upfront) and closes two hours later at 12 p.m. as shown in Figure 7. In the day-ahead market, the demand side is not allowed to submit complex bids. After the schedule is published, market agents have the possibility to change their commitment through six centralized auctions. These intraday sessions generally are open for 45 minutes (except the first session which is open for 105 minutes) and close a couple of hours before the delivery hour.

As OMIE does not take into account any technical constraints, the SO might find the need to redispatch certain generators. Therefore, the Spanish TSO, Red Eléctrica, runs a Technical Redispatch market to solve the technical problems. In this market, which is only open for generators, participants are paid pay-as-bid. Moreover, the TSO might find it appropriate to contract additional reserves and run therefore the additional upward reserve market (AUR). This market opens at 4 p.m. of the day before when low reserve margins are detected and closes 20 minutes later.

Subsequently the secondary (4 – 5.30 p.m.) and tertiary reserves (up until 1 hour before real time) are contracted. As all the conventional generators with available tertiary reserve are obliged to provide their reserves in this last market, there is only energy contracted in this market.

If the SO predicts an imbalance bigger than 300 MW for a specific hour and there is no more intraday session open for the relevant hour, an additional market can be called. In this deviation management market energy can be offered for the specific hour which will be paid with the marginal market price.

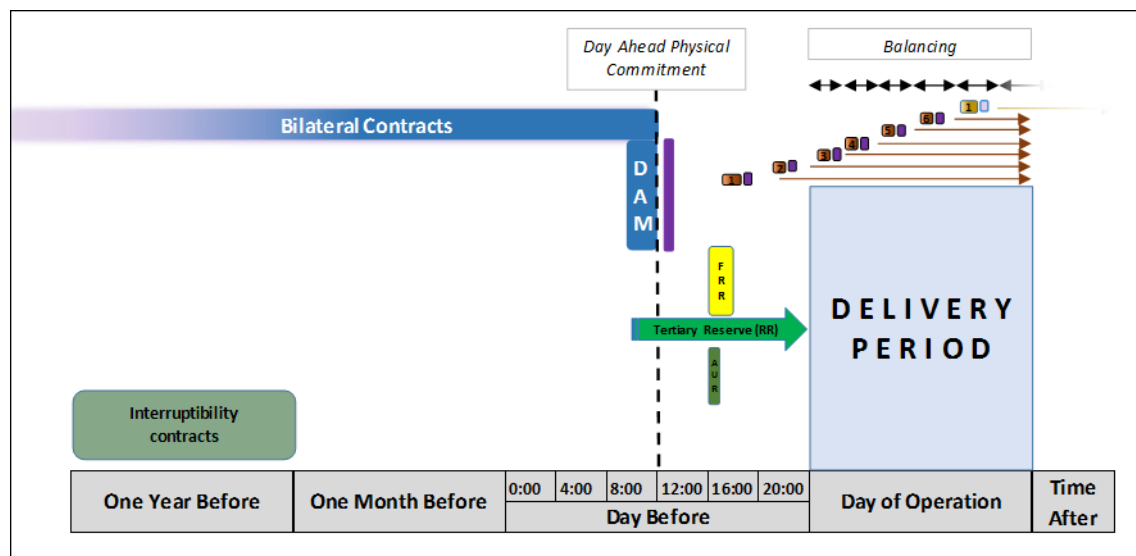


Figure 7: Schematic representation of the electricity markets in the Spain

2.3.3.2 The installed capacity

Today, Spain relies mostly on hydro and gas for its flexibility needs. Spain has an overcapacity due to the installation of a significant amount of renewable energy and CCGTs over the last decade. At the same time, there was a decline in demand after 2007, which has led to a situation in which the peak demand (around 40 000 MW) can be covered with 40% of the installed capacity (around 105 000 MW) (ENTSOE 2016; Valles, Gómez, and Frías 2015). Figure 8 shows the share of the different technologies in the total installed capacity.

