National Physical Laboratory

NPL REPORT MS 19

# Carbon savings of demand side response of a UK energy aggregator

ENGTSENG LAU, VALERIE LIVINA

SEPTEMBER 2015

# Carbon savings of demand side response of a UK energy aggregator

EngTseng Lau, Valerie Livina
Mathematics and Modelling Group

ISSN 1754-2960

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW



Internally reviewed by Keith Lines
Approved on behalf of NPLML by Helen Murphy
(Group Leader of Mathematics and Modelling)

# Contents

# ABBREVIATIONS

**CCGT** Combined Cycle Gas Turbine

**CHP** Combined-Heat and Power

**DSR** Demand Side Response

**Non-BM** Non-Balancing Mchanism

**OCGT** Open Cycle Gas Turbine

**STOR** Short Term Operating Reserve

**TD** Transmission and distribution losses

# 1 INTRODUCTION

Short-Term Operating Reserve, STOR, is one of the Demand Side Response (DSR) programme that are being run by the National Grid in the UK. The purpose of STOR programme is to reduce the load on the energy system by means of various subsitution and reduction techniques. In particular, STOR allows its subscribed providers to generate substituting power. In the STOR programme we study carbon savings based on data obtained from a UK based response aggregator company. This company provides various types of intervention (using diesel generators, Combined–Heat and Power (CHP) and demand reduction (turn–down)) at times of peak demand. Whether such DSR produces carbon savings or not, depends on the used technologies, as well as the scale of the interventions.

# 2 SHORT TERM OPERATING RESERVE

The STOR market information and tender round results are available on the National Grid website (National Grid, 2014). In this study, we use data from the contracted STOR period within season 6.3–6.6 in order to match the timeline data provided by from a UK-based demand response aggregator. The total accepted MegaWatts (MWs) within the seasonal spans is available in National Grid (2013a). The contracted capacity is shown in Table 1.

| Season | Dates | Accepted MWs (Flexible+Committed) |
|---|---|---|
| 6.3 | 20/08/12–24/09/12 | 2821 |
| 6.4 | 24/09/12–29/10/12 | 2923 |
| 6.5 | 29/10/12–04/02/13 | 3530 |
| 6.6 | 04/02/13–01/04/13 | 3573 |

Table 1: Contracted STOR period with accepted capacity

The STOR data from Table 1 can be used to to estimate the energy generation and carbon emissions for the STOR programme.

According to National Grid (2013b), there are two main types of STOR providers: Balancing mechanism (BM) and Non-Balancing Mechanism (Non-BM). BM providers have large supplies that are connected directly to the GB Transmission System. The non-BM providers are represented by smaller providers connected to the lower voltage distribution networks. Both categories are often referred to as 'demand side providers'. In this report we estimate the carbon emissions of one Non-BM aggregator.

The aggregator combines smaller loads into STOR units of $\geq 3$ MW and presents the aggregated energy volume to National Grid. Fig. 1 shows the composition of STOR volume (aggregated vs. total STOR volume).

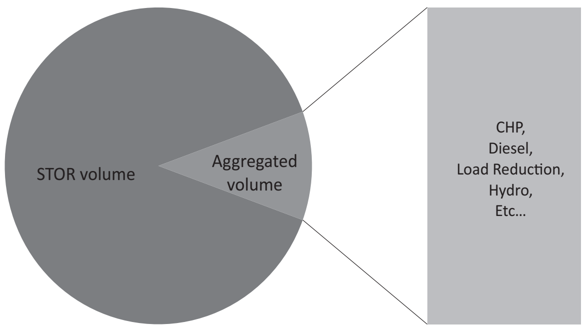


Figure 1: Composition of STOR volume (aggregated vs. total STOR volume).

# 3 CARBON EMISSION AND SAVINGS

We apply the methodology from references DEFRA (2013); Lau et al. (2014a, submitted) to quantify the amount of carbon emission and the associated savings for DSR programs.

The carbon emissions resulting from energy generated/consumed is formulated as:

$$\mathscr{E} = \sum_{t=1}^{N_t} E(t) \times G_{UK}(t) \tag{1}$$

where $\mathscr{E}$ denotes carbon emissions (tonnes$CO_2$), $E(t)$ is the amount of energy generated/consumed (kWh) and $G_{UK}(t)$ is the variable electricity grid carbon factor from the UK grid (tonnes$CO_2$/kWh), $N_t$ is the total number of time steps.

The carbon factors for electricity generation and consumption are parameters estimated using the Life Cycle Assessment (Royal Society of Chemistry, 2010) and measured in units of equivalent carbon dioxide mass (tonnes$CO_2$) per unit of energy (kWh). Calculation of national carbon footprints in the UK is performed by Ricardo-AEA (2014). For the energy consumptions for the UK energy grid, we calculate carbon factors that are dynamically derived from the fuel mix from Lau et al. (2014b, submitted) individually for the date and time of occurence of each event. Monte Carlo simulations are used for quantifying the uncertainties.

Carbon savings $S$ are determined as the difference between the business-as-usual $\mathscr{E}_B$ and those in the optimised/improved intervention $\mathscr{E}_O$ carbon emissions:

$$S = \mathscr{E}_B - \mathscr{E}_O \tag{2}$$

We calculate the half-hourly electricity grid variable carbon factor using the available fuel mix data from Elexon (Balancing Mechanism Reporting Systems, 2014). The transmission and distribution losses (TD) reported as 7.7 % by Digest of United Kingdom Energy Statistics (DUKES, 2013) are included in this report for further estimations. Uncertainty estimation is performed for those individual fuels used in electricity generation in particular power plants, using publicly available national average data. The resulting plot of the variable carbon factor is shown in Fig. 2, with error bars for standard error of mean values of the grid carbon factor.

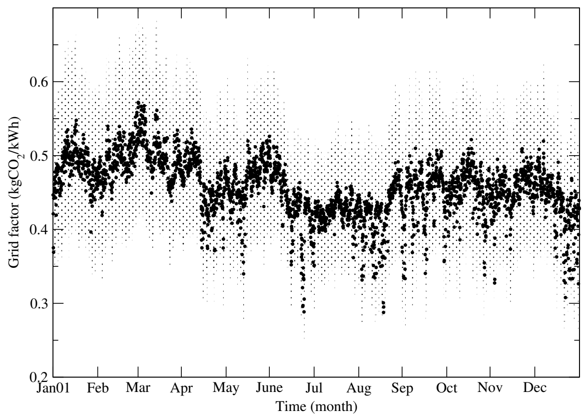


Figure 2: Electricity grid carbon factor (kg$CO_2$/kWh) with uncertainties for 2013.

