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ORIGINAL ARTICLE

Technical demand response potentials of the integrated steelmaking site of Tata Steel in IJmuiden

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Abstract Power generation from intermittent renewable energy sources in northwest Europe is expected to increase significantly in the next 20 years. This reduces the predictability of electricity generation and increases the need for flexibility in electricity demand. Data on demand response (DR) capacities of electricity-intensive consumers is limited for most countries. In this paper, we evaluate the DR potential that can be provided to the Dutch national grid by the integrated steelmaking site of Tata Steel in IJmuiden (TSIJ). TSIJ generates electricity from its works arising gases (WAGs). The DR potentials are evaluated by using a linear optimisation model that calculates the optimal allocation of WAGs of TSIJ in case of a call for DR by the transmission system operator. The optimisation is done subject to the technical constraints of the WAG distribution network, WAG storage capacities, the on-site demand for WAGs and the ramp-up rate of the power plant that runs on WAGs. Results show that TSIJ can supply 10 MW for two programme time units (equal to 15-min period in the Netherlands) of positive DR capacity (demand reduction) with an availability rate of 97%. This is not sufficient for participating in the current emergency capacity programs in the Netherlands, which require at least 20 MW for longer than one programme time unit. Tata Steel can provide 20 MW DR capacity with an availability rate of 65%. The negative DR capacity (demand increase) of Tata Steel in IJmuiden is found to be 20 MW supplied for three programme time units and four programme time units with doubling of blast furnace gas storage capacities.

Keywords Demand response · Electricity emergency balancing capacity · Integrated steelmaking · Linear optimisation

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Introduction

As part of the Climate Package, adopted in 2008, the European Union has set clear goals for increasing the use of renewable energy. For 2020, a target of 20% has been set as share of total final energy demand, and, for 2030, a target of 27% is proposed (European Commission 2016). These targets are differentiated per member state and range from 10% in Malta to 49% in Sweden in 2020. The pathways to the national targets are specified in national renewable energy action plans. The expected increase in renewable energy in 2020 compared to 2005 consists for 80% of wind power and photovoltaics (JRC 2017), which are both intermittent renewable energy sources. In the Netherlands, renewable energy targets have been set of 14 and 16% of energy demand in 2020 and 2023, respectively (Rijksoverheid 2016). To reach these targets, it is agreed to increase the onshore wind capacity to 6000 MW by 2020 and offshore wind capacity to 4450 MW by 2023 (Ministerie van Economische Zaken 2016; Van Hout et al. 2014). Due to the uncertain and intermittent nature of these resources, the predictability of electricity generation will be reduced (Holttinen et al. 2012; Doherty and O'Malley 2003; van Hout et al. 2014). Consequently, the electricity generation forecasts made in the wholesale electricity markets will deviate more strongly and more often from the actual real-time electricity generation, which sets higher requirements on the availability and activation of balancing reserves. Studies show that with higher penetration of intermittent renewable energy sources, the relative size of reserves increases as a percentage of the renewable capacity (Brouwer et al. 2014). In Europe, transmission system operators (TSOs) are responsible for different types of reserves to resolve these imbalances (European Commission 2017; TenneT 2016). Frequency containment reserves are provided by generators coupled synchronously to the grid and are activated automatically to stabilise the system frequency in case of a contingency event (Lampropoulos et al. 2012). Next, frequency restoration reserves with either automatic or manual activation restore the frequency and free the frequency containment reserves. In addition, in order to ensure the availability of sufficient balancing reserves in case of significant contingency events, the TSO contracts frequency restoration reserves in advance.

Positive balancing capacity, or upward adjustment, is activated when there is a shortage of electricity on the grid and can be realised by either increasing the electricity generation or reducing the electricity consumption. Negative balancing capacity, or downward adjustment, is needed when there is surplus of electricity on the grid and requires a reduction in electricity generation or an increase in electricity consumption.

The measures to adjust the electricity consumption are referred to as demand response (DR) options. DR is defined as "a change in the electricity consumption pattern of end-use consumers in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" (U.S. Department of Energy 2006). DR is considered to be a cost-effective balancing option besides flexible electricity generation, electricity storage, and international transmission (van Hout et al. 2014; Doherty and O'Malley 2003; Cappers et al. 2010) and can be applied by different sectors ranging from large industrial electricity customers to smaller consumers such as households.

The increasing need for DR has enhanced the research, development, and promotion of DR in western European countries (IEA 2013, 2014; DENA 2010; Paulus and Borggrefe 2011; Klobasa 2009; Thema Consultancy Group 2014). The International Energy Agency (IEA) has developed an international program in which 16 countries work together to develop and promote DR which has stimulated research in the field (IEA 2014).

Theoretical balancing capacities of various energy-intensive industrial sectors as well as households have been evaluated for various EU countries. In a study commissioned by the transmission system operator (TSO) of the Netherlands, TenneT, a knowledge gap is identified with respect to the technical as well as economic DR potentials (van Hout et al. 2014). Furthermore, often the benefits of DR are assessed from a grid operator perspective, but if DR is to play a role in the balancing markets, it also needs to be evaluated from a balancing capacity supplier point of view (DENA 2010; Klobasa 2009; Paulus and Borggrefe 2011; Paulus and Borggrefe 2009).

To address this knowledge gap, this paper aims to assess the technical and economic DR potentials of a specific energy-intensive industrial process. In addition, this paper intends to provide more insights to what extent DR can influence the balancing markets and to increase the awareness of industries on their DR potential and the benefits they can gain in utilising this potential. Such an industrial process-specific assessment of the technical and economic DR potentials can support TSOs with the design of their DR programmes.

As a case study, this paper quantifies the positive and negative balancing capacity potential of the integrated steel plant of Tata Steel in IJmuiden (TSIJ) Netherlands. We focus on TSIJ because it is a single plant which is responsible for substantial share of total national electricity consumption (3% of the total Dutch electricity consumption). Moreover, industrial DR studies have shown that steel production processes are among the industrial processes with the highest DR potentials as stand-alone options (DENA 2010; Paulus and Borggrefe 2011; Paulus and Borggrefe 2009; Klobasa et al. 2009).

Besides being a large electricity consumer, TSIJ generates electricity from works arising gases (WAGs), which are gases that are produced in different stages of the steel manufacturing process. On an annual basis, TSIJ was even a net electricity exporter to the grid in 2013 with a consumption of ~2740 GWh and a generation of ~3500 GWh.