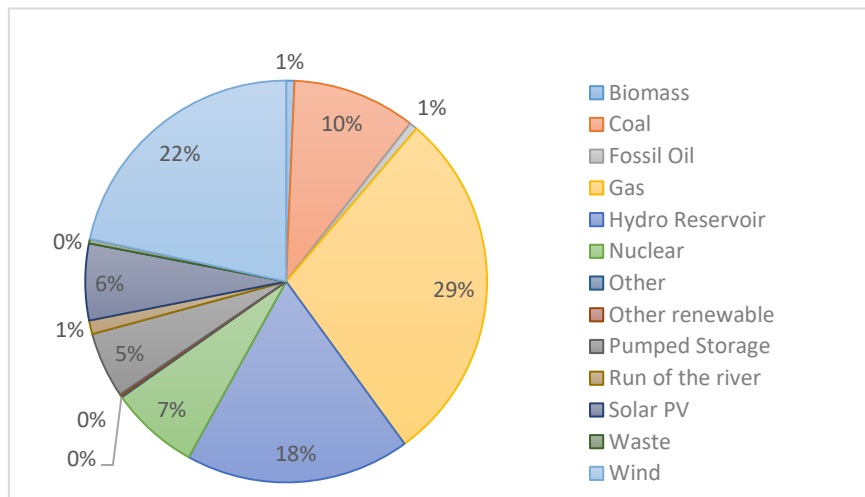


Figure 8: Installed Capacity in the Spain per Production Type (ENTSOE 2016)

2.3.3.3 Industrial Demand Response

As energy is more and more provided by distributed generation, the need for flexibility is increasing in Spain. However, the market currently still has an overcapacity, especially in flexible CCGT plants. This is one of the reasons why the development of DR remains very low. Other reasons are the fact that aggregation is not allowed and that there is only one DR scheme which is only reserved for large consumers. The balancing and the wholesale market are not (yet) opened for demand response (Smart Energy Demand Coalition 2017).

Up until now, there is only one program open for demand response, which is the interruptible load program. To participate in this program, it is necessary to comply with the minimum bid size of 5MW-blocks or 90 MW-blocks. This has led to a situation where only large industrial consumers are able to participate (Smart Energy Demand Coalition 2017). Furthermore, it is necessary to be connected to the high voltage grid.

2.3.4 Conclusions

At the moment that this study was finished (Summer 2017), demand is able to participate in several different markets in Belgium and the UK, the regulatory framework in Spain still does not allow this. In the UK, the demand is able to participate in a wider range of ancillary services, but the technical conditions are less suitable for demand than the ones in place in Belgium. Furthermore, the change from long-term contracts (typically one-year contracts) to short-term contracts (monthly and daily contracts) for

ancillary services in Belgium is a positive tendency following the regulation as it is already in place in the UK.

In the case of Spain, it is advisable that the technical requirements, the service contracting and the allowance for participation are changed if the country wants to attract a significant level of demand-side participation.

2.4 Models to estimate the value of DR

This section gives an overview of different mathematical models found in the literature to estimate the value of demand response from industrial consumers. At the end of the section, a summary of the different models can be found in Table 1.

2.4.1 Demand participation in the day-ahead market.

A rather straight forward approach is to assume that demand can be shifted within a certain time interval without any loss of efficiency. Most of the existing models start from a unit commitment model with a variable component that replaces the demand parameter. An example of this is a modified version of “Reliability and Operation Model for Renewable Energy Sources” that allows to implement demand response. ROM has been developed by the Institute for Research in Technology, ICAI School of Engineering. The model has been modified to see the effect of demand response on the results (Dietrich 2014).

ROM exists of two main parts: an optimization tool for the day ahead and a simulation tool for adapting the day-ahead program in real-time. In the model, demand response is implemented by adding a range (e.g. +/- 5% of the original demand curve) within which the demand can move as long as the total energy consumed within the same day is the same.