# 4 INTERVENTION MECHANISMS

Types of demand responses considered are: 1) turning down on-site appliances; 2) using stand-by/backup generators; 3) CHP installations. The Generator/CHP demand response type replaces the National Grid energy volume by on-site generation. Therefore, the site still uses the same amount of energy, but reduces the amount taken from the grid. On the other hand, the turndown demand response type means the national grid energy volume was not replaced, i.e., energy consumption was reduced (the site used less energy than normal during this period).

### 4.1 DEMAND TURN DOWN

This intervention implies switch-off appliances, thus there are no additional emissions caused by the intervention. In order to compute carbon savings, we multiply the electricity grid carbon factor $G_{UK}(t)$ by the volume reduction for the entire demand turn-down category. $G_{UK}(t)$ is being calculated individually for the date and time of each event.

This demand response results in direct carbon savings due to reduced volume of overall energy consumption. The formula for the calculation of carbon savings for the 'Turndown' response is

$$S_T = \sum_{t=1}^{N_t} E_T(t) \times G_{UK}(t) \tag{3}$$

where $S_T$ is the carbon savings due to the 'Turndown' response, $E_T(t)$ is the amount of energy reduced, $G_{UK}(t)$ is the variable UK electricity grid carbon factor based on the estimations from Fig. 2, $N_t$ is the total number of time steps of the DSR programme.

### 4.2 CHP

CHP systems generate heat and energy simultaneously in a single process DECC (2014). They can achieve overall efficiency as high as 80 % DECC (2014). The amount of carbon savings against all fuels for CHP is available in the DUKES documentation DUKES (2012, 2013). Table 2 shows the amount of carbon savings due to installed good performance of CHP per unit kWh of energy.

| Year | CHP operating hours per annual (hrs) | Carbon savings against all fuels ($kgCO_2$/kWh) (including renewable and non-renewable) |
|---|---|---|
| 2011 | 4450 | 0.339 |
| 2012 | 3807 | 0.412 |

Table 2: Carbon factor for modern CHP per unit of energy, kWh. Source: DUKES (2012, 2013)

The carbon savings given in Table 2 are based on estimation of fuel mix and are subject to annual revision (DUKES, 2012, 2013). For every unit of energy produced by a CHP plant, the carbon emissions (and other associated GHG emissions) are less than half of a conventional coal-fired plant. For instance, since the carbon factor for coal per kWh of electricity generated is approximated as 0.80-1.00 kg (DUKES, 2012; Moomaw et al., 2012; Tzimas et al., 2007) the carbon factor for a standard CHP system can be projected as 0.35–0.45 $kgCO_2$/kWh. Such estimations are similar to the carbon factor values shown in Table 2. For a detailed methodology in calculating the fuel and carbon emissions for CHP systems, see the paper by Hedman and Hampson (2011).

Similar to the turndown response, direct carbon savings in the CHP response are achieved as a result of the reduced volume of overall energy consumption. The formula for the calculation of carbon savings for CHP response is

$$S_C = \sum_{t=1}^{N_t} E_C(t) \times G_C(t) \tag{4}$$

where $E_C(t)$ is the amount of energy generated by CHP, $G_C(t)$ is the carbon factor for CHP, $N_t$ is the total number of time steps.

Uncertainties are estimated by Monte Carlo simulations with dynamic carbon factors in corresponding time intervals.

### 4.3 DIESEL GENERATORS

We estimate the reduction of carbon emissions resulting from the use of generators (diesel-fuel powered) as compared with a reserve power plant based on the balancing mechanism controlled by National Grid. The carbon emissions of diesel generators are compared with open cycled gas turbine (OCGT) and combined cycled gas turbine (CCGT) plant. Similar to Eq. (2), carbon savings based on generators are determined as the difference between the business-as-usual operation of both CCGT/OCGT providers in STOR volume and the diesel generation carbon emissions:

$$S^i = \mathscr{E}_B^i - \mathscr{E}_D \tag{5}$$

where $S^i$ is the carbon savings due to generator response in the case of CCGT/OCGT, $\mathscr{E}_B^i$ is the business-as-usual carbon emissions by CCGT/OCGT, $\mathscr{E}_D$ is the carbon emissions based on the intervention by diesel generators, $i$ indexes the OCGT and CCGT plant.

In order to determine the amount of $\mathscr{E}_B^i$ and $\mathscr{E}_D$, it is necessary to study the profiles of plants and generators throughout the operation of STOR program, taking into account specific time intervals of the STOR event. The carbon emissions of plants and generators are compared, with operational assumptions of firing up, efficiency, and corresponding energy generation.

#### 4.3.1 CCGT PLANT–OPERATIONAL PROFILE

A CCGT plant must be warmed up to reach the base load level as necessary to operate in a stable condition (above 55 % of the load) before it can generate energy (Environmental Agency, 2011). We assume that the CCGT plant will always operate at part-load level (50 percent to provide the right source of plant margin in order to maintain the security of energy supply (Flexitricity, 2013). In this case, multiple part-loaded fleets of a CCGT plant are employed to generate the same amount of energy as the diesel generator. This is in accordance with the need to provide balancing services of the electricity supply across the network, in order to mitigate the risks of power station failures, demand rises, and failure of renewable generation due to seasonal variations (Flexitricity, 2013).

It is stated in the regulation of electricity supply that plant margin of at least 20 % is strictly needed in mitigating the risk of power failures (National Grid, 2011). More details on plant margins are available in Flexitricity (2013); National Grid (2011).

As the CCGT plant is assumed to operate at 50 % part loaded, there will be a short term increase in fuel consumption (15–20 %) during the operations and also the increase in fuel consumption at different part-loading points, thus increasing the carbon emissions. Table 3 shows the percentage increase of fuel consumption for CCGT plants at different part-loads.

| Part load point ( %) | Percentage increase in fuel consumption ( %) |
|---|---|
| 25 | 79 |
| 50 | 20 |
| 75 | 10 |

Table 3: Percentage increase of fuel consumption at various loads for CCGT plants. Adapted from Flexitricity (2013)

Due to the inflexibility of instantaneous energy generation in responding to unpredictable energy demand, CCGT plants are therefore advised to operate at part-load level. Before generating energy, CCGT plants need to be in standby mode ('hot-standby mode' in this case) awaiting the despatching instruction by National Grid. It is normal that CCGT plants undergo a complete warm-up process but may not actually be needed (Flexitricity, 2013).