TSIJ could in theory provide positive balancing capacity in two ways: shutting down electricity-intensive production processes or ramping up its on-site electricity generation. Analogously, it can provide negative balancing capacity in two ways by starting up its electricity-intensive production processes or ramping down its on-site electricity generation. Regulation of production processes at an integrated steelmaking site such as TSIJ is not realistic: the potential for start-ups is too low as it almost runs on full capacity and shutdowns lead to production losses that cannot be compensated at a later point in time. In addition, shutting down production processes is difficult to manage from a production planning, safety, and logistics point of view. In this paper, we therefore focus on DR options provided by changing the electricity generation rate at TSIJ. Furthermore, we concentrate on the frequency restoration reserves which are contracted in advance, called emergency capacity in the Netherlands, as this type of balancing reserves has the longest activation duration which gives TSIJ more time to react to a call. The minimum bid size required for this type of reserves in the Netherlands is high and excludes small consumers from offering this type of reserves (see Table 1 for data in the Netherlands). In the Netherlands, the Dutch power system consists of one control area which is operated by the TSO, TenneT, who is also responsible for contracting sufficient frequency restoration reserves.

Methods

In this method, we assess the DR potentials at TSIJ based on ramping the on-site electricity generation from WAGs up or down to cause a net change in electricity consumption from the national grid compared to the consumption forecasted day ahead. These measures can be managed by optimising the WAG storage and flow levels. Figure 1 presents the WAG distribution network at TSIJ including gas storage locations. Coke oven gas (COG) is the richest in energy content with an average calorific value of ~19 MJ/Nm^3. The calorific value of the basic oxygen furnace gas (BOFG) is ~8 MJ/Nm^3 and of the blast furnace gas (BFG) ~3.7 MJ/Nm^3. The BFG is enriched by mixing it with natural gas and BOFG to a rich BFG (RBFG) with a calorific value of ~5.2 MJ/Nm^3 (see Fig. 1). WAGs are used in various production units such as blast furnaces, the pellet plant, the sinter plant, the hot strip mills, and boilers. In addition, the WAGs that are not utilised in production processes are transferred to power plants and are used for generating electricity (see Fig. 1).

TSIJ can offer DR to the power system by changing its net electricity demand profile for one or more certain programme time units[1] (PTU), on request of TenneT (Frunt 2011). In the case TSIJ consumes less electricity from the grid by ramping up its power plant than announced day ahead for a particular PTU when the measure is called, this will be a positive demand response (PDR) measure. Similarly, ramping down TSIJ's electricity production will lead to a net increase in TSIJ's electricity consumption from the grid than declared day ahead for that particular PTU and will be considered a negative demand response (NDR) measure.

To assess the technical DR potentials, we develop a linear programming model in MATLAB which is solved by a simplex algorithm (Murty 1983). The objective function of the model is to maximise the PDR and NDR capacity TSIJ can provide at different PTUs in case there would be a call for balancing power. The objective function is subject to technical constraints. These limit the extent to which WAG flows to the two power plants can change and are determined among others by the WAG demand of all the TSIJ production plants, the ramp-up and ramp-down rate of the power plants, and the WAG storage capacity. By changing the allocation of the WAGs to the TSIJ power plants, i.e. the decision variables in the linear programming model, the PDR or NDR capacity is maximised.

[1] PTU is the programme time unit of the intra-day balancing market. The length of the PTU on the balancing market is country dependent. Generally, it is 15, 30, or 60 min. In the Netherlands, the length of the PTU is 15 min.

Table 1 Characteristics of balancing capacities in the Netherlands (Frunt 2011; Lampropoulos et al. 2012)

	Automatic frequency restoration reserve	Manual frequency restoration reserve (non-contracted)	Manual frequency restoration reserve[a] (contracted)
Type	Secondary	Tertiary	Tertiary
Bid size[b]	≥4 MW	≥4 MW	≥20 MW
Activation method	Automatic	Manual	Manual[c]
Activation ramp rate	≥7 % /min	≥100 % /PTU	≥100 % /PTU

[a] Called "Emergency capacity" in the Netherlands

[b] Bid size is defined as the amount of reserve capacity supplied per PTU

[c] The balancing capacity supplier is called by the TSO to activate the measure

Objective functions and decision variables

Positive demand response

The analysed PDR measures are based on ramping up the on-site electricity generation. This requires an increase in WAG allocation to power plants at the supply period. The supply period is the period at which there is a call for balancing capacity by the TSO.

The objective function is to find the maximum amount of PDR capacity ($MaxPDR_m$) in MW for a certain supply period that starts at time slot m (starting from zero) and finishes at time slot M. One time step in our model is equivalent to 1 PTU or 15 min. The objective function is given by (1).

$$MaxPDR_m = \sum_{t=m}^{M}\sum_{k}^{K}\sum_{u}^{U}\left(\frac{Fup_{u,k,t}{}^{*}c_{k,t}}{3600}\right)*\eta_u \qquad \forall m \quad (1)$$

where

$c_{k,\ t}$, is the average calorific value of WAG k (k can be COG, RBFG, or BOFG) for electricity generation at time interval t. These are 19, 5.2, and 8.0 MJ/Nm^3, for COG, RBFG, and COFG, respectively.