Instead of assuming exogenous prices, the ROM model works in two steps in which the marginal price as a result of the first step is used as an input for the second step. Instead of adding endogenous prices through two steps, prices can also be implemented using a Lagrangian dual (Svoboda and Oren 1994). Unfortunately, the introduction of an endogenous price in a model always makes the model non-linear, which typically increases the calculation time drastically.

One way of solving this problem is by using a two-level iterative model in which the optimal solution of centralized mechanism is combined with the decentralized demand participation structure of dynamic pricing schemes (Papadaskalopoulos and Strbac 2013).

When considering industrial demand, the approach followed in (Dietrich 2014) could also lead to infeasible solutions. In reality, it could be the case that the change in demand is subjected to some ramping limits. This should be taken into account by adding intertemporal load constraints (Khodaei, Shahidehpour, and Bahramirad 2011).

Not only ramping limits can cause problems, also line congestions (Asuhaimi Bin Mohd Zin et al. 2016) and voltage limits can lead to infeasible solutions. Including these limits

in the model avoids infeasibilities, but increases the computational time drastically as the model becomes non-linear (Duan 2016).

(Gong et al. 2016) analysed the optimal production schedule for an individual industrial consumer using a MILP formulation. The production quantities and due dates were introduced as constraints. (J. Cheng et al. 2017) reformulated the problem and added a second criterion in the objective function when maximizing the benefits for an individual industrial consumer. Their bi-criteria model tries to find the optimal balance between the operation of the manufacturing plant and the possible electricity savings. Similarly (Fazli Khalaf & Wang, 2018) formulated the problem for a single manufacturing system as a 2-stage stochastic mixed integer linear programming problem. In the first stage the optimal energy usage schedule for the next day is determined, while in the second stage adaptations can be made to this predefined schedule based on real-time variability of renewable energy supply.

2.4.2 Reserve market

When the regulatory framework allows industrial consumers to participate in the ancillary reserve markets, the problem of determining the optimal allocation of the capacity becomes more complex. (Bao et al. 2017) used deterministic MILP to determine the potential what demand response has when participating in frequency control programs. A similar approach has been followed by (M. Cheng et al. 2017) but instead of maximizing the benefits for the consumers, the flexibility is taken as a resource that can be activated for the benefits of the system. (Ramin, Spinelli, & Brusaferrri, 2018) tried to estimate the benefits of participating in both energy and reserves market. The problems were modelled as two mixed integer optimization problems that are solved sequentially.

2.4.3 Balancing market

When the demand is also allowed to act in the balancing market, a number of issues occur that make the analysis more complex. It could be better for consumers not to act in the day-ahead market and to preserve their potential for the balancing market. Balancing markets can typically be modelled in a deterministic or a stochastic way. In the first approach, it is assumed that market participants have perfect information and their actions of them can be optimized for the whole day at once. (Malpica Morales 2016)

However, market participants in reality do not have perfect information about what will happen in the future. This could be integrated in the decision making process by introducing some stochastic component about the probably of power imbalances. Together with introducing a stochastic component, the decision-making horizon is changed to shorter decision-making periods with uncertainty about the future. (Abbaspourtorbati, Cherkaoui, and Zima 2015)

