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Assessing Storage and Substitution as Power Flexibility enablers in Industrial Processes

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***Abstract*—Renewable energy sources are currently presented as an economically viable and environmentally safe option in the near future. A major constraint to the incorporation of wind and solar generation at large scale is the increase of variability in the power system. To assure the perpetual balance between power production and gross consumption a significant improvement on power systems flexibility is required. Such flexibility in the power system can be achieved by two options on the demand side through demand response obtained through industrial processes: Storage and Substitution. The power system model in study contemplates the purchase of electricity from the Dutch Balancing Market. The electricity prices of the Balancing Market are considered unpredictable. The storage system is characterized by the size of the storage tank and by ramp up/down rates, reflecting the changing speed of the production levels. The substitution system is characterized by the ramp rate of substitution between electricity and an alternative energy carrier as input. The impact of the parameters on the Power System Flexibility when connected to the balancing market under several scenarios was analyzed by Linny-R, a software tool that applies Linear Programming optimization. For the storage system a bigger tank size, a higher ramp rate and a high level of predictability will increase the flexibility of the system. As the actual predictability of the balancing market is limited, the flexibility is limited too, which makes the storage system a questionable option. For the substitution system flexibility is increased by a higher ramp. The effect of the predictability is less dominant, which makes substitution a suitable flexibility enabler for the current Dutch market system. In this context, a restructure of the energy markets, considering the prices predictability, is suggested, as a way of easing the penetration of renewable energy sources.**

Keywords— Variability, Power Flexibility, Demand Response, Industrial Processes, Balancing Market

I. INTRODUCTION

Due to the industrial development and the growth of the world population, which occurred during the past centuries, the availability of sufficient energy sources is of paramount importance for our society. Relatively easily obtainable fossil energy carriers, such as hard coal, crude oil and natural gas, have powered local and national economies for decades and are still one of the most important energy sources to supply both the primary energy and the electricity demand [1]. However, they give rise to smog, acid rain and greenhouse gas emissions and the risk of a human-induced irreversible climate change. Since the nineties, the abatement of these negative side effects on the environment is on the international political agenda.

The European Union set in 2000 the 20/20/20 targets. These 2020 initiatives require the reduction of 20% of emissions in greenhouse gases, the rise of 20% of energy efficiency and the achieving of 20% of renewable generation in total energy consumption in the European Union. The international community has agreed that global warming should be kept below 2º C compared to the temperature in pre-industrial times [2]. To stay within this limit, scientific evidence shows that the world must stop the growth in global greenhouse gas emissions by 2020 at the latest, reducing them by at least half of 1990 levels by the middle of this century and continue reducing them after it [3].

Renewable energy resources are a serious option for the near future, since their sources are continuously replenished and abundant. Wind and solar energy have an enormous energetic potential. With appropriate technology, enabling an increasingly higher penetration of these resources, their potential energy production is considered to be almost enough to cover the entire electricity consumption [4]-[7]. Therefore, in the near future, wind and solar energy will play a more prominent role in the production of electricity.

As it can be seen in Figure 1, the World wind and solar installed capacity increased in the last years and is expected to keep increasing. This shows that the need of investing in wind and solar energy has already been widely accepted. Currently, governments of several countries around the World have ambitious targets in their policy agenda to increase the share of renewable energy in their generation system.

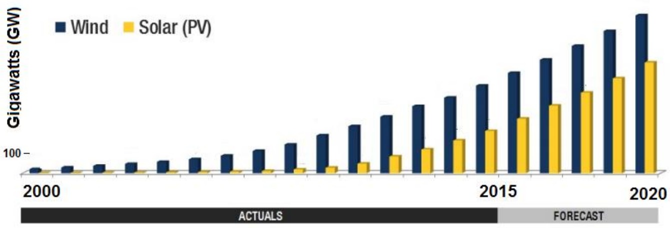

Figure 1: World Wind and Solar Total installed capacity with future predictions [8]

The role of wind and solar electricity is becoming more and more important. However, its stochastic nature will result in a major additional increase in the variability of power supply to the electricity grid. Variability is caused by unexpected rapid changes in supply and demand levels, such as transmission and distribution line outages and sudden load changes [9]. This variability hugely affects the economics and operations value of the renewable energy and the reliable operation of the electricity system

In closed electricity systems Kirchhoff's law requires that the grid must have an adequate balance between supply and demand. Uncontrollable variability must be compensated by controllable options in demand and supply, the so-called flexibility.