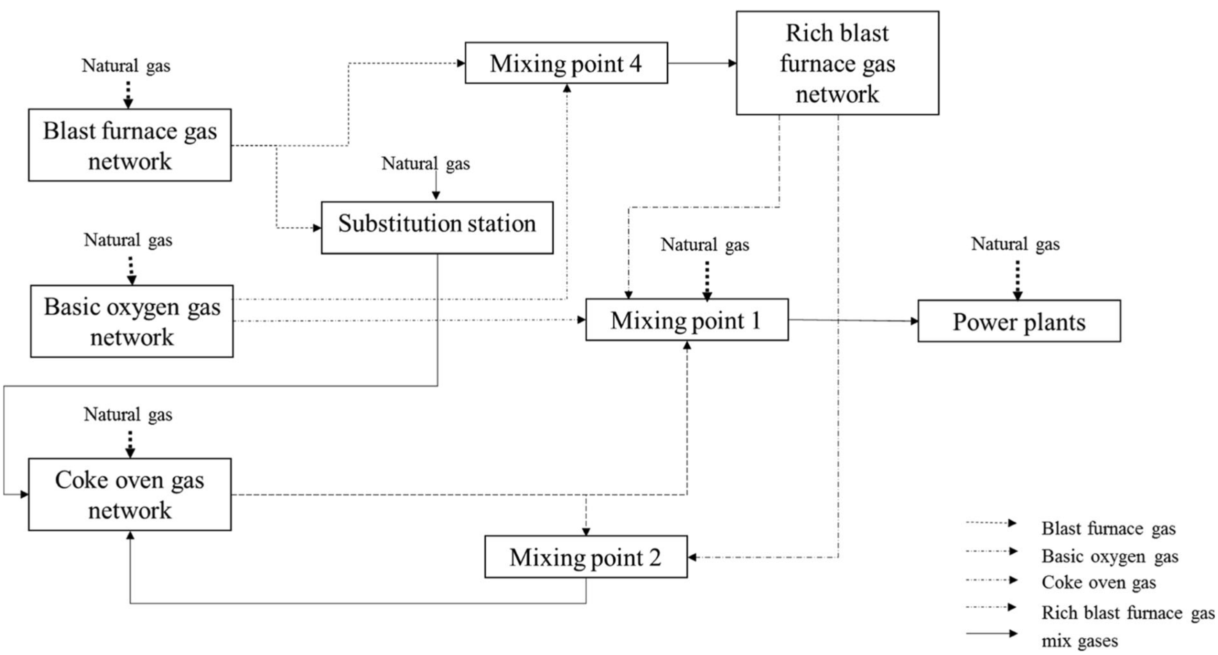

Fig. 1 Simplified representation of the works arising gas network of Tata Steel in IJmuiden

η_u, is the efficiency of power plant u. We assume a constant efficiency factor for each power plant.[2]

$Fup_{u,\ k,\ t}$, is the additional WAG volumetric flow (Nm^3/h) allocated to the power plant unit u at time t in case of a call for balancing capacity.

$Fup_{u,\ k,\ t}$ is the decision variable in the linear programming problem. $Fup_{u,\ k,\ t}$ is calculated as follows:

$$Fup_{u,k,t} = F_{u,k,t} - Fnc_{u,k,t} \quad \forall \ u, k, t \tag{2}$$

where

$Fnc_{u,\ k,\ t}$, is the WAG k allocation to power plant u within PTU t without a DR measure (under normal conditions (nc) (Nm^3/h).

The $Fnc_{u,\ k,\ t}$ amount is based on the day-ahead electricity generation planning. In case of a call for balancing capacity, the total gas k allocation to the power plant u at time unit t ($F_{u,\ k,\ t}$) should consist of the reference WAG allocation ($Fnc_{u,\ k,\ t}$) and the WAG allocation required for the additional electricity generation ($Fup_{u,\ k,\ t}$) in order to provide balancing capacity (2). Thus, $Fup_{u,\ k,\ t}$ is the volumetric flow of WAG allocated to the power plant unit u at time t in addition to the reference amount of gas allocation ($Fnc_{u,\ k,\ t}$).

Negative demand response

The NDR measures we analyse consist of ramping down the on-site electricity generation. In order to do so, the WAG k allocation (volumetric flow in Nm^3/h) to the power plant u ($F_{u,\ k,\ t}$) should be reduced compared to the reference value of WAG k allocation for that particular time slot t ($Fnc_{u,\ k,\ t}$) (3).

$$Fdown_{u,k,t} = F_{u,k,t} + Fnc_{u,k,t} \quad \forall \ u, k, t \tag{3}$$

$$MaxNDR_m = \sum_{t=m}^{M} \sum_{k}^{K} \sum_{u}^{U} \left(\frac{Fdown_{u,k,t} {}^{*} c_{k,t}}{3600} \right) {}^{*} \eta_u \quad \forall \, t \tag{4}$$

where

$Fdown_{u,\ k,\ t}$, gives the reduction in the WAG k flow rate (Nm^3/h) to power plant unit u as a DR measure at time interval t.

[2] The efficiency of the power plant depends on various factors such as gas quality and type of the gas used as well as the amount of gas. In order to limit the model complexity, we assume a constant power plant efficiency rate.

$Fdown_{u,\ k,\ t}$ is the decision variable for NDR. The maximum amount of NDR capacity ($MaxNDR_m$) in MW is given by (4).

Constraints

The linear programming problem is based on four main types of constraints

- Mass balance constraints
- Energy balance constraints
- Fuel input constraints
- Operational constraints

Mass balance constraints

The mass of a system is conserved. Therefore, WAG k generated ($Fgen_{k,\ t}$) has to be equal to the sum amount of WAG k consumed ($Fcon_{k,\ t}$) and stored ($Fstored_{k,\ t}$) at each time interval t and for each WAG k (5).

$$Fgen_{k,t} = Fstored_{k,t} + Fcon_{k,t} \quad \forall k, t \tag{5}$$

$Fcon_{k,\ t}$ is the sum of WAG k flows to all power plants and on-site processes (sp) including TSIJ factories and boiler houses. We combine the k WAG flow to the on-site processes at time unit t into one parameter (indicated by $F_{sp,\ k,\ t}$). WAG allocation to production processes should not be affected by the DR measure; therefore, the sum of all sp WAG demand is input as a parameter to the model (6).

$$Fcon_{k,t} = F_{sp,k,t} + F_{u,k,t} \quad \forall k, t \tag{6}$$

The mass balance for the WAG gas holders is given by (7). $GH_{k,\ t}$ is the amount of gas in the gas holder k at PTU t, which is equal to the sum of the amount of by-product gases at PTU $t-1$ and the difference between generation and consumption of WAGs in time interval Δt (i.e. the length of the PTU, being 900 s in this study).

$$GH_{k,t} = GH_{k,t-1} + \left(Fgen_{k,t} - Fcon_{k,t}\right) {}^{*} \Delta t \quad \forall k, t \tag{7}$$

Energy balance constraints

$$Egen_{u,t} = \left(\sum_{k=1}^{K} F_{u,k,t}{}^{*}c_{u,k,t}\right)/3600^{*}\Delta t^{*}\ \eta_u \quad \forall u, t, \quad (8)$$

The energy inflow and outflow from the system have to be balanced as energy cannot be produced or destroyed (8). $Egen_{u,\ t}$ gives the electricity generated (MWh) from power plant u at time interval t.