Title	Reference	Deterministic / Stochastic Prices	Industrial / Residential?	Network?	Day-ahead?	Intraday	Ancillary Services?	Firm Capacity
A power data driven energy-cost-aware production scheduling method for sustainable manufacturing at the unit process level	(Gong et al. 2016)	D	I	no	yes	no	no	no
Intertemporal Load Characteristics SCUC With Hourly Demand Response Considering	(Khodaei, Shahidehpour, and Bahramirad 2011)	D	/	yes	yes	no	no	no
A Balancing Market under Uncertainty with a Rolling Horizon for European Market Structure	(Abbaspourtorbati, Cherkaoui, and Zima 2015)	S	/	yes	no	yes	no	no
Decentralized Participation of Flexible Demand in Electricity Markets—Part I: Market Mechanism	(Papadaskalopoulos and Strbac 2013)	costs	/	no	yes	no	no	no
Demand response in electric systems: its contribution to regulation reserves and its role in aggregating distributed energyresources	(Dietrich 2014)	D/S	/	yes/no	yes	no	no	no
Demand side management in a day-ahead wholesale market: A comparison of industrial & social welfare approaches	(Jiang, Farid, and Youcef-Toumi 2015)	D	I	no	yes	no	no	no
A Price-Based Demand Response Scheduling Model in Day-Ahead Electricity Market	(Duan 2016)	D	/	yes	yes	no	no	no
Economic Evaluation of Incentive-Based Demand Response Programs Implementation on Congestion Management under Contingency Conditions	(Asuhami Bin Mohd Zin et al. 2016)	D	/	yes	yes	no	no	no
Day-Ahead Scheduling Considering Demand Response as a Frequency Control Resource	(Bao et al. 2017)	D	/	no	yes	no	yes	no
Performance of industrial melting pots in the provision of dynamic frequency response in the Great Britain power system	(M. Cheng et al. 2017)	D	I	no	no	no	yes	no
Economic assessment of the flexibility of large industrial electric consumers	(Malpica Morales 2016)	D	I	no	yes	no	yes	no

Table 1: Overview of existing models

3 Motivation for the thesis

The state of the art review showed that demand response for industrial consumers has attracted a lot of attention from both the industry and the academic world. This suggests that there has already been done a lot of research on the participation of industrial consumers in demand response programs. However, none of the existing literature is fully addressing the value of industrial demand response while taking into account the complexity of the industrial processes and the regulatory framework in place.

Firstly, the country analysis for Belgium, Spain and the UK has shown that the regulatory framework for demand-side participation in the different countries varies significantly. This is because there is no clear definition of the optimal regulatory framework to attract the maximum amount of demand-side participation. The aim of this work is to fill a first gap here and to provide regulators a guideline on how markets can be designed to enable and attract more demand-side participation. These guidelines will be focused on the participation in (day-ahead) energy markets and markets for ancillary services, as this is the main focus of this work.

These target countries are selected because those three markets are diverse enough to provide a framework for the diversity in markets within Europe. Because of its limited interconnection with France, Spain almost is an (electric) island with a significant amount of renewable energy installed. This is compared with the situation in the UK where the generation mix is completely different from Spain. Later we also show that the regulatory framework in the UK is very different from the one in Spain. As a third country, Belgium is studied to contrast the previously mentioned countries with a

country with a high interconnection capacity but with a lack of generation capacity. Therefore, the need for demand response has become more relevant, which makes it an interesting case study.

Secondly, many different detailed studies exist to estimate the potential of the different energy intensive industries. However, there is a need for a quantification of the aggregated value of the flexibility of all these industries. We will therefore try to develop some reference models for different industries in order to estimate an aggregated flexibility.

Lastly, the third part of the literature review showed that there is no existing model that captures all previously mentioned issues. The current models that estimate the value of demand response either simplify too much the aggregated flexibility of demand or focus too much on the technical details of one particular industry. Therefore, the thesis will also cover the development of mathematical models of the industrial flexibility, which will be aggregated in a later stage to a system-wide model to estimate the value of industrial demand response. This value will depend on all the previously mentioned issues, as there are the market design for energy and ancillary services, the generation mix in the target countries and the complexity of the industrial processes.

4 Research questions and PhD objectives

As described in the introduction, the main question of this work is **what the value is of industrial demand flexibility under different market designs**. We also want to know for which industries demand-side participation is more interesting. Another interesting question is at what the cost of the activation is for the industrial consumer and what the benefits are for the system of this particular flexibility. A last question is which incentives need to be given to individual industrial consumers such that they are willing to activate their flexibility.

These research questions can be translated into a number of objectives.

Main objective:

- To estimate the value of industrial demand response in different European electricity markets.