**Warm-up.** A conventional CCGT plant burns additional fuel for few hours throughout the warm-up period before it is capable of generating electricity. The long period of warming up is mainly due to the requirement for sequential loading of gas and steam turbine for hours before achieving the base load level (see Environmental Agency (2011) for a detailed explanation of warming up principles for conventional CCGT plants). For part-load operation we assume the warm-up duration of a CCGT plant is approximately 35 minutes (excluding the standby period when awaiting despatch instructions from National Grid). Due to the requirement of sequentially warming up a CCGT plant at different part loading points, such plants will introduce additional fuel consumptions as shown in Table 3.

**Operation.** The CCGT plant will generate the required level of energy as soon as all warming up sequences have been completed. Due to the requirement of at least 20 % plant margin, the CCGT plant is assumed to operate at 50 % capacity (multiple part-loaded CCGT fleets will generate the required level of energy) throughout the STOR event for the purpose of this study. This results an in additional 15-20 % increase of fuel consumption and carbon emissions as shown in Table 3.

**Shutdown.** The shutdown time for a CCGT plant is the interval from the initiation of shutdown starting at base load (approximately 50 %) to the 'flame-off' signal of the gas turbine (Baling, 2011). CCGT plants burn negligible emissions at standstill following the complete shutdown sequence (Baling, 2011). On the other hand, CCGT plants can 'park' at certain part-load levels instead of a complete shutdown (with additional emissions as a result). However, before the flame-off and the complete shutdown of a CCGT plant, the gas turbine rapidly de-loads. During the de-load sequence, the combustion system reverts to start-up mode with an associated short-term increase of carbon emissions (Environmental Agency, 2011). We assume there is a short-term increase of carbon emissions about 8–10 % before the CCGT plant shuts completely after the flame-off phase.

### 4.3.2 OCGT–OPERATIONAL PROFILE

In order to deal with the increased uncertainty of the energy system (for instance, wind generation intermittency and consumer demand) within short time intervals, National Grid allocates a large number of peaking power plants, especially OCGT plants in providing the standing reserve energy supply (Manchester Centre For Electrical Energy, 2004; National Grid, 2013b). OCGT plants are very flexible in providing standing reserve and often referred to as 'peaking plants' due to the higher efficiencies when operating at different part-loads and shorter duration of start-up time (Manchester Centre For Electrical Energy, 2004; Wärtsilä, 2012).

**Warm-up.** We assume that the OCGT plant will always operate at above 50 % load in order to avoid the increase of emissions concentration (Macak, 2001) and also to operate in a stable condition before it can generate energy. There will be a short–term increase in fuel consumption at different part–loading points during the start–up sequence, thus increasing the carbon emissions. Table 4 shows the percentage increase of carbon emissions for OCGT plants at different part-loads.

| Part-load point ( %) | Percentage increase in $CO_2$ emissions ( %) |
|---|---|
| Idle | 100.00 |
| 20 | 35.22 |
| 40 | 17.88 |
| 60 | 7.32 |
| 80 | 5.14 |
| Base–load | 6.70 |

Table 4: Percentage increase of $CO_2$ emissions at various part-loads for OCGT plants. Adapted from Macak (2001)

The OCGT profile is obtained from Macak (2001). Initially, the emissions corresponding to different part-loads are specified as carbon monoxide (CO) equivalent. To convert from CO to $CO_2$ we consider the ratio of their atomic weights. The atomic weights of carbon, CO and $CO_2$ are 12, 28 and 44 atomic mass units respectively. Therefore 1 tonne of carbon equates to $1\times44/12\approx3.67$ tonnes $CO_2$. The ordinary CO emissions at different part-loads analysed by Macak (2001) is further adapted in this study by converting CO into $CO_2$ equivalent emissions in terms of percentage scale at different part-loads.

One can see that carbon emissions performance improves as load increases (Table 4). In our approach we follow the method of Macak (2001) by considering a nominal 80 MW OCGT unit with dry and low

NOx combustors (several units are combined together to provide a required level of STOR capacity in this study). The configuration of OCGT adapted from Macak (2001) is compatible to most of OCGT plants installed in the UK.

An OCGT plant has a relatively fast start-up time and has the ability to reach full load in 10 or 30 minutes (Macak, 2001; Petzer and Burger, 2007; Riihimaki, 2012). We assume that the duration from start-up to full load for an OCGT plant is approximately 20 minutes.

**Operation.** The OCGT plant will generate the required level of energy as soon as the start-up sequence is complete. For the purposes of this study the OCGT plant is assumed to operate at base-load capacity throughout the DSR operations. This assumption introduces an additional 6.7 % increase of fuel consumption and the resultant carbon emissions as shown in Table 4.

**Shutdown.** The shutdown sequence of an OCGT plant can be achieved within 10 minutes (Macak, 2001). This sequence enables almost instant shutdown of OCGT plants. According to Macak (2001), the emissions during the shutdown sequences are not taken into account and the assessment of air quality is performed from the start-up sequence to base-load operations only. In this study, the amount of carbon emissions for the entire shutdown sequence of an OCGT plant is calculated. We assume there is a short-term increase in carbon emissions before the OCGT plant shuts completely. This assumption is based on different load operating conditions.

#### 4.3.3 DIESEL GENERATOR–OPERATIONAL PROFILE

Most diesel generators burn no fuel when waiting for peak demand or system failure (Flexitricity, 2013). Diesel generators have the ability to warm up and shut down very rapidly within 1-2 minutes (Independent Project Analysis Consulting, Econnect Ltd and Martin Energy, 2006). Due to the rapid response of diesel generators, they are very important in providing flexible reserve and contingency services. This is because most of the power plants, especially wind and solar, are unable to respond to sudden demand peaks, and hence are allowed to operate at part-load level only. However, most of diesel generators are small, have low efficiency (35 %) and use heavily emitting fuel. These factors mean that multiple diesel generators are required to generate the same amount of energy as one large-scale plant. Therefore, it is necessary to quantify the carbon footprint of the generators running on fossil fuels.