Operational constraints of power plants and gas holders

Operational constraints give the ranges within which the equipment can operate. These include the following constraints: the volumetric fuel input rates of different WAGs k (given by $Fmin_{u,\ k}$ and $Fmax_{u,\ k}$), change in volumetric WAG k input rate (given by $Fchmin_{u,\ k}$ and $Fchmax_{u,\ k}$), energetic fuel input rate (given by $Emininput_u$ and $Emaxinput_u$), change in energetic fuel input rate (given by $Echmininput_u$ and $Echmaxinput_u$), and the operational limits of the gas holders (given by $GHmin_{k,\ t}$ and $GHmax_{k,\ t}$) (9–13). The model includes constraints of the power generation units u and not the other processes on site, because the WAG supply to these processes remains unchanged. The constraints are based on technical operational characteristics of the different units.

$$Fmin_{u,k} \le F_{u,k,t} \le Fmax_{u,k} \quad \forall u, k, t \quad (9)$$

$$Fchmin_{u,k} \le \left(F_{u,k,t} - F_{u,k,t-1}\right) \le Fchmax_{u,k} \quad \forall u, k, t \quad (10)$$

$$Emininput_u \le Einput_{u,t} \le Emaxinput_u \quad \forall u, t \quad (11)$$

$$Echmininput_u \le Einput_{u,t} - Einput_{u,t-1} \le Echmaxinput_u \quad \forall u, t \quad (12)$$

$$GHmin_{k,t} \le GH_{k,t} \le GHmax_{k,t} \quad \forall k, t \quad (13)$$

Reference electricity generation constraints

After the PDR and NDR measure, TenneT requires that the emergency capacity supplier goes back to its reference electricity generation/consumption level. If a supply period starts at time slot m and finishes at time slot M and T is the total number of time units in 1 day, the reference electricity generation constraint for the power plants is given by (14).

$$F_{u,k,t} = Fnc_{u,k,t} \qquad \text{For } t = 1 : m \ \Lambda \ t = m + M : T; \forall \text{u}, k \quad (14)$$

Energy demand constraint

The energy demand constraint assures that the PDR and NDR measures do not affect the WAGs and electricity available for on-site operations. $F_{sp,\ k,\ t}$ is given as an input parameter in order to assure that the required WAGs are allocated to production processes. Therefore, the algorithm developed already makes sure that the electricity demand of the on-site processes is met. In case of PDR, the electricity generation is increased. This increase in generation is supplied as emergency capacity to the national grid; thus, the net amount of electricity and WAG available for on-site processes does not change.

Model implementation in MATLAB

The input data for the model includes WAG production rates by different processes, WAG consumption rates by different factories and boilers, and electricity generation in TSIJ power plants. For all these parameters, we obtained data with a time step of 15 min for 2014 from TSIJ's database.

In order to quantify the PDR and NDR potentials, we conduct 100 model runs each. The beginning time slot, m, is input parameter in the model and is picked up manually for each model run. The time slots were chosen in such a way that they include daily and seasonal differences as well as periods with different production rates and WAG availabilities at Tata Steel in IJmuiden. The specific time slots for the model runs are chosen such that daily and seasonal variations are captured. Results from 100 model runs for PDR and 100 model runs for NDR have been analysed with respect to the size of the DR capacity, the availability rate[3] of the DR capacity, and supply period as well as complexity of the measure. Moreover, in order to quantify the influence of future changes in factors such as power plant flexibility and WAG network constraints as well as emergency programme requirements, we conducted a sensitivity analysis.

[3] The availability rate gives the percentage of the emergency capacity calls that TSIJ can provide the required DR capacity.

Results

Positive demand response potentials

Current condition

The model outcomes show that the maximum supply period of a PDR measure is 45 min (or 3 PTUs). For a supply period of 1 PTU, TSIJ can provide 20 MW capacity with an availability rate of 97%. When increasing the supply period to 30 min (2 PTUs), the capacity drops to 10 MW/PTU with availability rate of 95% (see Fig. 2). If the capacity of the measure increases to 20 MW, the availability rate drops to 65%.

For 20 MW PDR measures with a supply period of 2 PTUs, the binding constraint for the first PTU is the ramp rate of the power plant for 75% of the runs. In the second PTU of the measure, the binding constraints are the amount of RBFG available in the gas holder for the PDR measure and/or the ramp-down rate of the power plants depending to the WAG amount in the holders at that point in time. Ramping down is required in the PTU right after the balancing supply period ends in order to reach the reference electricity generation pattern and thus the RBFG flow rate in the reference situation.

For a PDR measure with a supply period of 3 PTUs, the PDR capacity is 10 MW/PTU with an availability rate of 80%, and it drops to 47% when the capacity of the measure is 20 MW/PTU (see Fig. 2). The reason for the lower availability is that there is not enough RBFG to support the measure in the third PTU. For 20 MW PDR measures with a supply period of 3 PTUs, the WAG available in the gasholder is the most prominent binding constraint leading to very small PDR potentials in the second time slot of the measure. This effect is demonstrated in the model run example as shown in Fig. 3. In this particular case, there is not enough WAG available in the third PTU leading to a substantial drop in the PDR capacity.

Possible future conditions

In the previous section, it was shown that power plant ramp rate is among the main binding constraints for PDR measures with capacity higher than 10 MW and a supply period of 2 PTU. In order to calculate how future changes in power plant ramp rates can influence the PDR potentials, we conduct sensitivity analyses.

The sensitivity analyses show that for an increase in the power plant ramp rate of 50%, the availability rate of 20 MW for 2 PTUs increases from 65 to 97% and for 3 PTUs from 47 to 73%. The increases mainly occur in the first and second PTUs where the binding constraint is the ramp rate of the power plant. Increasing the power plant ramp rate does not cause any change for the third PTU as the binding constraint is mainly the WAG available in the buffer to support the measure. This effect is demonstrated in Fig. 4, where the increase in power plant increases the RBFG flow rate to the power plants substantially in the first PTU but the increase is small for the third PTU. This is also the reason why increasing the flexibility rate of the power plants even by 50% does not enable measures with supply periods longer than 3 PTUs.

Negative demand response potentials

Current potentials

For 75% of the runs, we find that the maximum NDR supply period that can be achieved without affecting the electricity generation rates prior or after the measure is 1 h and 15 min (5 PTUs). The average NDR

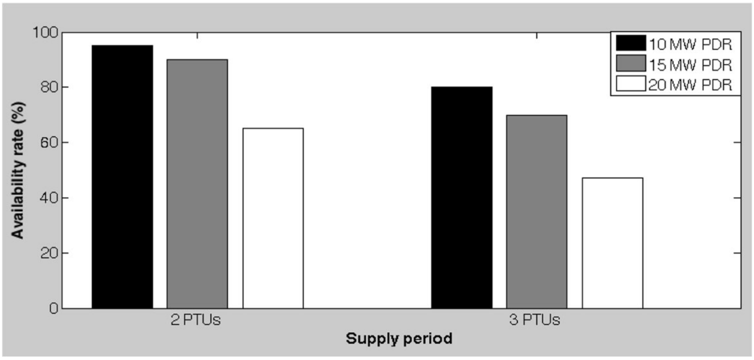

Fig. 2 Availability rates for PDR measures of 10 MW/PTU, 15 MW/PTU, and 20 MW/PTU with supply period of 2 PTUs and 3 PTUs