Electricity trading systems are in place to offer flexibility on the supply side for different characteristic periods of time. In the electricity markets the payment to or from the market operator is proportional to the amount of electricity actually delivered to or withdrawn from the grid. In The Netherlands, the electricity markets are: the forward, the day-ahead, the intra-day, and balancing ones. The electricity markets can be distributed in different timescales, depending on the frequency or time variability of demand and supply. In Table 1, an association between the electricity market and its timescale is made [10].

TABLE I. FLEXIBILITY OF DUTCH ELECTRICITY MARKETS [10]

Type of Market	***Flexibility time scale***
Balancing Market	Short-Term – 15mins
Intra-day /Day-ahead	Mid-Term – Day
Future Contract	Long-Term - Season

The type of demand flexibility should be associated with the timescale of the considered market. The balancing market, which in the Netherlands has a time frame of 15 minutes, exists to take care of unforeseen events or last minute variations in the equilibrium of supply-demand. Due to its unpredictability, a high level of the power system's flexibility is needed. The possibility of fast response from the demand side system may be suitable to offer short-term flexibility. Considering the short-term flexibility, able to respond to a short-term market, the balancing market will be the focus of this research.

Flexibility can also be offered on the demand side. Demand response is the ability to intentionally modify the electricity consumption, in response to electricity prices, through a wide range of actions and technologies. Regulatory authorities are increasingly considering demand response, for enhancing system management [11]. Due to the introduction of smart grid concept, to the increasing use of distributed generation and to the contribution of consumers into the electricity market, demand response is effectively considered as a new kind of resource [12].

The smart grid concept merely focuses on households and electric vehicles. However, many industries can offer flexibility by temporarily changing the production level or by switching to alternative energy sources. They use significant amounts of electricity in their primary production processes.

The objective of this research is to formulate a general approach for assessing flexibility options in industrial processes.

II. DEMAND RESPONSE BY INDUSTRIAL PROCESSES

From the different sectors: commercial, industry and residential, even though industry is the second sector with more electricity consumption, comparing with the other sectors, the industrial response is the most advantageous due to several characteristics: the magnitude of power consumption by an industrial manufacturing plant and the change in power it can provide are generally very large; usually the industrial plants already have the infrastructures for control, communication and market participation, which enables the provision of demand response [13].

Demand response in the industry would have a significant impact in the power system with possibilities of alleviating the power congestion. One of the possibilities of having demand response in the industry is through industrial processes that can give certain flexibility to the Power System.

From the different types of industry, the products price can be highly dependent of the electricity price, or electricity may not have a significant impact. The focus of the research is on the energy-intensive industries (the price of the product is highly dependent of the electricity price). Flexible Industrial Processes will allow adjusting power consumption, so the industry can actually reduce/increase its electricity demand and thus contribute to the matching of supply and demand. This will reduce the need of other expensive alternative forms of flexibility like storing energy or backup plants from the supply side.

Demand response in the process industry will allow the use of cheap renewable electricity and to contribute to the grid stability in light of the Energy Agreement. With demand response, the process industry can have flexibility and control its production.

Since the future electricity prices in balancing market are almost unpredictable, the decisions relative to industrial processes are limited, as well as the demand response opportunities. If it would possible to predict the prices of a certain number of steps ahead – Look Ahead Steps, would it have consequences in the capacity of responding to price variations? These consequences are studied in this research.

The aim of this section is to analyze and characterize the Industrial Processes (Storage and Substitution) and its surrounding, showing its variables and constrains. The research was based on these considerations.

A) Industrial Processes in the Power System

A Power System is a complex network formed by the production and transmission components and the end-users, which are the consumers of the produced electricity. Power systems are designed to ensure a temporal and spatial balancing of generation and consumption at all times. The flexibility of a power system represents the way that the system adapts to the variability of electricity generation and consumption as needed to maintain system stability in a cost-effective manner, and to maintain continuous service in the face of rapid and large swings in supply or demand.

The target industrial processes are the *Storage System*, which involves the production of raw materials by electrolysis and its consequent storage, and *Substitution System*: the possibility of changing between the energy supplies of production according to price variations.

B) Characterizing a Storage System Option

A storage system, which is composed by a chemical reactor and a storage tank, has the function of storing the materials produced by the industry. The flow of production changes according with the electricity prices variations.

