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 large electricity consumers is limited for most countries. Steel production processes are among the industrial processes with the highest DR potentials. In this study, we focus on DR options provided by changing the electricity generation rate at Tata Steel in IJmuiden (which produces 3 % of total electricity consumption in the Netherlands). For evaluating the technical DR potential we have developed a linear programming model in MATLAB. The model calculates the optimal allocation of works arising gases of Tata Steel in IJmuiden in case of a call for emergency balancing power. The optimization is done subject to the technical constraints of the distribution system and storage potential of the works arising gases, the demand of the Tata Steel plants for these gases, and the ramp-up rate of the power plant that runs on these gases. Results show that Tata Steel in IJmuiden can supply 10 MW for two Programme Time Units (i.e. PTU is defined as a 15 minute period in the Netherlands by TenneT) of positive DR capacity with an availability rate of 97 %. This is not enough for participating in the current emergency capacity programs in the Netherlands, which require at least 20 MW for longer than 1 PTU. Tata Steel can provide 20 MW DR capacity with an availability rate of 65 %. Therefore, if the availability rate requirements for emergency balancing programs in the Netherlands do not drop, Tata Steel would need to pool with other suppliers in order to participate in such programs. The negative demand response potential of Tata Steel in IJmuiden is found to be 20 MW supplied for 3 PTUs and 4 PTU with doubling of blast furnace gas storage capacities.

Introduction
The Netherlands targets to increase its renewable energy from 4.5 % in 2013 to 14 % of the national energy use by 2020 (International Energy Agency, 2014b). This will reduce the predictability of electricity generation due to the uncertain and intermittent nature of renewable energy sources (Doherty & O'Malley, 2003; Holttinen et al., 2012; van Hout, Koutstaal, Ozdemir, & Seebregts, 2014). Lower predictability of electricity generation means that there is higher probability for deviations between the electricity generation forecasts made day-ahead and the actual real-time electricity generation. Therefore, the demand for both positive and negative balancing capacities that will accommodate the variability of renewable energy source is expected to increase (van Hout et al., 2014).

Positive balancing capacity, or upward adjustment, is activated when there is a shortage of electricity on the grid, and it consists of increasing the electricity generation or reducing the electricity consumption. Negative balancing capacity, or downward adjustment, takes place when there is surplus of electricity on the grid and involves reduction in electricity generation or increase in electricity consumption.

Based on the Energy Agreement reached in 2013, the Netherlands aims to increase its offshore wind capacity to 6,000 MW by 2020 and onshore wind capacity to 4,450 MW by 2023 (van Hout et al., 2014). The Energy Research Centre of the Netherlands (ECN) estimates that this will lead to an increase in the positive balancing demand from 595 GWh in 2012 to 2,340 GWh in 2023 and in the negative balancing demand from 368 GWh in 2012 to 2,041 GWh in 2023 (van Hout et al., 2014). Some options for meeting the future balancing needs are: highly flexible electricity generation, more electricity storage, an increase in the interconnection capacities between countries and demand response (DR) (Cappers, Goldman, & Kathan, 2010; Doherty & O'Malley, 2003; van Hout et al., 2014). In this research we focus on DR.

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 one of the most cost-effective balancing options and it 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 (DENA, 2010; International Energy Agency, 2013, 2014a; Klobasa, 2009; Paulus & Borggrefe, 2011; 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 (International Energy Agency, 2014a).

Theoretical balancing capacities of various energy intensive industrial sectors as well as households have been evaluated for various EU countries. A study by the transmission system operator (TSO) of the Netherlands – TenneT and the ECN concludes that there is a knowledge gap regarding the technical as well as economic DR potentials (van Hout et al., 2014). Due to the lack of literature on DR in the Netherlands, a study by Kema and CE Delft quantifies the DR potentials of industry and households for the Netherlands is mainly based on practical trials in other countries instead of in-depth sector specific analysis (Blom, Bles, Leguijt, & Rooijers, 2012). Furthermore, economic DR potential analyses have mainly been done from the perspective of grid operators (DENA, 2010; Klobasa, 2009; Paulus & Borggrefe, 2011, 2009). Detailed economic analyses on DR from the perspective of the balancing capacity supplier are missing for the EU countries (Paulus & Borggrefe, 2009). Filling this knowledge gap requires evaluating the technical and economic DR potential of electricity consumers (DENA, 2010). In addition to improving country's knowledge base on DR, these types of studies stimulate electricity consumers to participate in DR programs by informing them about their DR potential and the economic benefits they can get from using these potentials. Also, sector or process specific technical and economic DR studies help the transmission grid operator to identify high DR capacity sectors and processes as well as their specific characteristics. Based on these, the grid operator can design its DR program.

This study contributes in filling this knowledge gap by quantifying the positive and negative DR capacity that the integrated steel plant of Tata Steel in IJmuiden (TSIJ) in the Netherlands can provide. We focus on TSIJ because it is one of the biggest electricity consumers in the Netherlands (3 % of the total electricity consumption of the Netherlands) and consequently can have a substantial influence on the Dutch electricity grid. In addition, industrial DR studies for other countries have shown that steel production processes are among the industrial processes with the highest DR potentials as stand-alone options (DENA, 2010; Klobasa, Erge, & Wille-haussmann, 2009; Paulus & Borggrefe, 2011, 2009).