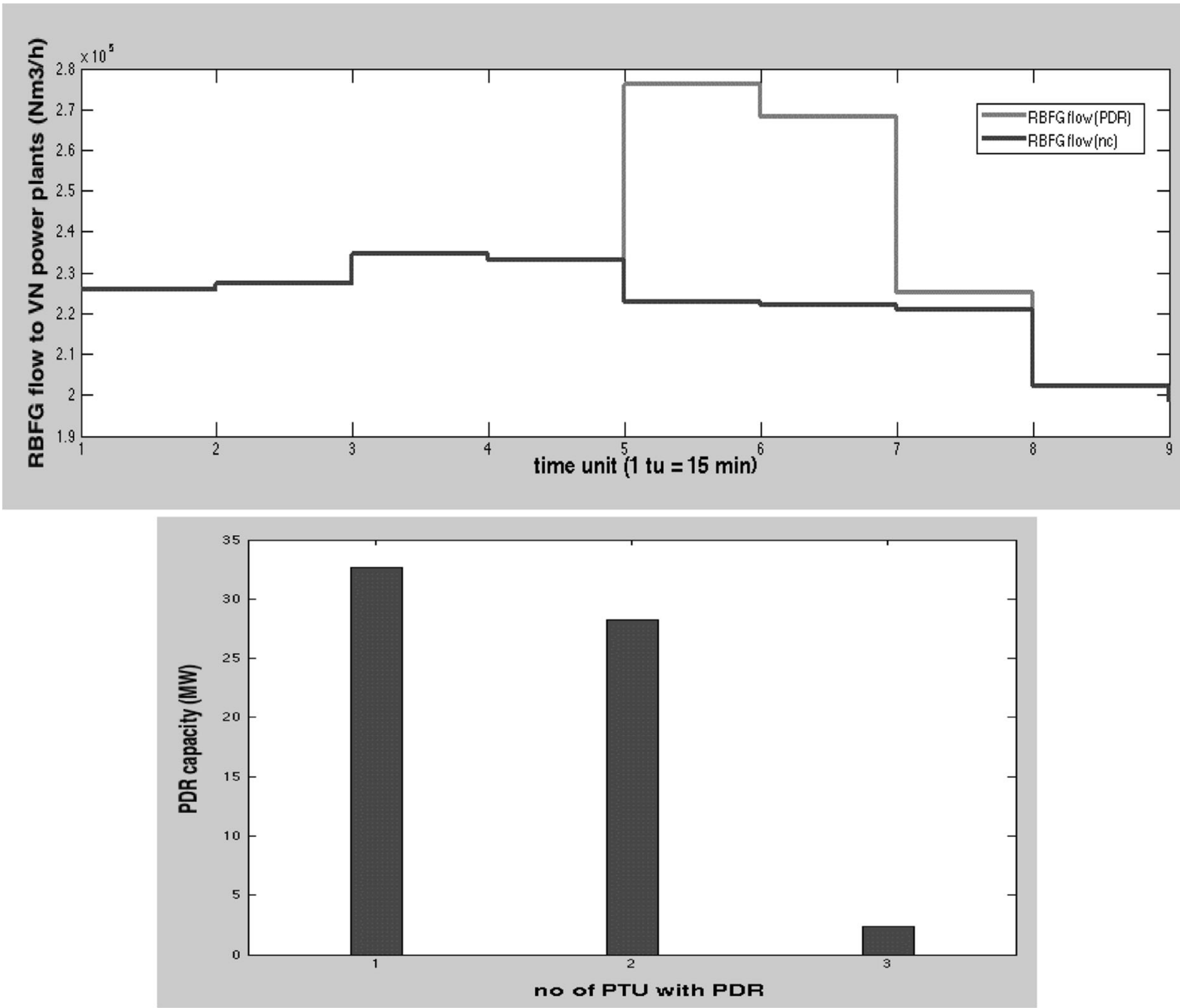

Fig. 3 RBFG flow rates to power plants (graph in the upper part) and the PDR potentials (graph in the lower part) for a PDR measure lasting 45 min (21 September 2013, 21:00–21:45)

potentials for measures with supply periods between 2 PTUs and 5 PTUs are found to be above 20 MW/PTU in most of the cases.

To assess the feasibility of being able to supply a particular NDR capacity at a particular time period, we analyse the availability rates of different NDR capacities for different supply periods. The availability rate for 10 MW/PTU NDR capacity is 91% for NDR measures with supply period 4 PTUs and drops to 87% for a measure with supply period of 5 PTUs (see Fig. 5). For 15 MW/PTU of NDR capacity, the availability rates are between 82 and 88% for measures with supply periods between 2 PTUs and 5 PTUs. For 20 MW/PTU of capacity, the availability rate reduces substantially to 60% for measures with supply period of 4 and 5 PTUs.

One of the main binding constraints for NDR measures shorter or equal to 3 PTUs is the "reference electricity generation" constraint. This constraint requires that the electricity generation reaches its reference values (planned electricity generation levels) after the demand response measure. This constraint is linked to the ramp rate of power plants. Therefore, increasing the ramp rate of the power plant improves the NDR capacity of measures with supply period equal or shorter than 3 PTU. For measures longer than 3 PTUs, there is a higher gas storage demand than for shorter measures with the same capacity because the net amount of WAG power plant inflow reduction is higher. In this case, the binding constraint is the gasholder capacity.

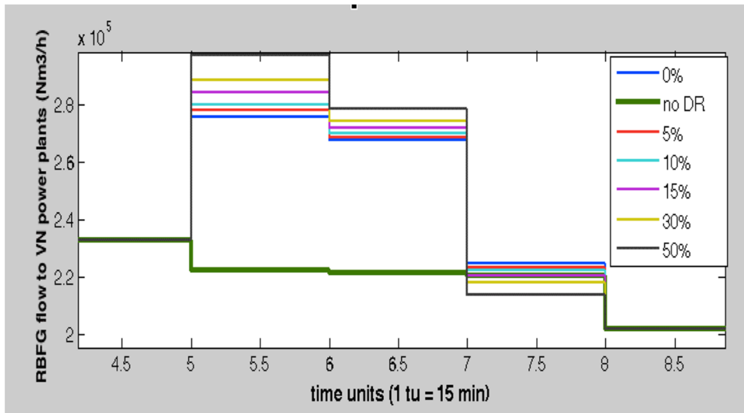

Fig. 4 Change in the RBFG flow to the power plants when the increase in the flexibility of the power plants ranges from 0 to 50% of current power plant flexibility. "No DR" stands for a RBFG flow rate under normal operational conditions (in case of no call for demand response)

Future potentials

As previously discussed, the power plant ramp rate is a binding constraint for NDR measures with supply period of ≤3 PTUs. Figure 6 shows that a 20% increase in the gas holder does not influence the NDR potential of a 2 PTU measure (Fig. 6—upper part), whereas it leads to 10 MW/PTU NDR capacity measures of 5 PTUs (Fig. 6—lower part).