Sub objectives:

- Model and quantify which industrial processes have the most flexibility.
- Build a number of reference models for industries with different characteristics which represent the essential process which offer flexibility without the need to model all the other processes in a detailed way.
- Calculate the costs of the provision of the available flexibility and identify which incentives should be given to individual consumers.
- Compare alternative market designs and power system structure on the value of industrial demand flexibility.

- Draw market design (with respect to energy and ancillary services) and policy recommendations that facilitate the development of industrial demand response.
- Run a sensitivity analysis with respect to the expected future generation mix in the target countries and demand scenarios.

5 Methodology

The idea of this thesis is to start with an in depth analysis of the regulatory framework regarding demand response in the target countries. This will be done by analyzing the information published by the NRAs or TSOs in those countries. This information will be further elaborated through bilateral meetings with different experts among the target countries.

After this analysis, a model will be developed in GAMS to quantify the benefits of demand-side participation. The first step here will be to develop a number of reference models for the most energy intensive industries that give a good approximation of their flexibility. The aim here is to give an indication at which costs their flexibility can be activated, from which incentives can be defined for this activation.

Then, the reference models will be used to aggregate similar industries to be used in a system-wide model. The model shall be based on a unit commitment model where the demand is replaced by a flexible demand. These new parameters will be based on the results of the flexibility analysis of the different industrial process in the country under investigation. This means that we assume that the demand provides bids to the market to indicate at which price their flexibility can be activated.

The output will contain the new marginal costs for each hour and the new schedule about when the demand will consume. These outputs are then used to produce policy recommendations to identify which of the current regulation is putting up barriers for the participation of the demand side in the electricity markets.

In this first model, all the parameters will be deterministic. Energy bids and balancing services will be seen as separated markets without any strategic behaviour between the two. Later we will try to see what the influence can be of modelling them as competitive markets, to add stochasticity (demand, generation mix,...)

The possibility to have different market designs (different availability for reserves, different technical parameters, ...) in the model will also be included to evaluate the effect of a market design on the value of demand response. In addition, from this analysis, we will be able to draw some policy recommendations.

Originally, interconnections will be assumed as a given input that cannot be changed. However, our aim is to analyse as well what happens when ancillary services are contracted on a European-wide basis and if this affects the value of demand-side flexibility.

6 Work plan

6.1 Tasks

6.1.1 State of the art

The first task was to investigate what already had been written about the topic of this thesis. We divided this task in three parts. This task finished in July 2017.

6.1.1.1 Industrial demand response

The first step was to investigate which type of industries have the greatest potential to participate in demand-side programs.

6.1.1.2 Regulation of demand-side participation in target countries

The second step was to evaluate the value of demand-side participation in the regulatory framework that is in place in different European countries.

6.1.1.3 Models to estimate the value of demand-side participation

The last step is to investigate which models already exist to estimate the value of demand-side participation. In this step, we defined the shortcomings of the existing models and we identified where the major contribution of this thesis will be.

6.1.2 Development of reference models for different industrial processes

Determining which industries can participate into demand response programs, requires first to isolate the energy intensive processes and to quantifying how much flexibility these processes have. Our approach here will be an “is-similar-to” approach, which means that we will try to categorize different industrial processes. An example of this approach is the simplified methodology developed by VITO in which they try to map an industrial process into a battery model (VITO 2016).

6.1.3 Integrate these reference models in an optimization model

After developing reference models for the most energy intensive processes, we will develop an optimization model to estimate the value of these flexible industrial processes under a given regulatory framework. The aim is also to implement those reference models into the already existing ROM model, that has been previously develop by the IIT (see section 2.4.1).

6.1.4 Evaluate market designs to integrate demand response

The main contribution of this work comes from the analysis of different market designs in European countries and the effect on demand-side participation. Therefore, we will analyse the current regulatory frameworks in Belgium, the UK and Spain, implement an approximate market designs into the general optimization model and evaluate the effect on demand-side potential.