Besides being a large electricity consumer, TSIJ also generates electricity from its Works Arising gases (WAGs) (i.e. coke oven gas, blast furnace gas and basic oxygen furnace gas). Each moment, the net electricity required by TSIJ from the national grid dependents on its electricity consumption and the electricity generation rate at that moment. In this study, we focus on DR options provided by changing the electricity generation rate at Tata Steel in IJmuiden. For assessing the technical DR capacities we have developed a linear programming model in MATLAB. The model calculates the optimal allocation of work arising gases of TSIJ in case of a call for emergency balancing power. The optimization is done subject to the technical constraints of the distribution system and storage potential of the WAGs, the demand of the Tata Steel plants for these gases, and the ramp-up rate of the power plant that runs on these gases.

Background

ELECTRICITY BALANCING MARKET IN THE NETHERLANDS

The Dutch power system consists of one control area which is operated by TenneT (Lampropoulos et al., 2012). TenneT is responsible for maintaining the physical balance between electricity generation and consumption, the reserve of active and reactive power, and frequency regulation. In order to balance the electricity generation and consumption, the national electricity generation in the Netherlands is planned in advance according to the forecasted national electricity consumption (ENTSOE, 2014). Electricity trading takes place in different markets such as bilateral market, day-ahead spot market and intraday spot market.

Even though in the day-ahead market TenneT makes sure that the electricity generation equals the forecasted electricity demand, intraday mismatches between the two takes place mainly due to forecast imperfections. Based on real time differences between the load and electricity generation, the electricity system can be in a Programme Time Unit[1] (PTU) in one of the following conditions (Frunt, 2011): state 0 – No imbalance in the whole PTU; state -1: the system has surplus (called a "long" position); state 1: the system has shortage (called a "short" position); state 2: the system has both a "short" and a "long" position within the PTU. In case of surplus the system requires negative balancing capacity and in case of shortage the system requires positive balancing capacity in order to correct the system imbalance. The characteristics of balancing capacity types available in the Netherlands are given in Table 1[2, 3, 4, 5].

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 minutes. In the Netherlands, the length of the PTU is 15 minutes.

2. Bid size is defined as the amount of emergency capacity supplied per PTU.

3. Automatic activation method for reserve capacity: The TSO activates the balancing capacity.

4. Activation method for emergency capacity: The balancing capacity supplier is called by the TSO to activate the measure.

5. Activation duration: The amount of time in which the balancing capacity should be provided.

Table 1. Characteristics of different balancing capacity types in the Netherlands (Frunt, 2011; Kundur, 1994; Lampropoulos et al., 2012).

	Regulating capacity	Reserve capacity	Emergency capacity
Type	Secondary	Tertiary	Tertiary
Bid size	≥ 4 MW	≥ 4 MW	≥ 20 MW
Activation method	Automatic	Automatic/Manual	Manual
Deactivation method	N/A	Systematically at the end of 1st full PTU	Manually at end of PTU
Activation ramp rate	≥ 7 %/min	≥ 100 %/PTU	≥ 100 %/PTU
Activation duration	≥ 4 sec	≥ 15 min	≥ 15 min

In this study we focus on emergency capacity programs because TSIJ can provide capacity only as long as the activation method is manual, i.e. no direct interference by TenneT as this can affect production processes of TSIJ. Also, TSIJ needs at least 15 minutes to ramp up or ramp down.

THE ENERGY SYSTEM OF TATA STEEL IN IJMUIDEN

Steel production involves energy intensive processes and electricity is a big part of the total consumed energy. The total electricity consumption of TSIJ was ~2,740 GWh/year and the total electricity generation is ~3,500 GWh/year in 2013 making TSIJ a net electricity exporter to the grid.

At TSIJ energy rich WAGs are produced as an output from the steel manufacturing processes. The WAGs produced at TSIJ are coke oven gas (COG), rich blast furnace gas (RBFG)[6] and basic oxygen furnace gas (BOFG). The WAG distribution network of TSIJ is connected to three power plants through two mixing units. A simplified representation of the WAG network of TSIJ is shown in Figure 1.

TSIJ can provide positive balancing capacity in two ways: shutting down electricity intensive production processes and ramping up its on-site electricity generation. Shutting down electricity intensive processes has major consequences for the production process that are higher than benefits from current DR programs in the Netherlands. Therefore, we focus in this article on the balancing potentials by ramping up/ramping down the on-site electricity demand. Ramping down TSIJ's electricity production will lead to a net increase in TSIJ's electricity consumption from the grid providing negative balancing capacity or negative demand response capacity (NDR). Ramping up TSIJ's electricity generation will lead to a net reduction of TSIJ's electricity consumption from the grid providing positive balancing capacity or positive demand response capacity (PDR).[7]

Methods

We develop linear programming models in MATLAB for evaluating the PDR and NDR potentials of TSIJ. The mathematical algorithms are to optimize the NDR and PDR capacities subject to technical constraints of the WAGs distribution network of TSIJ. The technical constraints considered in the optimization can be classified in four groups:

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

OBJECTIVE FUNCTIONS AND DECISION VARIABLES

Positive Demand Response

The PDR measures we analyse consist of ramping up the on-site electricity generation. In order to ramp up the electricity generation, the WAGs flow rate to the power plant needs to be increased. Therefore, the objective is to find the maximum amount of PDR capacity (*MaxPDR*) for which the supply period starts at time slot *m* and finishes at time slot *M*. One time step in our model is equivalent to 1 PTU or 15 minutes. Based on this, the objective function is given by (1) where $c_{u,k,t}$ is the average calorific value of WAG *k* (i.e. the gases COG, BFG, or BOFG) flowing to the power plant unit *u* (VN24 unit, VN25 unit, or the IJMO1 unit) at time interval *t*, η_u is the efficiency of unit *u*.