#### 4.3.4 UNCERTAINTY ESTIMATION

According to JCGM_100:2008 (2008) (the 'Guide to the expression of uncertainty in measurement (GUM)' methodology), when the standard uncertainty (denoted as $\sigma$ with a corresponding index) of the measurement is obtained from the values of other quantities, they are combined into a standard uncertainty $\sigma_c$ as the square root of the sum of variances corresponding to different measurements. Thus, the combined standard uncertainty $\sigma_c$ in the case of generator response is obtained as

$$\sigma_c = \sqrt{\sum_{i=1}^{3} \sigma_i^2} \tag{6}$$

where $\sigma_i$ is the standard error of carbon emissions of the OCGT, CCGT and diesel generators of a particular event (warm up, STOR operation, and shutdown). The combined estimate of the total carbon savings $x_c$ is the sum of the carbon savings for the entire STOR event. We calculate $x_c \pm \sigma_c$ and summarise the findings in the results section.

## 5 TRANSMISSION AND DISTRIBUTION LOSSES

Since CHP and diesel generator are employed to provide energy for STOR program, direct emissions are produced. As such interventions do not suffer from the TD losses, such interventions may improve the overall carbon emission levels. However, because in some cases the emissions from the intervention programs exceed emissions from the default grid energy consumption, obtained carbon savings values may be negative, which indicates that actual savings are not achieved; such intervention may introduce additional emissions.

# 6 STOR PROGRAM MODELLING METHODOLOGY

Based on Fig. 1, the three types of interventions (turn down, CHP and diesel generation) are the Non-BM contributors in the STOR programme. For turndown and CHP response, the carbon savings can be directly determined based on Eqs. (3) and (4) .

For generator response, we assume if there were no existing STOR programme, National Grid would call conventional plants (OCGT and CCGT plants) to contribute the total capacity of STOR. The demand response aggregator used in this report substitutes a proportional part of this capacity by generating 402.03 MWh (diesel fueled) within season 6.3–6.6. This allows the estimation of carbon emissions and savings from the replacement of conventional plants that do not operate by diesel generators of the aggregator in the same scale of generation.

The ratio of the aggregator's diesel generation capacity to the full STOR capacity of CCGT/OCGT is:

$$k' \approx \frac{D_a}{G_s} \tag{7}$$

where $k'$ is the aggregated CCGT/OCGT STOR volume as in the same scale generation with the aggregator $D_a$ is the aggregated volume of diesel generator by the aggregator, $G_s$ is the overall STOR volume contracted to OCGT and CCGT.

Through Eq. (7), we compare the emissions resulting from the CCGT/OCGT plant $\mathscr{E}_G^{k'}$ and diesel generators $\mathscr{E}_D^k$.

$$\mathscr{E}_G^{ik'} \sim \mathscr{E}_D^k \tag{8}$$

where subscript $k$ indicates the nominal amount of generation, $k'$ is the rescaled energy generation from Eq. (7), $i$ indexes the OCGT and CCGT plant.

From Eq. (5), as $\mathscr{E}_B^i$ is the business-as-usual carbon emissions by OCGT and CCGT plant, the augmented carbon savings resulting from diesel generation becomes

$$S^{ik} = \mathscr{E}_G^{ik'} - \mathscr{E}_D^k \tag{9}$$

where $\mathscr{E}_G^{ik'}$ indicates the business-as-usual carbon emissions by CCGT/OCGT plant, $\mathscr{E}_D^k$ is the carbon emissions resulting from diesel generators, $i$ indexes the OCGT and CCGT plant.

## 6.1 TECHNOLOGICAL PARAMETERS

Table 5 shows the characteristics of CCGT/OCGT plant and diesel generators participating in the STOR programme that are the prerequisite to modelling energy generation and the resulting carbon emissions in our model.

We calculate emissions for typical CCGT and OCGT plants and then emissions of diesel generators providing equivalent energy generation.

# 7 RESULTS

For the case of generator response, we model the period of STOR operation as 49.8 hours long. CCGT, OCGT and diesel generators will fire up a total of 56 times over the period (data from aggregator). We apply the method of least squares fitting based on the input data given in Tables 1 and 3 to 5 and then apply the dynamically derived parameters to determine the non-linear relationship between the load factor and carbon emissions level during the warm-up and shutdown sequences of the OCGT plant. Three

| Criteria | CCGT | OCGT | Diesel generator |
|---|---|---|---|
| Warm–up duration | 35 minutes (part load) | 20 minutes (full load) | 1 minute |
| Shutdown duration | $\leq$ one hour | 10 minutes | nil |
| Standby duration | 1–2 hours | nil | nil |
| Additional warm–up emissions | Yes, at different part loads | | nil |
| Additional operation emissions | 15–20 % at part-load | 6.70 % operating at nominal load | nil |
| Additonal shut down emissions | Yes, at different part loads | | nil |
| TD losses | 7.7 % | | nil |
| Efficiency | 52–60 % | 35–42 % (Lower heating value) | 35 % |
| Carbon intensity ($kgCO_2/kWh$) | 0.365–0.400 | 0.460–0.480 | 0.710 (at 35 % efficiency) |

Table 5: Characteristics of CCGT, OCGT and diesel generators

types of data (load factor, carbon emission level, and the resultant carbon emissions) are obtained in each warm-up and shutdown profile for the CCGT/OCGT plant.

Fig. 3 shows the plot of carbon emissions for an OCGT plant (including warm-up and shutdown). We model STOR operation over two hours in order to illustrate the clear trend of the OCGT profile per STOR event. The warm-up sequence is complete approximately in 20 minutes. After warm-up sequence the OCGT plant is assumed ready to generate energy until the end of STOR operation. The slight increase in carbon emissions during the STOR operation (from $20^{th}$ minute until 2.3 hours) is due to the nominal-load operation and TD losses. During the entire shutdown period, we assume that the OCGT plant will shut down within 10 minutes (note the sharp drop of carbon emissions at 2.3 hours).

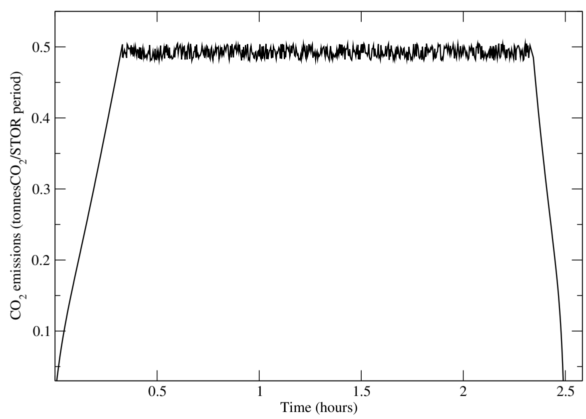


Figure 3: Carbon emissions of OCGT plant in a STOR period.