6.1.5 International exchanges

There is a plan to have a short-time stay at VITO in Belgium, with the team lead by Daan Six, and Imperial College in the UK, with the team of Goran Strbac. We have been collaborating in research projects with both research groups, in the IndustRE project and other activities. The stay in VITO will focus on the individual modelling of industries for electricity demand flexibility. A common research paper will be an output of this stay. On the other hand, during the stay at Imperial, the goal is to learn from their European electricity model to analyse the impact of a high-penetration of demand-side flexibility, and try to include the aggregated detailed models of different industries.

6.1.6 Writing of JCR articles

We have planned to submit several articles to JCR journals.

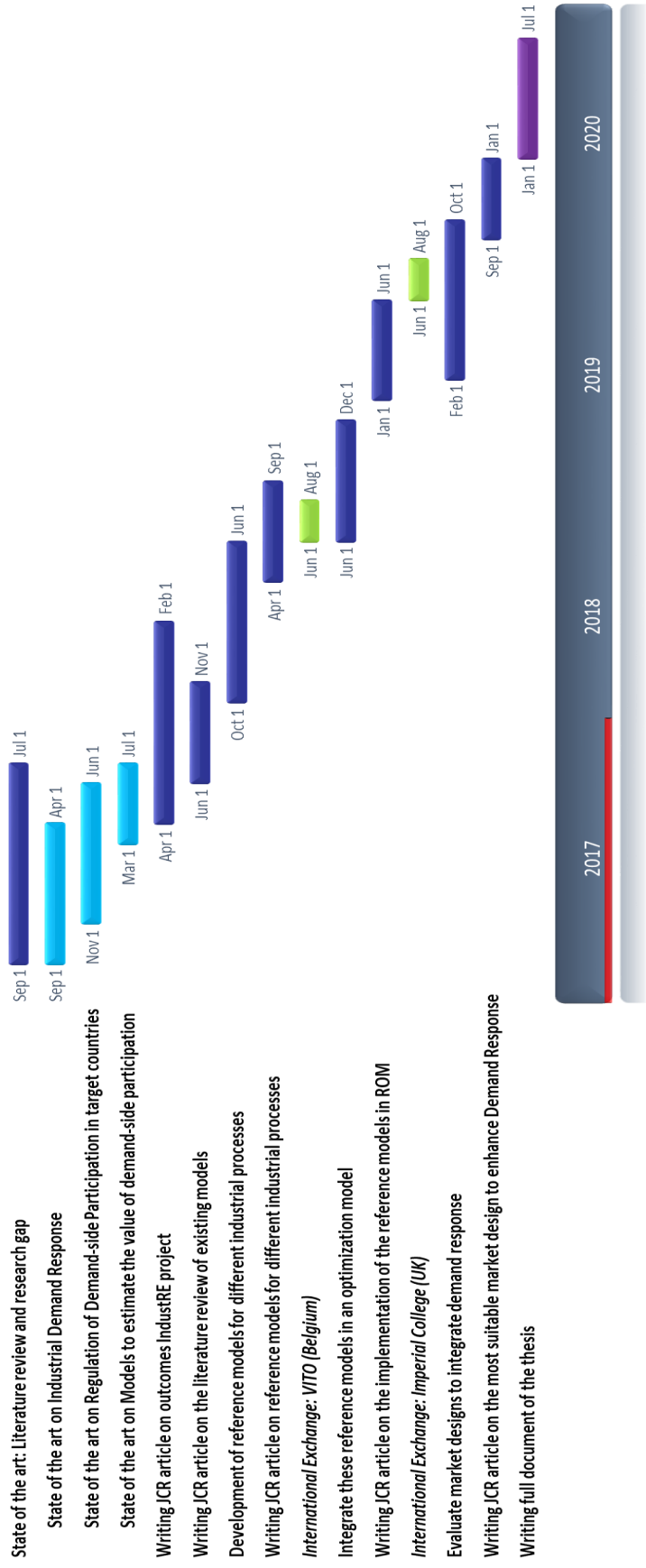
	Topic	Planned date of submission	Progress up to now	Related task
1	State of the art review on existing models for industrial demand response valuation	November 2017	60%	6.1.1
2	IndustRE business models and policy recommendations	January 2018	75%	[project results]
3	Reference model(s) for industrial processes	September 2018	-	6.1.2
4	Implementation of the reference models in ROM	June 2019	-	6.1.3
5	Most suitable market design to enhance Demand Response	January 2020	-	6.1.4

6.1.7 Writing final thesis document

At the end of this study, the results will be written down in a thesis document that comprises the results of the articles submitted to JCR journals.