The materials, after their production in the reactor, follow directly to the client or to the storage tank. Whereas that they go to the storage tank, the flow of product is restricted by the maximum input flow allowed by the tank inlet. The tank has also restrictions of the storage quantity, in order to operate in the appropriated conditions, having a required minimum and maximum level. The useful storage size is its reference size. The output flow of product is also limited. The features of a storage system are represented in the scheme of Figure 2.

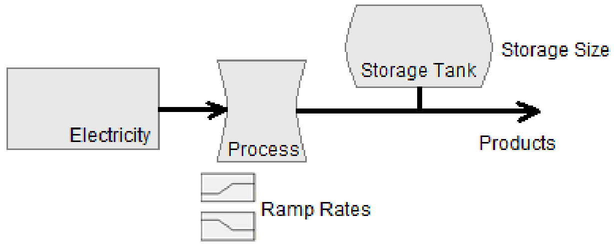

Figure 2: Characteristics of the Storage System

In the case that the production is changed, this fluctuation does not occur instantaneously, being described by the ramp rate function of the reactor which defines how fast is the system's response.

Regarding the power flexibility study, having a storage tank integrated in a power system enables to control the production quantity (consequently the demand of electricity) concerning the variations of electricity prices. In this research, the useful size of the storage tank (Quantity), and the ramp rates (Power/Time) were the chosen characteristics to define the storage system's flexibility. The flexibility assessment considers also the characteristics of the surrounding power system.

C) Characterizing the Substitution System

The objective of having a substitution system is to swap between energy supplies in response to their price changes. Currently, this system is often used for the production of steam, changing the power consumption between electricity and gas.

The substitution system is characterized by a complex linkage of parameters. Starting from the technical characteristics of the reactors, they are characterized by the efficiency of the power supply transmission, the maximum ramping-up rate and the maximum ramping-down rate. Since the objective is to vary between the power supplies, and this does not occur immediately, the substitution system is characterized by the ramp rate of the change from alternative power supply to electricity and the ramp between of the change from electricity to the alternative power supply.

Due to the high complexity of the system, the chosen characteristics to define the flexibility of the substitution system are: the ramp rate of the changes between electricity and gas (Power/time) and the ramp rate of substitution between gas and electricity (Power/time). In figure 4, a resume of the power flexibility parameters of the substitution system is presented. The assessment of these characteristics has to consider all the surrounding system and its constraints.

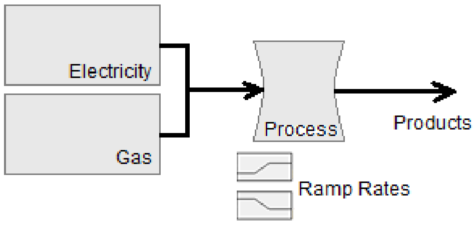

Figure 3: Characteristics of the Substitution System

III. METHODOLOGY

The research employs both qualitative and quantitative research methods in order to characterize and quantify industrial processes through their flexibility. The impact of the industrial processes parameters in the power system's flexibility will be analyzed and quantified.

The Power System model considered in the research has three elements: Energy Markets, Industry and the Client. The Energy Markets are an externality: the input information consists on electricity and gas prices curves, collected from data, regarding the balancing and gas market respectively. The electricity volumes, from the same time period of the electricity prices, are also input information from the Energy Markets. Gas volumes are not considered as a restriction (so it is possible to acquire always the desired quantity only with the system response restriction).

The industry, which is responsible for the fuel acquisition, production of materials and their sale, represents the connection between the energy market and the client. The client establishes the amount of desired material (Quantity/Time).

The industrial processes, storage and substitution, are going to be analyzed through several experiments in Linny-R. Linny-R, developed by Pieter Bots, is a software tool which uses Linear Programming to calculate how processes should be scheduled to produce the desired quantities of end products while maximizing profit (or minimizing cost). This program uses the lp_solve library version 5.5.2.0 developed by Michel Berkelaar, Kjell Eikland, and Peter Notebaert, and the API for Delphi developed by Henri Gourvest.

To model the power system in Linny-R, it is necessary to introduce a production system as (clusters of) processes that have products as inputs and outputs. The model of the power system includes the energy markets with the respective prices and volumes, the reactor with the demand response restrictions and the objectives of the client. Linny-R also gives the possibility of including the parameter Look Ahead and with this predicts the energy prices a certain number of times. With the introduction of this parameter the solver will use more information from the energy markets and give an optimal solution.