Fig. 4 shows the equivalent plot of carbon emissions for a CCGT plant with the same STOR operating period as the OCGT plant. The warm-up duration is approximately 35 minutes. During the STOR operation, there is an increase of fuel emissions due to part-load operation (an additional 15–20 % emission increase) and TD losses. During the entire shutdown period, the CCGT plant instantly de–loads from the base load (note the sharp drop of carbon emissions at 2.5 hours). The shutdown initiation starts as soon as the load is smaller than the base-load, until the flame-off signal. We assume that the CCGT plant will shut down completely instead of 'parking' at a certain load, and the plant would emit negligible emissions after the flame-off phase.

The detailed warm-up and shut down carbon emission profiles for OCGT and CCGT plants with respect to the distributions of different load factors and percentage increase of the carbon emissions are shown in Appendices A and B.

Due to the straightforward nature of the operation of diesel generators, the carbon emissions can be directly determined from the diesel generation data provided by the aggregator. Since carbon emissions for diesel generators $\mathscr{E}_D^k$ are defined as the product of the carbon factor and the energy generated, $\mathscr{E}_D^k$ is compared with the same scale generation by both OCGT and CCGT plants (denoted by $\mathscr{E}_G^{ik'}$) using Eq. (8). The carbon savings are later computed using Eq. (9).

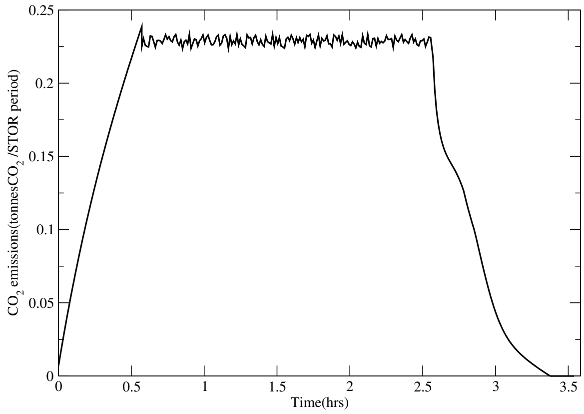


Figure 4: Carbon emissions of CCGT plant in a STOR period.

The carbon emissions for the OCGT and CCGT plants in comparison with diesel generators are shown in Tables 6 and 7 respectively. The total carbon savings in Tables 6 and 7 are obtained by estimation of carbon emissions during DSR interventions throughout the warm-up, STOR operation (56 STOR runs with a total of 49.8 hours of operation) and shutdown period of reserve plants. These emissions are compared with emissions of diesel generators. The total amount of saved carbon in the case of **CCGT** plants is 3.48±1.17 tonnes. Similarly, 5.43±0.59 tonnes of carbon is saved by substituting **OCGT** plant generation capacity with diesel generators. The carbon emissions are obtained assuming that the National Grid would call CCGT/OCGT plants to contribute the total capacity of STOR with the aggregator substitutes proportional part of total STOR capacity. Due to the specific operational conditions, CCGT/OCGT plant produces a higher amount of carbon emissions than diesel generators in this case.

The high carbon emissions by diesel generators during the STOR operation period are compensated for by operational conditions of the CCGT/OCGT plant (initiations of warm-up,stand-by and shutdown). Hence, diesel generation still produces carbon savings.

| | Warm up | Operation | Shut down | Overall $CO_2$ savings (tonnes$CO_2$) |
|---|---|---|---|---|
| CCGT | $13.01 \pm 0.36$ | $34.99 \pm 1.06$ | $9.47 \pm 0.26$ | |
| Diesel | $0.99 \pm 0.01$ | $53.00 \pm 0.23$ | 0 | |
| | $12.02 \pm 0.36$ | $-18.01 \pm 1.08$ | $9.47 \pm 0.26$ | $3.48 \pm 1.17$ |

Table 6: Carbon emissions and savings of diesel generators in comparison with an **CCGT** plant, based on 56 STOR runs with 49.8 hours of operations.

| | Warm up | Operation | Shut down | Overall $CO_2$ savings (tonnes$CO_2$) |
|---|---|---|---|---|
| OCGT | $11.74 \pm 0.12$ | $44.03 \pm 0.53$ | $3.65 \pm 0.04$ | |
| Diesel | $0.99 \pm 0.01$ | $53.00 \pm 0.23$ | 0 | |
| | $10.75 \pm 0.12$ | $-8.97 \pm 0.58$ | $3.65 \pm 0.04$ | $5.43 \pm 0.59$ |

Table 7: Carbon emissions and savings of diesel generators in comparison with an **OCGT** plant, based on 56 STOR runs with 49.8 hours of operations.

For the case of turndown and CHP response, carbon savings can be determined directly through Eqs. (3) and (4) respectively. Table 8 shows the amount of carbon savings for turndown, CHP and generator response.

| Demand response types | Electricity provided (MWh) | Event duration (hrs)* | Event frequency* | Carbon savings (tonnes$CO_2$) |
|---|---|---|---|---|
| Turn down | 61.09 | 47.38 | 40 | 12.66±2.29 |
| CHP | 11.50 | 5.08 | 4 | 5.38±0.27 |
| Diesel | 402.03 | 49.80 | 56 | 3.48±1.17** <br> 5.43±0.59*** |
| Overall $CO_2$ savings | | | | 26.95±2.65 |

Table 8: Carbon savings under turndown, CHP and generator (diesel) response. *–the duration is determined based on parallel despatching of STOR event instructions; **–based on the comparison with CCGT plant; ***–based on the comparison with OCGT plant.

# 8 CONCLUSION

We report carbon emissions and savings (tonnes$CO_2$) of the STOR programme based on data from a UK demand response aggregator company that utilises diesel generators, CHP and turn down methods.

As turndown response reduces actual energy use, direct carbon savings (12.66±2.29 tonnes$CO_2$) can be determined. On the other hand, due to the significantly lower value of carbon factor in CHP compared to generator, and to the slightly lower value compared to the grid carbon factor in CHP scenario carbon savings are achieved (5.38±0.27 tonnes$CO_2$).