6.2 Time line [Gantt Chart]

In the following diagram the schedule of the activities during the PhD are shown. In dark blue the main tasks are highlighted, and in green the different stays.



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Appendix 1: Technical Information Ancillary Services

Belgium – UK – Spain (Jan 2017)

Services	Features	Energy (DAM)		Energy (ID)	Primary Reserve (Freq. Response)		Secondary Reserve (Freq. Response)		Tertiary Reserves				Black Start	Minimum Reactive Power	
		YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES			YES
Exist?	Belgium	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	Spain	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	UK	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Where to buy	Belgium	EX/Bi	Continuous ID	Continuous ID	Obl./Tender	Tender	Tender	Tender	Tender	Tender	Tender	Tender	Tender	Tender	YES
	Spain	EX/Bi	Block ID	Block ID	EX	EX	EX	EX	EX	EX	EX	EX	EX	EX	N/A
	UK	EX/Bi	Continuous ID	Continuous ID	Obl./Tender	Tender	Tender	Tender	Tender	Tender	Tender	Tender	Tender	Tender	Bi
Gate Closure	Belgium	12:00	5 min	5 min	Monthly/Yearly	Monthly	Monthly	Monthly	Yearly	Yearly	Yearly	Yearly	Yearly	Yearly	N/A
	Spain	12:00	5,25h-2,25h	5,25h-2,25h	N/A	Daily	Daily	Daily	Yearly	Yearly	Yearly	Yearly	Yearly	Yearly	N/A
	UK	11:00	1 h	1 h	Monthly	Monthly	Monthly	Monthly	Yearly	Yearly	Yearly	Yearly	Yearly	Yearly	N/A
Minimum Bid Size	Belgium	0.1MW/h	0.1MW/h	0.1MW/h	1 MW	1 MW	1 MW	1 MW	5 MW	5 MW	0.1MW/h	0.1MW/h	0.1MW/h	0.1MW/h	100/200MW
	Spain	N/A	N/A	N/A	10 MW	10 MW	10 MW	10 MW	10 MW	10 MW	5MW/90MW	5MW/90MW	5MW/90MW	5MW/90MW	N/A
	UK	N/A	N/A	N/A	10/3 MW	1 MW	50MW	50MW	3 MW	3 MW	N/A	N/A	N/A	N/A	N/A
Minimum Bid Unit	Belgium	N/A	N/A	N/A	1 MW	1MW/0.1MW	1MW/0.1MW	1MW/0.1MW	1MW/0.1MW	1MW/0.1MW	N/A	N/A	N/A	N/A	N/A
	Spain	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	UK	N/A	N/A	N/A	N/A	10 MW	10 MW	10 MW	Bi	Bi	N/A	N/A	N/A	N/A	N/A
Maximum Bid Size	Belgium	N/A	N/A	N/A	50 MW ¹	50 MW	50 MW	50 MW	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Spain	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	No limit	No limit	No limit	No limit	N/A
	UK	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Minimum Price	Belgium	-500	-9999.99	-9999.99	Pay as bid (MW)	0 (Pay as bid, MW)	0 (Pay as bid, MW)	0 (Pay as bid, MW)	Pay as bid	75/MW/h	3000/MW/h	3000/MW/h	3000/MW/h	3000/MW/h	N/A
	Spain	N/A	N/A	N/A	0 (MW)	MW	MW	MW	MP?	MP?	No limit	No limit	No limit	No limit	N/A