The experiments will have the following considerations of the Energy Markets:

- Data Electricity Price Curves of the Dutch Balancing Market from 1/06/2015 to 31/05/2016 [14];
- The price used for gas refers to the medium price of gas for 2016, referent to companies that consume more than 1000TJ per year, and the price only considers energy taxes (not considering VAT) [15].

For the experiments, 1 year of data was considered to be a range of time acceptable, since it is a timeline that includes all the seasons and possible variations due to meteorological conditions. 1 year of data includes 35136 time steps (96 time steps for each day, and each step is of 15 minutes.

The experiments will have the following considerations of the Industry:

- The storage system has a reactor producing Chlorine. 4,38MWh are necessary to produce 1ton of Chlorine;
- The substitution system, instead of Chlorine, considers the production of steam: 1KW of electricity will produce 0,95kg of steam, and 1kW of gas will produce 0,85kg of steam;
- The ramp up rate and ramp down rates of the reactor are assumed to have the same value. Due to the complexity of the functions is going to be considered only the slope of the function (%) which is related with the percentage of the upper bound of the reactor that is possible to fill in one step (15 minutes).
- The costs associated with the maintenance and acquisition of the products and processes are not taken into account: costs associated with storing the product, investment costs, etc.

The experiments will have the following considerations of the Client:

- The client orders a constant quantity of product equal to 1 ton (for all experiments).

Buying electricity from balancing markets, currently, does not allow predicting how the price will change in the future. A new concept is introduced in this research: Look ahead Step. Look ahead step means the number of time steps that is possible to know all the information of the energy market. The parameter Look Ahead step is considered essential in the study of flexibility in power systems, due to its possible implications on the power system flexibility. Even if nowadays it is almost impossible to predict the electricity prices, in the case that this becomes possible, its consequences on flexibility will be already studied and can be an influence for futures policies.

To assess the flexibility in the different power system arrangements, the comparison parameter will be the parameter *Flex*. This parameter is dimensionless and represents the relation between the total value paid for energy by the industry (producer of materials) in a certain period of time, in this case 1 year data, related with the value paid for energy in the same period of time but without any flexibility enabler. Since a better response to variability will have economic consequences, this was the selected criterion to assess the flexibility value.

The experiments include the following studies:

A) The influence of the tank size of the Storage System;
B) The impact of the number of Look ahead Steps in the Storage and Substitution Systems;
C) The influence of the ramp rate variations in the Storage and Substitution Systems.

IV. RESULTS AND DISCUSSION

Individual analyzes were carried out in order to study the impact of each individual parameter in the parameter Flex. The predictability of the balancing market (Look Ahead was considered).

A) The influence of the tank size

Starting with the storage system, the influence of the tank size with the parameter look ahead was studied. The tank size means the relative quantity of the tank with the quantity ordered by the client (in the experiments this quantity is equal to 1000kg). The ramp rate was fixed with a Delta equal to 100%, so this parameter would not influence the flexibility. From the experiments, it was possible to obtain the graphic of Figure 4.

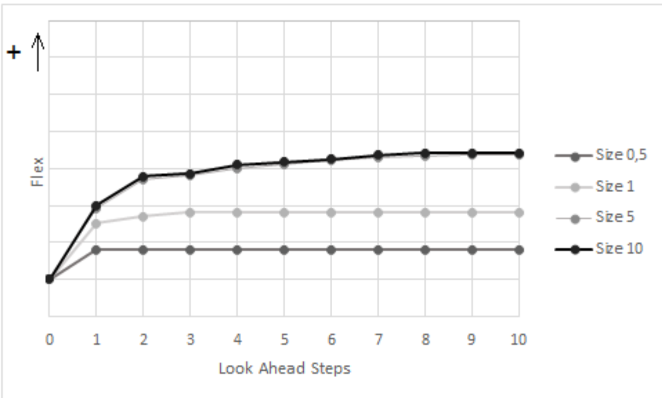

Figure 4: Influence of the Parameter Tank Size and Look Ahead Steps on the Parameter Flex for the Storage System

From the the graphic and obtained results, it is possible to observe:

- For a Look Ahead Step equal to 0 the results of the Parameter Flex are equal to the results of a model without Storage nor Substitution Systems (Inflexible System).
- The parameter Flex increases with the increase of the size of the tank. The difference of the Parameter Flex from a tank size bigger than 5 is not significant. From this, in the next studies the parameter tank size equal to 5 will be consider to high enough so its impact on the Parameter Flex will not be significant.
- The Look Ahead Step has a great influence in the parameter Flex. With the increase of predictability of the balancing market the Power System Flexibility will increase.