CHP installations, with constantly improving technologies and increasing efficiency, have very good potential of increasing carbon savings and may become mainstream technology in the UK energy market. If well-optimised, several types of interventions combined together may lead to both energy usage optimisation and carbon savings, and this is where technology and control programs may provide the best results for industry and customers.

In this study we focus on estimation of carbon savings of diesel generator compared with CCGT/OCGT plants participating in the STOR event considering 49.8 hours of operation and 56 STOR runs. The analysis is based on the comparison between the full allocated STOR capacity for both CCGT/OCGT plant (business-as-usual) and substituted STOR volume by aggregators using diesel generators. We estimate a total amount of 5.43±0.59 and 3.48±1.17 tonnes$CO_2$ saved for the STOR event by substituting diesel generators proportionate to OCGT and CCGT plants respectively. Through the intervention by diesel generators, the high amount of emissions are compensated by operating conditions of CCGT/OCGT plants.

It can be argued that for high demand periods it is better to use greener yet stable fuel plants to balance the remaining amount of energy, and one of the known solutions is hydro-generation. However, some greener fuel plants (e.g. nuclear and CCGT plants) have limited flexibility in responding to sudden peak demands and subsequently may only operate at base load (Flexitricity, 2013). Therefore, the 'peaking' plant such as OCGT plants may provide reserve to compensate for the peak demand problems but may result in a high emissions, and here self-generation with diesel installations provides not only security of supply but also a reduction in carbon emissions.

Although diesel fuel is amongst the most polluting, the diesel generators in this particular DSR programme produce a substantial amount of carbon savings. However, such carbon savings may not be achieved if the capacity of diesel generators is beyond the threshold limit of the reserved capacity. Hence, diesel generators are efficient for both energy generation and carbon savings only during reserve/contingency periods (short runs) and are not advisable to operate continuously as compared with CCGT plants. In the normal mode of operation (where there is a steady demand), normal gas-fired plants (e.g. CCGT) are most efficient and least polluting.

At the moment, generators are the easiest DSR solution that helps provide the necessary return on investment. However, as the technology and knowledge for providing DSR improves through greater usage (for instance, optimised operating conditions of CCGT/OCGT plants, CHP installations and greater usage of turn down), the cost of investment will decrease. Further DSR innovations that enable more sustainable interventions are an important area of future research.

All estimations are given with the standard uncertainty $\sigma_c$ due to the variations of resultant carbon emissions at different load factors, carbon footprints due to fuel mixes of the electricity generation, and percentage increase of fuel consumption associated with the STOR program.

This study compares only the carbon emissions; no further assessment has been made regarding respective levels of other GHG polluting compounds and gases. Furthermore, some National Grid installations prioritize balancing cost and efficiency in supplying electrical energy to customers. Carbon emissions are considered as secondary priority, especially during the current economic crisis. We suggest that assessment of carbon emissions and savings should be taken into account in all DSR programmes, present anf forthcoming.

## ACKNOWLEDGEMENTS

The authors would like to thank Patrick Hynes (National Grid) for advice on technological cycles of the power plants used in the British energy industry, and Mitchell Curtis (University of Reading) for advice on demand responses in the UK.

## Bibliography

Balancing Mechanism Reporting Systems. BM reporting. http://www.bmreports.com, 2014. (accessed online on October 28th, 2014).

Baling, L. Fast cycling and rapid start-up: new generation of plants achieves impressive results. http://www.energy.siemens.com/hq/pool/hq/power-generation/power-plants/gas-fired-power-plants/combined-cycle-powerplants/Fast_cycling_and_rapid_start-up_US.pdf, 2011. (accessed online on April 30th, 2014).

DECC. CHP benefits. Available:http://chp.decc.gov.uk/cms/chp-benefits/?phpMyAdmin=ff232c1d3b302ac6e951f554eeeaefdf, 2014. (accessed online on July 14th, 2014).

DEFRA. Government GHG conversion factors for company reporting. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224437/pb13988-emission-factor-methodology-130719.pdf, 2013. (accessed online on October 1st, 2014).

DUKES. Chapter 7–combined heat and power. Technical Report ISBN 9780115155284, London: National Statistics, 2012. Published with the permission of the DECC on behalf of the Controller of Her Majesty's Stationery Office.

DUKES. Chapter 7–combined heat and power. Technical Report ISBN 9780115155284, London: National Statistics, 2013. Published with the permission of the DECC on behalf of the Controller of Her Majesty's Stationery Office.

Environmental Agency. TWG 5–principles for determining start up and shut down criteria for gas turbines. http://test.environment-agency.gov.uk/static/documents/Business/UKTWG5_Final_gas_SUSD.pdf, 2011. (accessed online on April 30th, 2014).

Flexitricity. The carbon costs of system balancing. http://www.flexitricity.com/docLibrary/30041-0420Carbon%20costs%20of%20system%20balancing%201-1.pdf, 2013. (accessed online on May 9th, 2014).

Hedman, B. A. and A. C. Hampson. Fuel and $CO_2$ emissions savings calculation methodology for combined heat and power (CHP) systems. *ASHRAE Transactions*, 117:961–973, 2011.

Independent Project Analysis Consulting, Econnect Ltd and Martin Energy. Reducing the cost of system intermittency using demand side control measures. http://www.ipaeconomics.com/publications/69441kel0003460000.pdf, 2006. (accessed online on September 30th, 2014).

JCGM_100:2008. Evaluation of measurement data - Guide to the expression of uncertainty in measurement (GUM). *Joint Committee for Guides in Metrology (JCGM)*, pages 1–116, 2008.

Lau, E. T., Q. Yang, A. B. Forbes, P. Wright, and V. N. Livina. Modelling carbon emissions in electric systems. *Energy Conversion and Management*, 80(59):573–581, April 2014a.

Lau, E. T., Q. Yang, G. A. Taylor, A. B. Forbes, P. Wright, and V. N. Livina. Optimisation of carbon emissions in smart grids. In *Proceedings of the 49th International Universities' Power Engineering Conference, UPEC*, pages 1–4, Cluj-Napoca, Romania, 2014b. IEEE. doi: 10.1109/UPEC.2014.6934796.

Lau, E. T., Q. Yang, G. A. Taylor, A. B. Forbes, P. Wright, and V. N. Livina. Carbon savings in smart interventions in electrical systems. *IEEE Transactions on Power Systems*, submitted.

Macak, J. J. Evaluation of gas turbine startup and shutdown emissions. In *Air and Waste Management Association Annual Conference Proceedings, Orlando, FL*, 2001.