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

$Fup_{u,k,t}$ is the amount of WAG flow to the power plant units in addition to the reference amount of gas flow ($Fnc_{u,k,t}$), which is the amount of WAG that is sent to the power plants without a DR measure (2). Therefore, $Fup_{u,k,t}$ is the decision variable for PDR.

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

Negative Demand Response

The NDR measures we analyse consist of ramping down the on-site electricity generation. In order to do so the WAGs flows to the power plant need to be reduced. Based on this, the maximum amount of NDR capacity (*MaxNDR*) for which the supply period starts at time slot *m* and finishes at time slot *M* is given by:

$$MaxNDR_t = \sum_{t=m}^{M}\sum_{k=1}^{K}\sum_{u=1}^{U}\left(\frac{Fdown_{u,k,t} * c_{u,k,t}}{3600}\right) * \eta_u \quad \forall\, t \qquad (3)$$

$Fdown_{u,k,t}$ is the decision variable. It gives the reduction in the WAG *k* flow rate to power plant units as a DR measure at time interval *t*, which is the decision variable for NDR. The surplus of gas obtained from ramping down the electricity generation process has to be stored in the gas holders.

6. Rich blast furnace gas is produced by mixing blast furnace gas, natural gas and basic oxygen furnace gas.

7. Even though the capacity is not ensured by varying TSIJ's electricity consumption, it leads to a change in TSIJ's electricity demand from the national grid therefore it has been considered as a demand response measure.

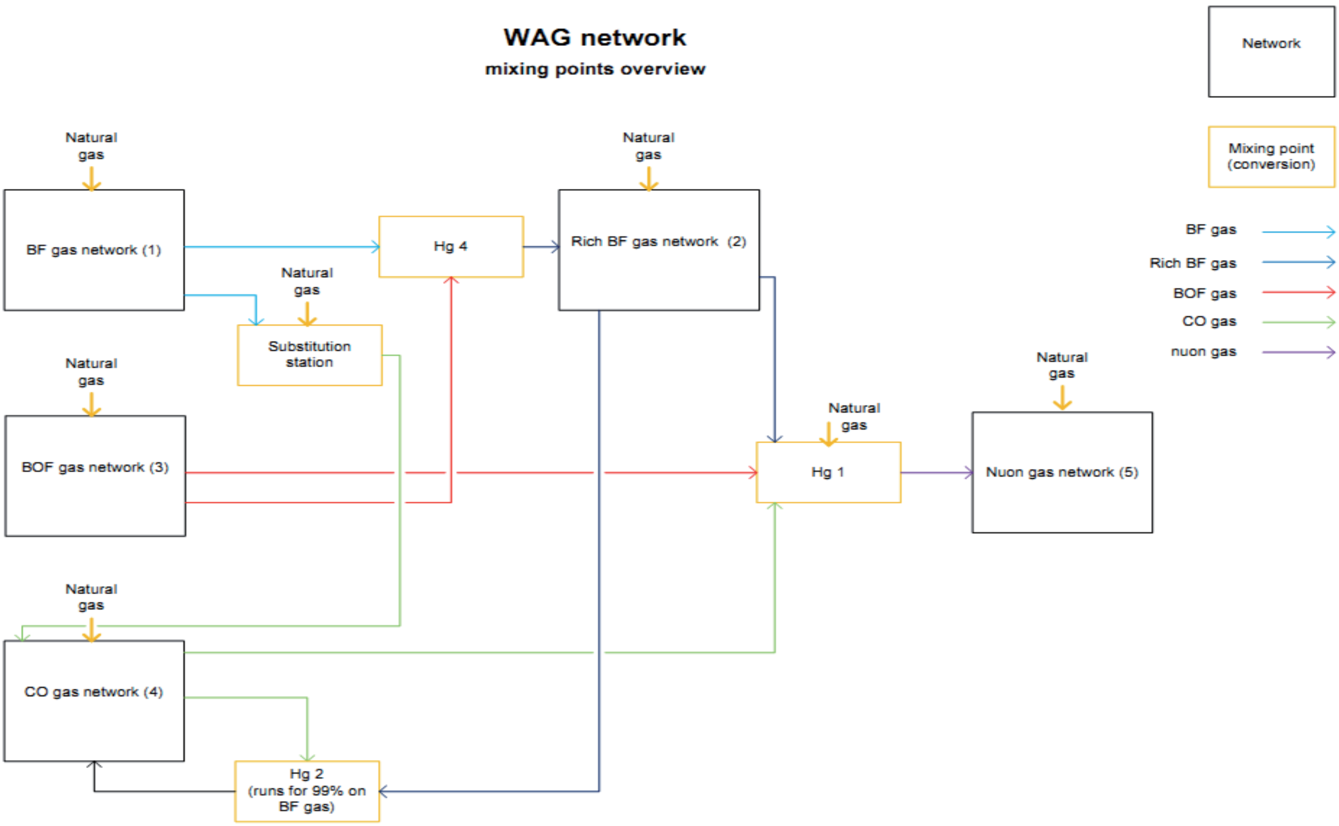

Figure 1. Simplified representation of the WAG network of TSIJ (Pronk et al., 2013).