	UK	-500	-9999.99	-9999.99	Pay as bid (MW+MW/h)	/h+/MW/h	/h+/MW/h	/h+/MW/h	MW+MW/h	N/A	N/A	N/A	N/A	N/A	N/A
Maximum Price	Belgium	3000	9999.99	9999.99	Pay as bid	40+C _{ten}	40+C _{ten}	40+C _{ten}	N/A	1,08*DAP	3000/MW/h	3000/MW/h	3000/MW/h	3000/MW/h	N/A
	Spain	180.3	180.3	180.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	UK	3000	9999.99	9999.99	Pay as bid	Pay as bid	Pay as bid	Pay as bid	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Minimum Time	Belgium	1 h	N/A	N/A	15 min	15 min	15 min	15 min	15 min	15 min	N/A	N/A	N/A	N/A	N/A
	Spain	1 h	N/A	N/A	30 sec	100 sec	100 sec	100 sec	No limit	No limit	N/A	N/A	N/A	N/A	N/A
	UK	1 h	N/A	N/A	10+20 sec	2 min/15min	2 min/15min	2 min/15min	2 hours	2 hours	N/A	N/A	N/A	N/A	N/A
Maximum Time	Belgium	24 h	N/A	N/A	N/A	N/A	N/A	N/A	No limit	2/4/8h	4/12h	4/12h	4/12h	4/12h	N/A
	Spain	24 h	N/A	N/A	14 min	15 min	15 min	15 min	3-4 hours	N/A	N/A	N/A	N/A	N/A	N/A
	UK	24 h	N/A	N/A	30 sec	5 min	5 min	5 min	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Maximum Response Time	Belgium	N/A	N/A	N/A	30 sec	7.5 min	7.5 min	7.5 min	15 min	3 min	1.5 h	1.5 h	1.5 h	1.5 h	3/5 hours
	Spain	N/A	N/A	N/A	30 sec	30 sec	30 sec	30 sec	15 min	N/A	0/15min/120min	0/15min/120min	0/15min/120min	0/15min/120min	N/A
	UK	N/A	N/A	N/A	10 sec	2 min	2 min	2 min	240 min	2 sec	N/A	N/A	N/A	N/A	N/A
Automatic	Belgium	YES	YES	YES	YES	YES/NO	YES/NO	YES/NO	NO	NO	NO	NO	NO	NO	N/A
	Spain	YES	YES	YES	YES	YES	YES	YES	NO	NO	YES	YES	YES	YES	N/A
	UK	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO	N/A
Mandatory	Belgium	NO	N/A	N/A	YES/NO	NO	NO	NO	>75 MW	NO	NO	NO	NO	NO	N/A
	Spain	Quasi	N/A	N/A	YES	NO	NO	NO	YES	NO	NO	NO	NO	NO	N/A
	UK	NO	N/A	N/A	>100MW ³	NO	NO	NO	NO	NO	NO	NO	NO	NO	N/A
Symmetric	Belgium	YES	YES	YES	YES/NO	YES	YES	YES	NO	NO	NO	NO	NO	NO	N/A
	Spain	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO	N/A
	UK	YES	YES	YES	YES	NO	NO	NO	YES	YES	YES	YES	YES	YES	N/A
Open for demand	Belgium	YES	YES	YES	YES	NO	NO	NO	NO	YES	YES	YES	YES	YES	N/A
	Spain	YES	YES	YES	YES	NO	NO	NO	NO	YES	YES	YES	YES	YES	N/A
	UK	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	N/A
Single or Double	Belgium	Double	Double	Double	Single	Single	Single	Single	Single	Single	Single	Single	Single	Single	N/A
	Spain	Double	Double	Double	Double	Double	Double	Double	Double	Double	Double	Double	Double	Double	N/A
	UK	Double	Double	Double	Double	Double	Double	Double	Double	Double	Double	Double	Double	Double	N/A

Tabla 2: Technical requirements ancillary services Belgium - UK - Spain



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