Manchester Centre For Electrical Energy. The future value of storage in the UK with generator intermittency. http://webarchive.nationalarchives.gov.uk/20100919181607/http:/www.ensg.gov.uk/assets/dgdti00040.pdf, 2004. (accessed online on September 30th, 2014).

Moomaw, W., P. Burgherr, G. Heath, M. Lenzen, J. Nyboer, and A. Vbruggen. Annex ii: Methodology, 2012. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [Edenhofer O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. Stechow(eds)]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

National Grid. Chapter specific terminology–plant margin. http://www.nationalgrid.com/NR/rdonlyres/0580EB05-E883-4A72-8417-E199B84F1799/46997/NETSSYS2011AppendixI.pdf, 2011. (accessed online on April 30th, 2014).

National Grid. STOR market information report: Tender round 18. Technical report, National Grid PLC, 2013a.

National Grid. Short term operating reserve, fuel type analysis –Season 7.5 (28/10/13–03/02/14). Technical report, National Grid PLC, 2013b.

National Grid. Short term operating reserve. http://www2.nationalgrid.com/uk/services/balancing-services/reserve-services/short-term-operating-reserve/, 2014. (accessed online on September 29th, 2014).

Petzer, G. and L. Burger. Air quality assessment for the open cyclc gas turbine (OCGT) power plant's additional units in Mossel Bay. Technical Report APP/07/SHA-01 Rev 1.0, Airshed Planning Professionals (Pty) .Ltd, South Africa, 2007.

Ricardo-AEA. Ricardo-AEA: Home. http://www.ricardo-aea.com/cms/, 2014. (accessed online on October 28, 2014).

Riihimaki, V. Wärtsilä smart power generation. http://www.wartsila.com/file/Wartsila/en/1278526256147a1267106724867-DanskeBankSeminarRiihimaki2012.pdf, 2012. (accessed online on September 30th, 2014).

Royal Society of Chemistry. 2010-last update, note on life cycle assessment. http://www.rsc.org/images/LCA_20100215_tcm18-97943.pdf, 2010. (accessed online on June 11th, 2014).

Tzimas, E., A. Mercier, C. Cormos, and S. D. Peteves. Trade-off in emissions of acid gas pollutants and of carbon dioxide in fossil fuel power plants with carbon capture. *Energy Policy*, 35(8):3991–3998, 2007.

Wärtsilä. Ofgem's electricity SCR initial consultation - a response from Wa*rtsila* corporation: supporting modellingy. https://www.ofgem.gov.uk/ofgem-publications/40779/wartsila-ebscr-ic-response-3.pdf, 2012. (accessed online on September 30th, 2014).

# A CCGT OPERATIONAL PROFILE

**The warm up profile for CCGT plant**

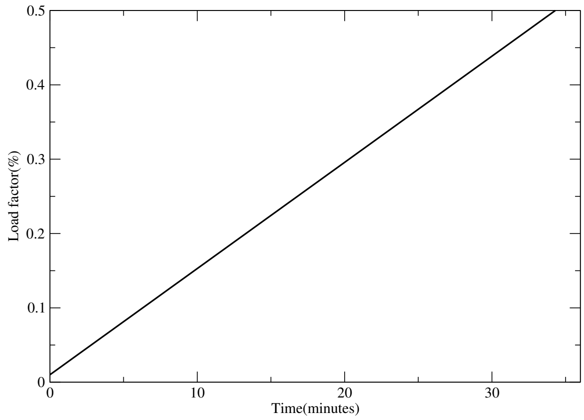


Figure 5: The load factor for CCGT plants for the warm-up period. The warm-up duration is 35 minutes.

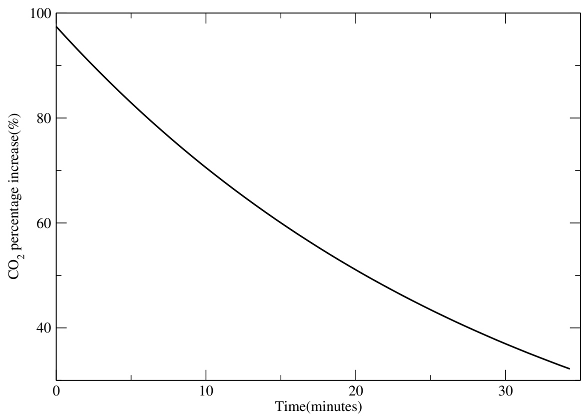


Figure 6: The percentage increase of carbon emissions during the warm-up period. The percentage increases of carbon emissions are dependent on different levels of load factors.

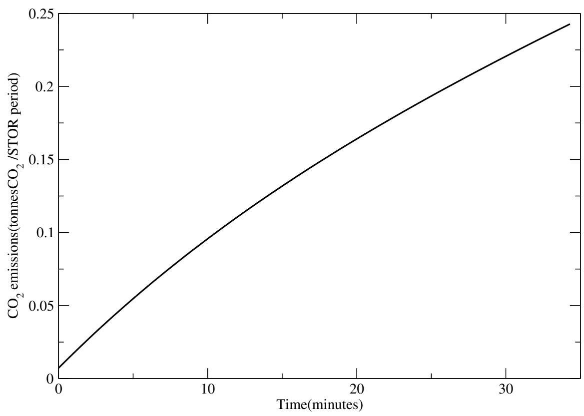


Figure 7: Carbon emissions for CCGT plants for the entire warm-up period.

**The shutdown profile for CCGT plant.**

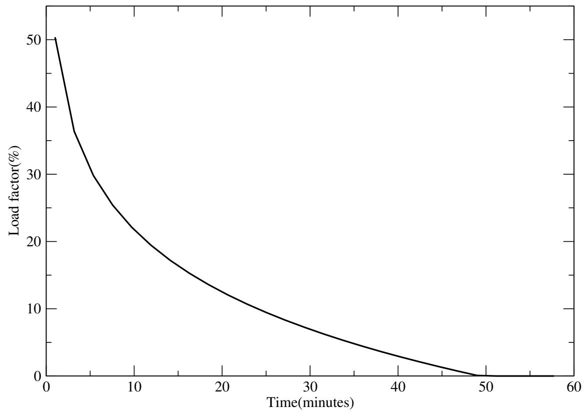


Figure 8: The load factor for CCGT plants for the shutdown period.