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 each WAG k (4).

$$Fgen_{k,t} = Fstored_{k,t} + Fcon_{k,t} \quad \forall\, k, t \qquad (4)$$

$Fcon_{k,t}$ is the sum of WAG k flows to all power plants and on-site processes including TSIJ factories and boilers (5). We combine all the WAG flows to these on-site processes into one flow (indicated by 'sp'). WAG flows to on-site 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.

$$Fcon_{k,t} = F_{sp,k,t} + F_{VN,k,t} + F_{IJMO1,k,t} \quad \forall\, k, t \qquad (5)$$

The mass balance for the WAG gas holders is given by (6). $GH_{k,t}$ is the amount of gas in the gas holder k at time interval t, which is equal to the sum of the amount of by-product gases at time $t-1$ and the difference between generation and consumption of WAGs in time interval Δt.

$$GH_{k,t} = GH_{k,t-1} + \left(Fgen_{k,t} - Fcon_{k,t}\right) * \Delta t \quad \forall\, k, t \quad (6)$$

Energy balance constraints

The energy inflow and outflow from the system has to be balanced as energy cannot be produced or destroyed (7).

$$Egen_{u,t} = \left(\sum_{k=1}^{K} F_{u,k,t} * c_{u,k,t}\right) / 3600 * \Delta t * \eta_u \quad \forall\, u, t, \quad (7)$$

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 rate (given by: $Fmin_{u,k}$ and $Fmax_{u,k}$), change in volumetric fuel 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 $GHmax_{k,t}$ (8–12).

$$Fmin_{u,k} \le F_{u,k,t} \le Fmax_{u,k} \qquad \forall\, u, k, t \quad (8)$$

$$Fchmin_{u,k} \le \left(F_{u,k,t} - F_{u,k,t-1}\right) \le Fchmax_{u,k} \qquad \forall\, u, k, t \quad (9)$$

$$Emininput_u \le Einput_{u,t} \le Emaxinput_u \qquad \forall\, u, t \quad (10)$$

$$Echmininput_u \le Einput_{u,t} - Einput_{u,t-1} \le Echmaxinput_u \qquad \forall\, u, t \quad (11)$$

$$GHmin_{k,t} \le GH_{k,t} \le GHmax_{k,t} \qquad \forall\, k, t \quad (12)$$

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 one day, the reference electricity generation constraint for the power plants is given by (13).

$$F_{u,k,t} = Fnc_{u,k,t} \quad \text{For } t = 1{:}tm \ \Lambda \ t = tm + a{:}T; \ \forall \ \text{u}, k \quad (13)$$

Energy demand constraint

The energy demand constraint assures that the PDR and NDR measure does 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 on-site processes. The algorithm developed already assures 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 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 real time electricity generation in TSIJ power plants. For all these parameters we obtained data with a time-step of 15 mins for 2014 from TSIJ's databases. The data on operational constraints for the WAG network and power plants have been obtained from the energy optimizations software currently used by TSIJ to optimize the usage of WAG gases.

In order to quantify the PDR and NDR potentials we conduct 100 model runs for different days. Part of the PDR capacity slots chosen for the model runs are time slots when TenneT was actually called to provide emergency capacity in 2014. The time slots of the NDR runs are chosen arbitrarily, because historic data were not available as there was no emergency capacity program in the Netherlands. The specific time slots for the model runs are chosen such that 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 of the DR capacity, 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, WAG network constraints as well as emergency program requirements are adapted in a sensitivity analysis for both PDR and NDR model runs.

Results

POSITIVE DEMAND RESPONSE POTENTIALS

Current condition

The model outcomes show that the maximum supply period of a PDR measure is 45 minutes (or 3 PTUs). For a 1 PTU measure, TSIJ can provide 25 MW/PTU capacity with an availability rate of 97 %. When increasing the supply period to 30-minute (2 PTUs), the capacity that can be provided drops to 10 MW/PTU with availability rate of 95 % (see Figure 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. 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 Figure 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 Figure 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 conducted 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

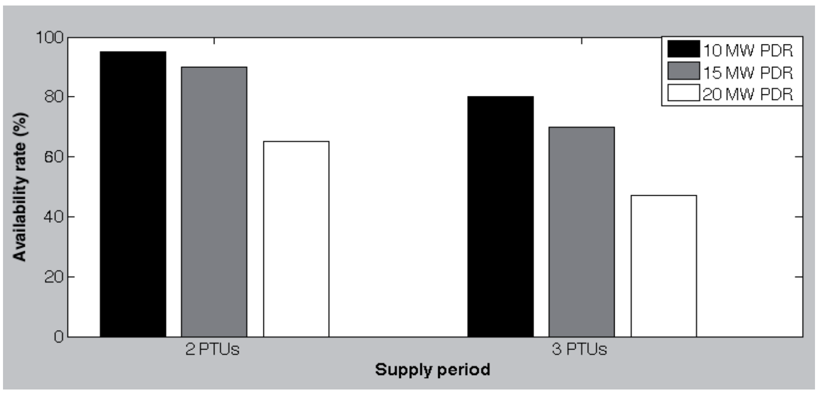

Figure 2. Availability rates for PDR measures of 10 MW/PTU, 15 MW/PTU, 20 MW/PTU with supply period of 2 PTUs and 3 PTUs.