For NDR measures with a supply period of 2 PTU of 25 MW/PTU capacity, the availability rate increases from 68 to 82% when the power plant ramp rate down increases by 50%. Similarly, for a NDR measure with supply period of 3 PTUs, the availability rate increases from 52 to 82% (see Fig. 7). In case of the 3 PTU measure, power plant ramp rate increase affects mainly the capacity in the first and last PTUs of the measure while it causes only a 1 MW/PTU increase on average for the second PTU.

In contrast to power plant ramp rates, the gas holder capacity has a more prominent effect on NDR measures with a supply period ≥3 PTUs. For NDR measures with supply period of 4 and 5 PTUs and NDR capacity of 20 MW/PTU, the availability rate increases from 60 to 95% for gas holders with double the current capacity. As the supply period gets longer, the gas holder capacity gains importance such

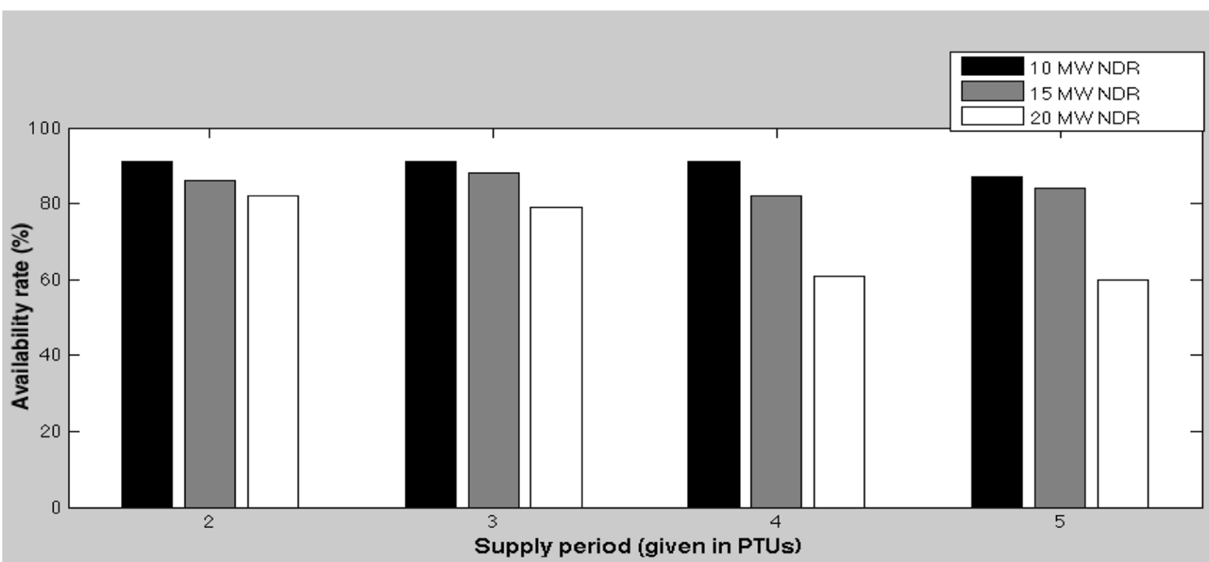

Fig. 5 Availability rate of 10 MW/PTU, 15 MW/PTU, and 20 MW/PTU NDR measures with supply periods ranging between 2 and 5 PTUs

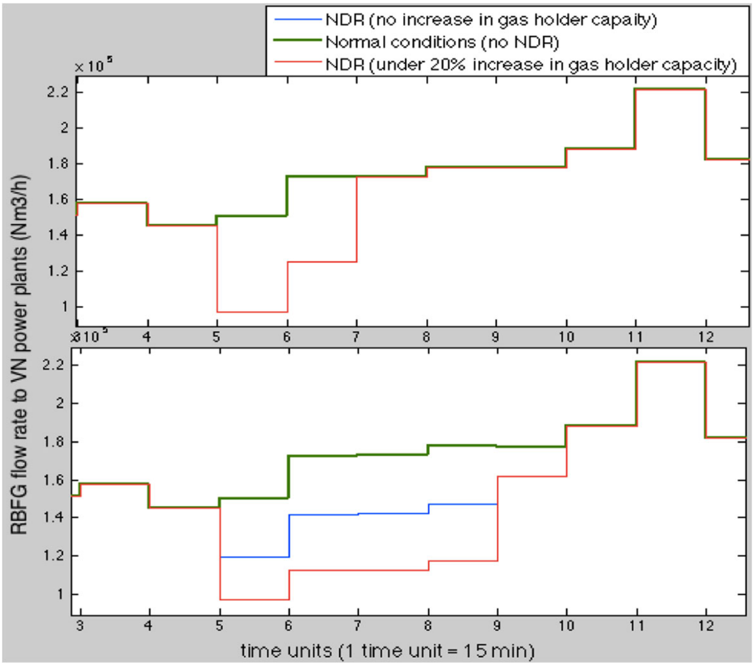

Fig. 6 NDR potential for measures with supply period of 2 PTU (upper figure) and 5 PTU (lower figure) when increasing the RBFG gasholder capacity by 20%

that 50% increase in the gas holder capacity leads to NDR capacity up to 25 MW/PTU for measures with supply period of 4 PTUs and up to 27 MW/PTU for measures with supply period of 5 PTUs (see Fig. 8). Even though the gain of increasing the gas holder capacity leads to a substantial increase in NDR for measures with relatively long supply period, increasing the gas holder capacity is very costly and not required for TSIJ (under current production levels).