B) The impact of the number of Look ahead Steps;

Considering now the study of the Look Ahead Step in the Flexibility of the Substitution and Storage Systems. For the Storage System the Tank Size is equal to 5. Both systems have an instantaneous response: Ramp Rate with a Delta equal to 100%.

The results can be analysed on figure5.

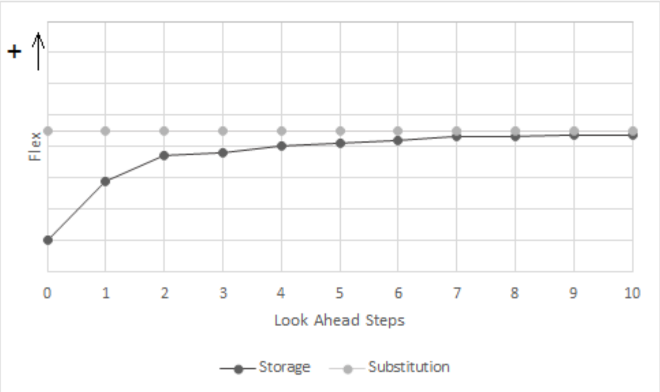

Figure 5: Influence of the Parameter Look Ahead Step on the Parameter Flex for Storage and Substitution Systems

From Figure 5 it is possible to perceive:

- For the storage system, the parameter Look Ahead Step has a great influence on the results. The parameter Flex increases with the increase of the predictability of the balancing market.
- For the substitution system, contrary to the storage system, and for an instant response of the System, the Parameter Look ahead Step does not have influence in the Parameter Flex.

From other experiments of the substitution system, in the case that the response of the system is not instantaneous, the parameter Look Ahead will influence the parameter Flex, even though this influence is not significant.

C) The influence of the ramp rate variations.

Considering now a Look Ahead equal to 1, the following study of Figure 6 intends to describe the influence of the Ramp Rate Parameter in both Storage and Substitution Systems. The tank size in the storage system is equal to 5. Since the Delta is the (%) of the upper bound of the reactor, it was considered to have a reactor five times bigger than the quantity ordered by the client for both scenarios.

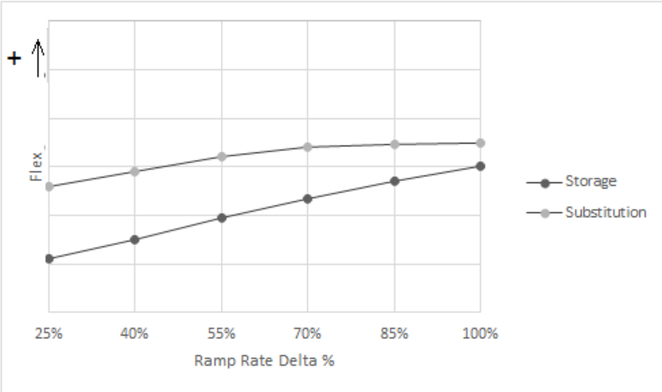

Figure 6: Influence of the Ramp Rate Parameter on the Parameter Flex for Storage and Substitution Systems

- The parameter flex increases for faster response of the system.
- For a system, whose ramp rate is low, in a way that compromises the good operation of the power system, its integration should be questionable and studied. The graphic only considers the ramp rate equal or higher than 25% since for lower ramp rates the percentage of failures to the client is higher than 20%.

V. CONCLUSIONS

Considering the actual functioning of energy markets, Look Ahead Step equal to 0, the unpredictability of the balancing market may question the use of the storage system since the results were similar to an inflexible system. The substitution system has the possibility of offering flexibility through demand response in the actual context of electricity markets, although its opportunities will increase with the predictability of electricity prices.

If real-time prices are made available, the volatility in the different market prices will have an influence on the flexibility of the power system, and consequently in the profits that can be gained, which would change the participation rate of producers.

The actual balancing market is too complex and not transparent, which for the value that it represents becomes unattractive for future solutions. From this, in order to increase the integration of renewable energy sources, flexibility in the power system is needed, and its increase needs incentives, as for example a restructuring of the markets design in the context of prices predictability. A solution can be to incentivize the market parties to submit accurate energy schedules and support the system balance in real-time. Another solution can be based on the introduction of long term commitment to one or more parties, according to their possibilities of offering power flexibility.

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