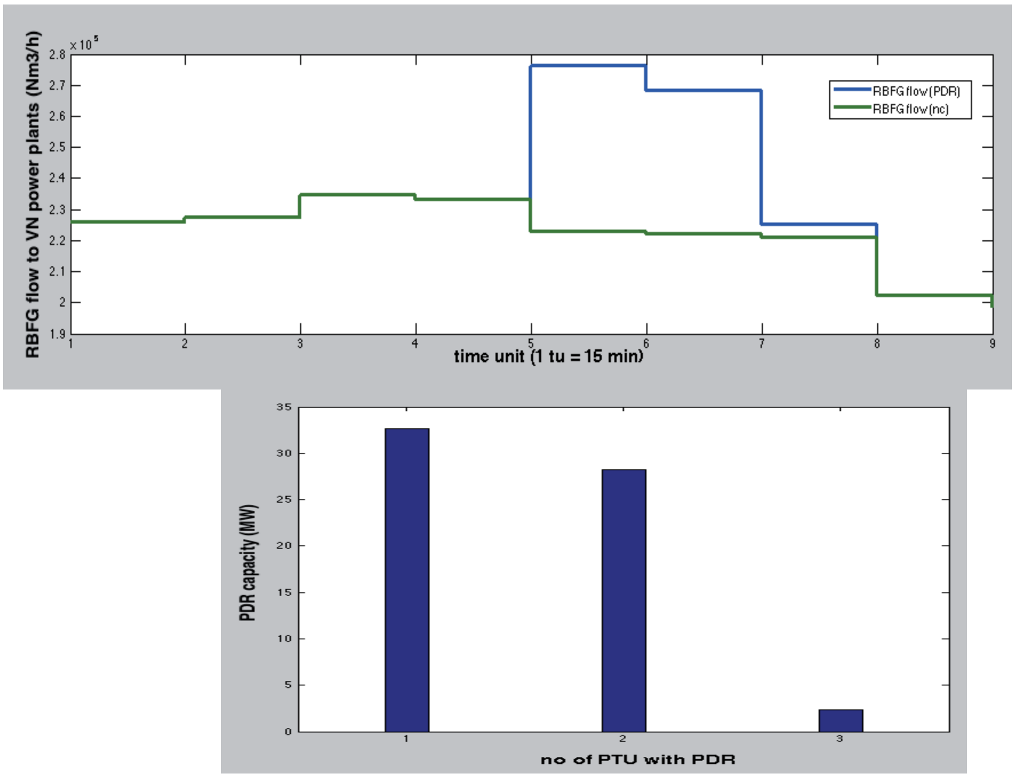

Figure 3. RBFG flow rates to VN24 and VN25 power plants (graph in the upper part) and the PDR potentials (graph in the lower part) for a PDR measure lasting 45 minutes (21 Sep 2013, 21:00–21:45).

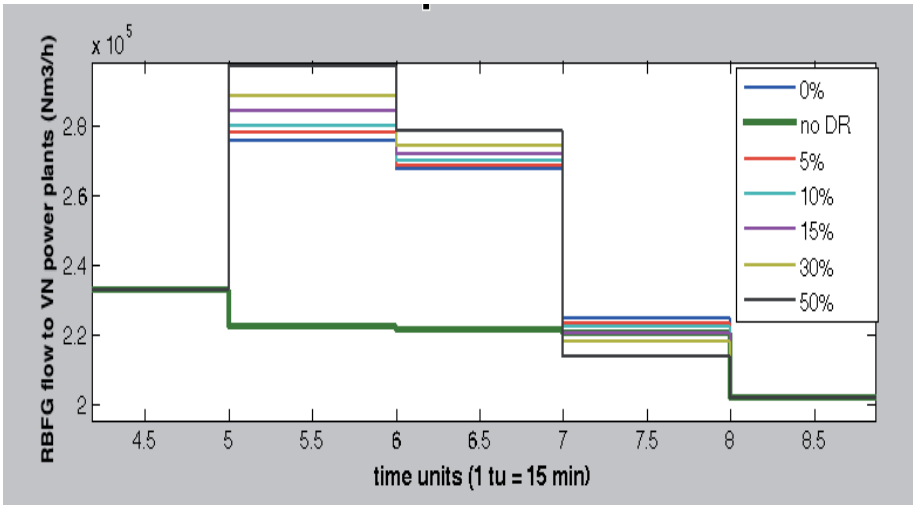

Figure 4. Change in the RBFG flow rate to the power plants as the flexibility of the power plants increases from 0 % (current power plant flexibility) to 50 %. "No DR" stands for a RBFG flow rate under normal operational conditions (in case of no call for demand response).

from 47 % to 73 %. The increases mainly occur in the first and second PTU 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 3rd PTU as the binding constraint is mainly the WAG available in the buffer to support the measure. This effect is demonstrated in Figure 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 hour and 15 minutes (5 PTUs). The average NDR 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 Δt, 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 Figure 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 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. However, as the supply period increases there is a longer time period for the electricity generation to stabilize before it has to ramp up. 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. Thus, in this case the binding constraint is the gasholder capacity.