Discussion

TSIJ can offer 10 MW/PTU of PDR capacity with availability rate of 97% for a supply period of 30 min. This does not fulfil the capacity requirement of 20 MW/PTU for emergency capacity programmes in the Netherlands. That is why Tata Steel, with the current available PDR capacity, cannot participate in emergency capacity programs. The longer supply period comes at

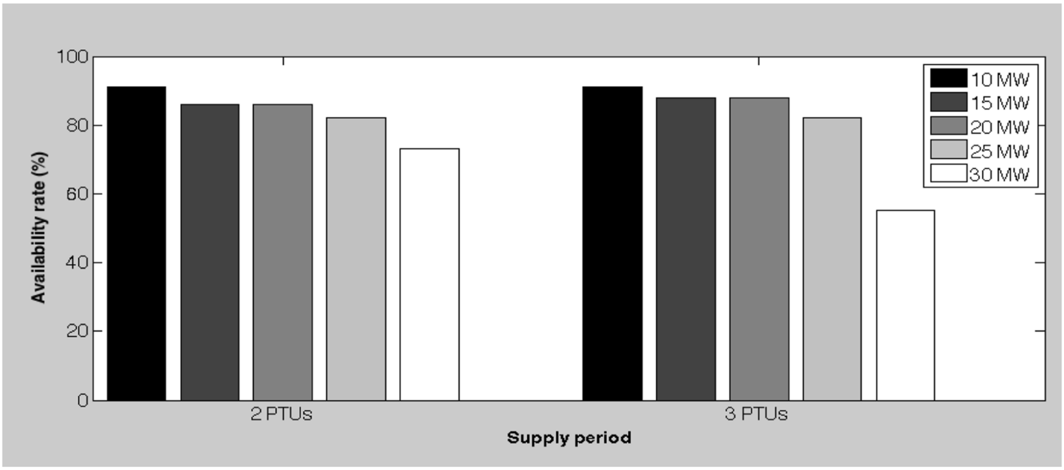

Fig. 7 Availability rate of 10 MW/PTU, 15 MW/PTU, 20 MW/PTU, 25 MW/PTU, and 30 MW/PTU NDR measures with supply periods of 2 and 3 PTUs under a 50% increase in power plant flexibility

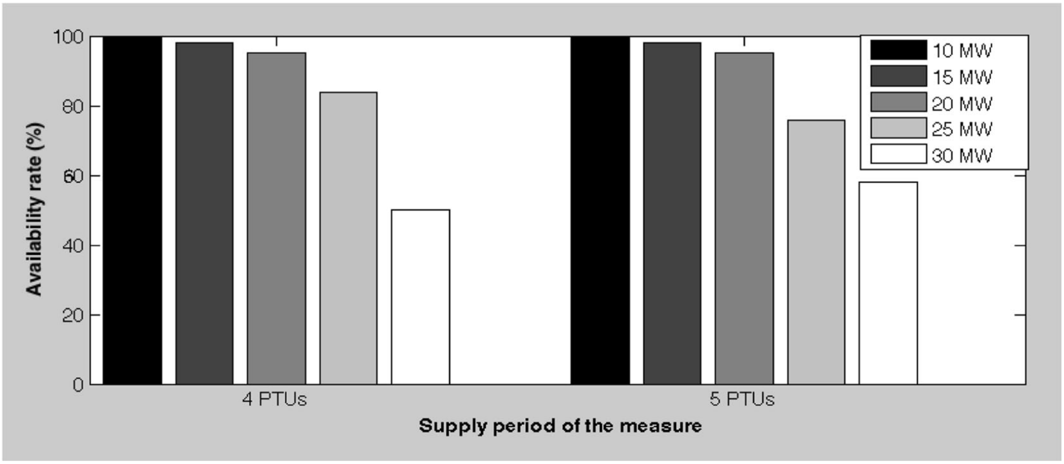

Fig. 8 Availability rate of 10 MW/PTU, 15 MW/PTU, 20 MW/PTU, 25 MW/PTU, and 30 MW/PTU NDR measures with supply periods of 4 and 5 PTUs under a 50% increase in gas holder capacity

the cost of lower PDR capacity that is only half of the minimum bid size of 20 MW/PTU.

Towards 2030, the emergency capacity program requirements in the Netherlands are expected to change as the demand for emergency capacity enhances due to the increase in electricity generation from renewable energy sources (van Hout et al. 2014). If the availability rate required for participating in emergency demand response programs drops from 97 to 90%, TSIJ can commit to capacity of 15 MW/PTU, and if the availability rate requirement drops to 65%, TSIJ can commit for 20 MW/PTU with a supply period of 30 min. The latter would be sufficient for TSIJ to participate in emergency power programmes as a stand-alone emergency capacity provider. On the other hand, if emergency capacity programme requirements stay the same, TSIJ needs 50% increase in its power plant flexibility in order to have 20 MW/PTU PDR capacity.

Another option for Tata Steel to be able to use the PDR potentials is pooling with other PDR suppliers. Due to the increasing emergency capacity demand in the recent years, positive capacity pooling has gained importance in the Netherlands. Pooling programmes are likely to be successful in the future because they generally are able to provide higher capacities and availability rates than stand-alone options, decrease the administrative burden both for the TSO and for emergency program participants, and reduce the risk for suppliers.

With respect to the NDR potential, TSIJ can commit to 20 MW/PTU of NDR measure with a supply period of 3 PTUs and 80% availability under current WAG buffering capacities. If the RBFG gas holder capacities increase by 50%, it increases NDR capacity up to 25 MW/PTU for measures with a supply period of 4 PTUs. Negative emergency programmes have been only recently implemented in the Netherlands. Further analyses comparing the NDR capacity characteristics and capacity programme requirements are needed in order to assess the feasibility of participation for TSIJ.

Comparison of the results with other DR potential studies

The PDR capacities of TSIJ obtained by increasing the WAG input rate to power plants are found to be insufficient for participating in emergency demand response programmes in the Netherlands. Yet, the quantities and specifications of the PDR capacity can still be valuable. The total amount of PDR capacity of households in Germany by 2020 is estimated to be 53 MW/PTU (DENA 2010). In order to make this capacity available, high investment costs are required (DENA 2010). On the other hand, TSIJ can supply 10 MW/PTU for a supply period of 30 min with close to zero investment requirements. This is a substantial value especially when compared to the total capacity of the German household sector.

Theoretical demand PDR potentials of industrial sectors in Germany, such as cement, aluminium (electrolysis), chlorine (based on chlorine alkali electrolysis membrane method), and paper production are found to be 314, 277, 685, and 311 MW respectively (DENA 2010). The average NDR of Germany energy-intensive industrial sectors such as chlorine and paper industry are 346 and 94 MW NDR potential respectively (DENA 2010;

Paulus and Borggrefe 2009). For TSIJ, we obtained 20 MW/PTU of NDR capacity for a supply period of 45 min with an availability rate ≥97%. The PDR and NDR potentials that we obtained for TSIJ are substantially lower than these values. The first reason for this is that these are sectoral estimates while we concentrated specifically to the Tata Steel plant in IJmuiden. In addition, we looked into the technical potentials that are generally lower than the theoretical potentials and we evaluated the potentials of one DR measure and not the entire plant (e.g. "production process shutdowns" were excluded).

Assessment of the method

In the available literature on DR potentials of integrated steel plants, two main research approaches are used for evaluating the DR potentials for different DR programs.