Future potentials

As previously discussed, the power plant ramp rate is a binding constraint for NDR measures with supply period of ≤3 PYUs. Figure 6 shows that a 20 % increase in the gas holder does not influence the NDR potential of a 2 PTU measure (Figure 6 – upper part), whereas it leads to 10 MW/PTU NDR capacity measures of 5 PTUs (Figure 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 increases by 50 % (see Figure 7). Similarly, for a NDR measure with supply period of 3 PTUs, the availability rate increases from 52 % to 82 % (see Figure 7). In case of the 3 PTU measure, power plant ramp rate

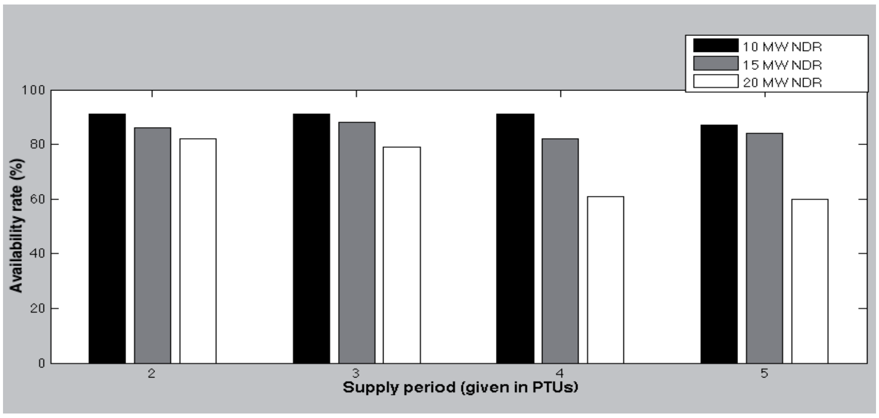

Figure 5. Availability rate of 10 MW/PTU, 15 MW/PTU and 20 MW/PTU NDR measures with supply periods ranging between 2 and 5 PTUs.

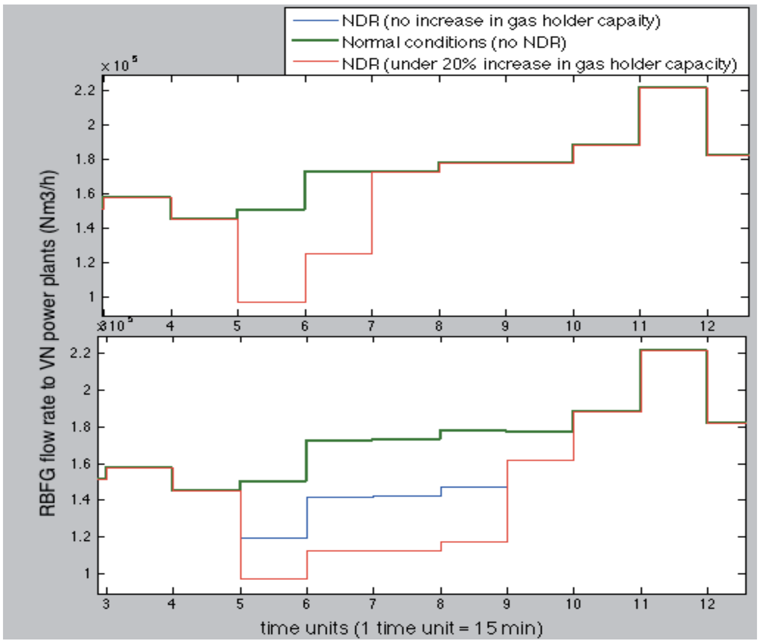

Figure 6. NDR potential for measures with supply period of 2 PTU (upper figure) and 5 PTU (lower figure) when increasing the gasholder capacity by 20 %.

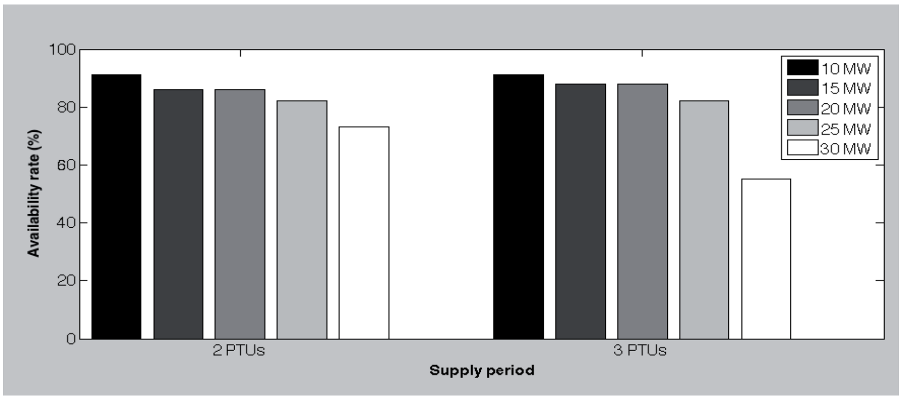

Figure 7. Availability rate of 10 MW/PTU, 15 MW/PTU, 20 MW/PTU, 25 MW/PTU and 30 MW/PTU NDR measures with supply periods of 2 and 3 PTUs under a 50 % increase in power plant flexibility.

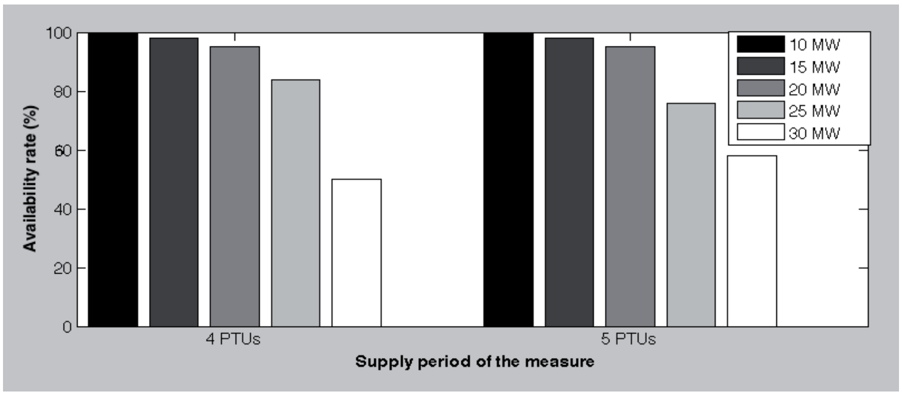

Figure 8. Availability rate of 10 MW/PTU, 15 MW/PTU, 20 MW/PTU, 25 MW/PTU and 30 MW/PTU NDR measures with supply periods of 4 and 5 PTUs under a 50 % increase in gas holder capacity.

increase affects mainly the first and last PTU 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 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 Figure 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 a 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 minutes. This does not fulfil the capacity requirement of 20 MW/PTU for emergency capacity programs 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 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 minutes. The latter would be sufficient for TSIJ to participate in emergency power programs as a stand-alone emergency capacity provider. On the other hand, if emergency capacity program requirements stay the same, TSIJ needs 50 % increase in its power plant flexibility in order to have 20 MW/PTU PDR capacity.

Another option is that Tata Steel makes use of the PDR potentials by 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. As of 2015, VEMW is offering 85 MW of PDR capacity supplied by 40 different companies ranging from hospitals to data-centres each offering a capacity between 500 and 3,000 kW (NL Noodvermogenpool, 2015). Pooling programs 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 TenneT 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 % leads to NDR capacity up to 25 MW/PTU for measures with supply period of 4 PTUs. Negative emergency programs have been only recently implemented in the Netherlands. Further analyses comparing the NDR capacity characteristics and capacity program 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 is found to be insufficient for participating in emergency demand response programs 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 cost are required (DENA, 2010). On the other hand, TSIJ can supply 10 MW/PTU for a supply period of 30 minutes with close to zero operational and investment costs. 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 and chlorine, are found to be between 260 MW and 685 MW (DENA, 2010). The PDR potentials that we obtained for TSIJ are substantially lower than these values. There can be various reasons for this such as: we looked into the technical potentials that are generally lower than the theoretical potentials, we evaluated the potentials of one DR measure and not the entire plant (e.g. “production process shut downs” were excluded).

The NDR of electricity intensive industries in Germany is assessed to be 32 MW with an availability rate of 97 % and supply period generally limited to 1 hour (DENA, 2010; Paulus & Borggrefe, 2009). For TSIJ we obtained 20 MW/PTU of NDR capacity for a supply period of 45 minutes with an availability rate ≥97 % which is substantially higher when compared to the theoretical potentials of the German industry.

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; Gils, 2014; Klobasa et al., 2009; Klobasa, 2009; Paulus & Borggrefe, 2011).
2. DR potentials through electricity demand planning based on electricity price (e.g. time of use programmes) (Ashok & Banerjee, 2000; Ashok, 2006; Bego, Li, & Sun, 2014; Fernandez, Li, & Sun, 2013; Hadera, Harjunkoski, Sand, Grossmann, & Engell, 2014; Lee & Reklaitis, 1995; Mignont & Hermia, 1996; Wang & Li, 2013).

These studies analyse the balancing capacity supplied by shutting down steel production processes mainly focus on the theoretical DR potential. The first group of calculate the DR potentials based on the electricity intensities of the processes while they are not taking into account how much of these potentials can actually be realized based on the technical constraints of the processes involved in the demand response measure. On the other hand, the linear optimization 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 concentrate on production planning based on electricity prices. The models developed as part of these set 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 part. 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 Vattenfall 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 different time slots. In order to increase the accuracy of the results the number of runs should be increased.

Conclusion

In this research, we have used linear optimization programming in order to evaluate the PDR and NDR potential of TSIJ. We need these estimates in order to analyse the feasibility of TSIJ to participate in electricity Emergency Capacity programs.

The study concludes that TSIJ can not 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 utilize its capacity while reducing the risk of failing to provide the DR capacity when required. This options is a 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 flexibility by 50 % is required in order 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 programs has to be evaluated in the future as NDR emergency programs 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, this research results give TenneT an insight into the demand response potentials of big electricity consumers such as TSIJ and the suitability of these potentials to the emergency capacities programs currently in place.

RECOMMENDATIONS FOR FUTURE RESEARCH

Regarding the future positioning of TSIJ in the balance market, 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.

Nomenclature

SETS

u	Units (power plants: VN24, VN25, IJMO1)
sp	boilers (K15, K16, K23, K24, K41, AK11) and TSIJ factories
t	Time step

VARIABLES

$GH_{k,t}$	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_t	Negative demand response capacity at time interval t (MW)
PDR_t	Positive demand response capacity at time interval t (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)
$c_{u,k,t}$	Average calorific value of WAG k flowing to unit u 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)

References

Ashok, S. (2006). Peak-load management in steel plants. *Applied Energy*, *83* (5), 413–424.

Ashok, S., & Banerjee, R. (2000). Load-management applications for the industrial sector, *66*, 105–111.

Bego, A., Li, L., & Sun, Z. (2014). Identification of reservation capacity in critical peak pricing electricity demand response program for sustainable manufacturing systems, (July 2013), 728–736. doi:10.1002/er.

Blom, M. J., Bles, M., Leguijt, C., & Rooijers, F. J. (2012). *Maatschappelijk kosten en baten van intelligente netten*. Delft.