1. DR potentials through production planning for incentive-based demand response programs (e.g. tertiary balancing capacity) (DENA 2010; Paulus and Borggrefe 2011; Klobasa 2009; Gils 2014; Klobasa et al. 2009)
2. DR potentials through electricity demand planning based on electricity price (e.g. time of use programmes) (Ashok and Banerjee 2000; Ashok 2006; Bego et al. 2014; Fernandez et al. 2013; Hadera et al. 2014; Lee and Reklaitis 1995; Mignont and Hermia 1996; Wang and Li 2013)

These studies, in which the balancing capacity supplied by shutting down steel production processes are assessed, mainly focus on the theoretical DR potential. The first group calculates the DR potentials based on the electricity intensities of the processes while it is not taking into account how much of these potentials can actually be realised based on the technical constraints of the processes involved in the demand response measure. On the other hand, the linear optimisation MATLAB model used in our study takes into account the technical constraints of the WAG network and the constraints of each unit involved in the measure. This allows for a more accurate estimation of the potentials as it gives the technical potential of what actually can be achieved instead of the theoretical potential. The second group of studies, on the other hand, mainly concentrates on production planning based on electricity prices. The models developed as part of these sets of studies do not give insight on how those processes can be used for balancing capacity purposes such as emergency balancing capacities considered in this study.

There are also various limitations of this study. Firstly, it was assumed that the change in WAG flow rate to the power plants will not affect the parts of the WAG network connecting to the on-site processes. However, this cannot always be assured because an increase in the pressure in one part of the network can lead to a change in the other parts. Secondly, in the model, we only include technical constraints of the WAG and power plants at TSIJ. However, in addition to technical constraints, there are also contract-related constraints. For example, the amount of WAGs that TSIJ can send to the power plants is limited by contract agreements between the two parties. Thirdly, the PDR and NDR capacities in this study are statistical representations for model runs of 100 days. In order to increase the accuracy of the results, the number of runs should be increased.

Conclusion

In this research, we have used linear optimisation programming in order to evaluate the positive demand response and negative demand response potentials of Tata Steel in IJmuiden. We need these estimates in order to analyse the feasibility of TSIJ to participate in electricity emergency capacity programs.

The study concludes that TSIJ cannot fulfil the requirements for participating in demand response programs in the Netherlands that require 20 MW/PTU with availability rate of 97% for at least 2 PTUs. For this availability level, TSIJ can provide up to 10 MW/PTU for a supply period of 2 PTUs. Therefore, there are two options for Tata Steel to participate on DR programs in the future. The first option is to pool with other DR suppliers. Pooling reduces the capacity and availability requirements giving TSIJ a chance to utilise its capacity while reducing the risk of failing to provide the DR capacity when required. This option is viable but requires more in-depth research on DR pooling opportunities available for TSIJ. The second option is increasing the power plant flexibility of TSIJ. An increase in power plant ramp rate by 50% is required in order for TSIJ to be able to provide 20 MW/PTU PDR. However, this is not a feasible option due to high costs involved.

TSIJ can provide 20 MW/PTU of NDR measures with a supply period of 3 PTUs and 80% availability with WAG storage capacity being the main binding constraint. 20 MW/PT of NDR capacity for a supply period of 4 PTUs and availability rate of 95% can be reached through 35% increase in the RBFG storage capacity. The feasibility of participating in NDR emergency capacity programmes has to be evaluated in the future as NDR emergency programmes develop in the Netherlands.

The results of this research contribute in developing a knowledge base for demand response potentials in the Netherlands and improve TSIJ's demand response strategy. In addition, these research results provide the TSO insight into the demand response potentials of big electricity consumers such as TSIJ and the suitability of these potentials to the emergency capacity programmes currently in place.

Recommendations for future research

Regarding the future positioning of TSIJ in the balancing markets, it is important to analyse the emergency capacity pooling options in the Netherlands. This involves, but is not limited to, a detailed analysis of the current and future conditions for participating in emergency pools and benefits obtained from such participation. Moreover, the modelling approach developed in this study can be used for evaluating the PDR and NDR capacities of other steel plants as well as other industrial processes.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Nomenclature

Abbreviations *BFG*, blast furnace gas; *BOFG*, basic oxygen furnace gas; *COG*, coke oven gas; *DR*, demand response; *NDR*, negative demand response measure; *PDR*, positive demand response measure; *PTU*, programme time units; *RBFG*, rich BFG; *TSIJ*, Tata Steel in IJmuiden; *TSO*, transmission system operator; *WAGs*, works arising gases

Sets u, units (power plants: VN24, VN25, IJMO1); sp, boilers and TSIJ factories

Notation t, time step

Variables

Notation $GH_{k,t}$, amount of gas in the gas holder k at time interval t (Nm^3); $F_{u,k,t}$, average flow rate of WAG k to unit u at time interval t (Nm^3); $Fup_{u,k,t}$, increase in WAG k flow rate to unit u as a DR measure at time interval t (Nm^3/h); $Fdown_{u,k,t}$, reduction in WAG k flow rate to unit u as a DR measure at time interval t (Nm^3/h); $Fcon_{k,t}$, total consumption of WAG k at time interval t (Nm^3/h); $Fstored_{k,t}$, average flow rate of WAG k to the corresponding gas holder at time interval t (Nm^3/h);$Egen_{u,t}$, electricity generated from power plant u at time interval t (MWh); NDR_m, negative demand response capacity at time interval m (MW); PDR_m, positive demand response capacity at time interval m (MW)

Parameters η_u, efficiency of unit u (%); $Fgen_{k,t}$, amount of WAG k generated at time interval t (Nm^3/h); $Fnc_{u,k,t}$, average flow rate of WAG k to unit u under normal conditions (without a DR measure) at time interval t (Nm^3/h); $Edem_t$, electricity demand of the on-site processes at time interval t (MWh); $c_{k,t}$, average calorific value of WAG k at time interval t (MJ/Nm^3); $Fmin_{u,k,t}$, minimum k gas flow rate to unit u (Nm^3/h); $Fmax_{u,k,t}$, maximum k gas flow rate to unit u (Nm^3/h); $Fchmin_{u,k}$, minimum change in k gas flow rate to unit u; $Fchmax_{u,k}$, maximum change in k gas flow rate to unit u; $Emininput_u$, minimum energy input to unit u (MJ/h); $Emaxinput_u$, maximum energy input to unit u (MJ/h); $Echmininput_u$, minimum change in energy input to unit u ((MJ/h)/15 min); $Echmaxinput_u$, maximum change in energy input to unit u ((MJ/h)/15 min); $GHmin_{k,t}$, minimum gas level that should be attained at gas holder k (Nm^3); $GHmax_{k,t}$, maximum gas level that should be attained at gas holder k (Nm^3)

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