Cappers, P., Goldman, C., & Kathan, D. (2010). Demand response in U.S. electricity markets: Empirical evidence. *Energy*, *35* (4), 1526–1535. doi:10.1016/j.energy.2009.06.029.

DENA. (2010). *Integration of renewable energy sources in the German power supply system from 2015–2020*. Berlin.

Doherty, R., & O'Malley, M. (2003). Quantifying reserve demands due to increasing wind power penetration. In *IEEE Bologna PowerTech – Conference Proceedings* (Vol. 2, pp. 59–63). doi:10.1109/PTC.2003.1304288.

ENTSOE. (2014). *ENTSO-E Network code on electricity balancing* (Vol. 6). Brussels.

Fernandez, M., Li, L., & Sun, Z. (2013). Just-for-Peak " buffer inventory for peak electricity demand reduction of manufacturing systems. *Intern. Journal of Production Economics*, *146* (1), 178–184. doi:10.1016/j.ijpe.2013.06.020.

Frunt, J. (2011). *Analysis of balancing requirements in future sustainable and reliable power systems*. Technical University of Eindhoven. Retrieved from http://alexandria.tue.nl/extra2/711271.pdf.

Gils, H. C. (2014). Assessment of the theoretical demand response potential in Europe. *Energy*, *67*, 1–18.

Hadera, H., Harjunkoski, I., Sand, G., Grossmann, I. ., & Engell, S. (2014). Optimization of steel production scheduling with complex time-sensitive electricity cost. *Computers and Chemical Engineering*. doi:10.1016/j.compchemeng.2015.02.004.

Holttinen, H., Milligan, M., Ela, E., Menemenlis, N., Dobschinski, J., Rawn, B., … Detlefsen, N. K. (2012). Methodologies to determine operating reserves due to increased wind power. *IEEE Transactions on Sustainable Energy*, *3* (4), 713–723. doi:10.1109/TSTE.2012.2208207.

International Energy Agency. (2013). *Implementing agreement on demand-side management technologies and programmes: 2012 annual report*. Stockholm. Retrieved from http://www.ieadsm.org/Files/Exco File Library/Annual Reports/2012_Annual_Report.pdf.

International Energy Agency. (2014a). IEA DSM. Retrieved November 5, 2014, from http://www.ieadsm.org/Publications.aspx?ID=18.

International Energy Agency. (2014b). *World Energy Outlook 2014*. Paris.

Klobasa, M. (2009). *Dynamische Simulation eines Lastmanagements und Integration von Windenergie in ein Elektrizitätsnetz*. Fraunhofer IRB.

Klobasa, M., Erge, T., & Wille-haussmann, B. (2009). *Integration von Windenergie in ein zukünftiges Energie- system unterstützt durch Lastmanagement*. Freiburg.

Kundur, P. (1994). *Power system stability and control*. New York: McGraw-Hill.

Lampropoulos, I., Member, S., Frunt, J., Nobel, F. A., Virag, A., Bosch, P. P. J. Van Den, & Kling, W. L. (2012). Analysis of the market-based service provision for operating reserves in the Netherlands. In *European Energy Market (EEM), 9th International Conference on the IEEE* (pp. 1–8).

Lee, B., & Reklaitis, G. V. (1995). Optimal scheduling of cyclic batch processes for heat integration—I. Basic formulation. *Computers & Chemical Engineering*, *19* (8), 883–905. doi:10.1016/0098-1354(94)00091-2.

Mignont, D., & Hermia, J. (1996). Peak utility load reduction in batch processes operated periodically and under uncertainty. *Computers & Chemical Engineering*, *20* (3), 249–263. Retrieved from http://www.sciencedirect.com/science/article/pii/0098135495000410.

NL Noodvermogenpool. (2015). *Noodvermogen afregelend*. Amsterdam: VEMW.

Paulus, & Borggrefe, F. (2011). The potential of demand-side management in energy-intensive industries for electricity markets in Germany. *Applied Energy*, *88* (2), 432–441.

Paulus, M., & Borggrefe, F. (2009). Economic potential of demand side management in an industrialized country – the case of Germany. In *10th IAEE European conference, energy, policies and technologies for sustainable economies* (pp. 7–10). Vienna: 10th IAEE European Conference, Energy, Policies and Technologies for sustainable economies.

Pronk, P., van Rixel, B., Bakker, J., Deen, M., Rozendaal, T., Blok, H., & Speets, R. (2013). *ISOLDE for IJmuiden production gases and steam – Detailed functional design*. IJmuiden.

Thema Consultancy Group. (2014). *Demand response in the Nordic electricity market: Input to strategy on demand flexibility*. Copenhagen: Norden.

U.S. Department of Energy. (2006). *Benefits of demand response in electricity markets and recommendations for achieving them*. Retrieved from http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_Benefits_of_Demand_Response_in_Electricity_Markets_and_Recommendations_for_Achieving_Them_Report_to_Congress.pdf.

van Hout, M., Koutstaal, P., Ozdemir, O., & Seebregts, A. (2014). *Quantifying flexibility markets*. Petten. Retrieved from http://www.tennet.eu/nl/fileadmin/downloads/About_Tennet/Publications/Technical_Publications/TenneT_ECN_Quantifying_flexibility_markets.pdf.

Wang, Y., & Li, L. (2013). Time-of-use based electricity demand response for sustainable manufacturing systems. *Energy*, *63*, 233–244. doi:10.1016/j.energy.2013.10.011