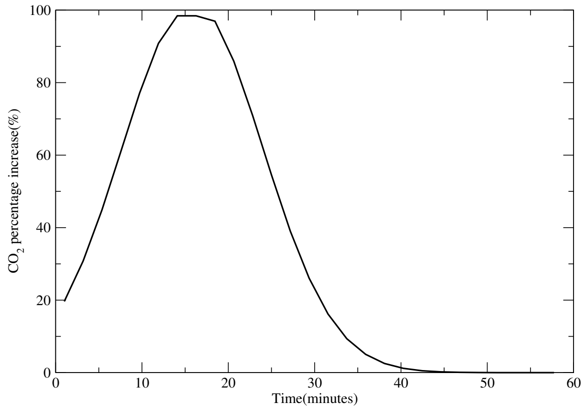


Figure 9: The percentage increase of carbon emissions for the shutdown period.

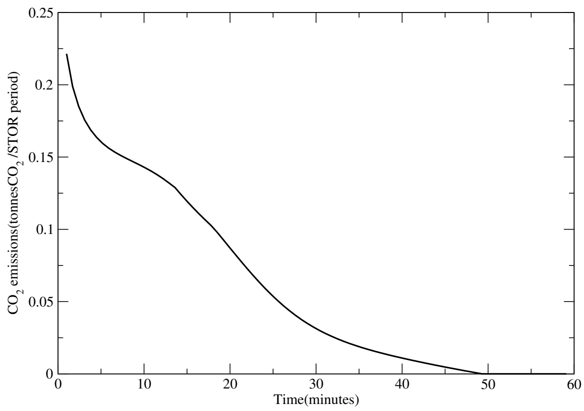


Figure 10: Carbon emissions for CCGT plants for the shutdown period. It is assumed that the CCGT plants will shut down completely instead of 'park' at certain loads. Hence the plants would emit negligible emissions after the flame-off phase (at 49th minute).

# B OCGT OPERATIONAL PROFILE

### The warm up profile for OCGT plant

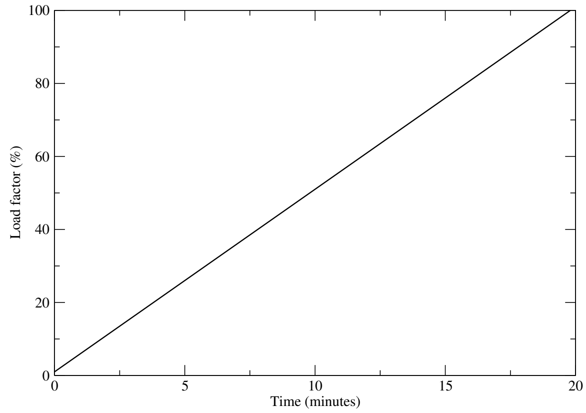


Figure 11: The load factor for OCGT plants for the warm-up period. The warm-up is complete at $20^{th}$ minute.

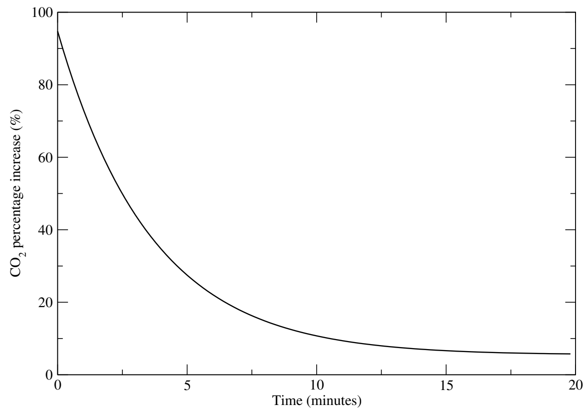


Figure 12: The percentage increase of carbon emissions during the warm-up period.

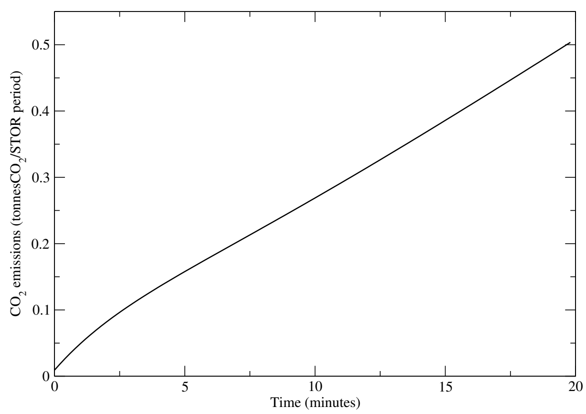


Figure 13: Carbon emissions for the entire warm-up period.

**The shutdown profile for OCGT plant.**

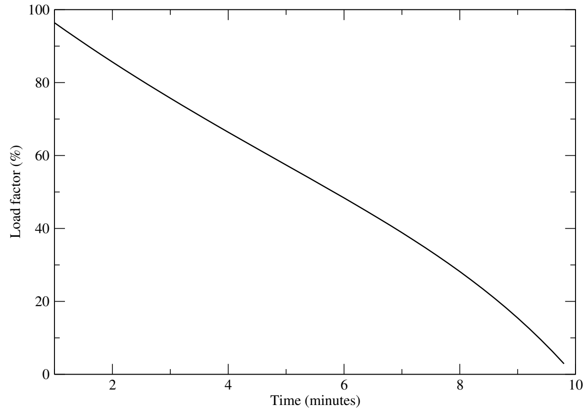


Figure 14: The load factor for OCGT plants for the shutdown period.

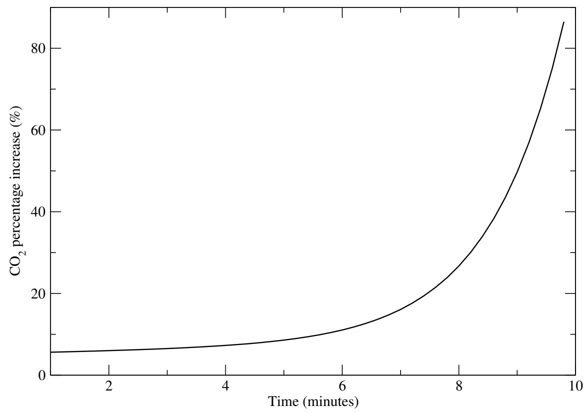


Figure 15: The percentage increase of carbon emissions for the shutdown period. The percentage increases of carbon emissions are dependent on different level of load factors.

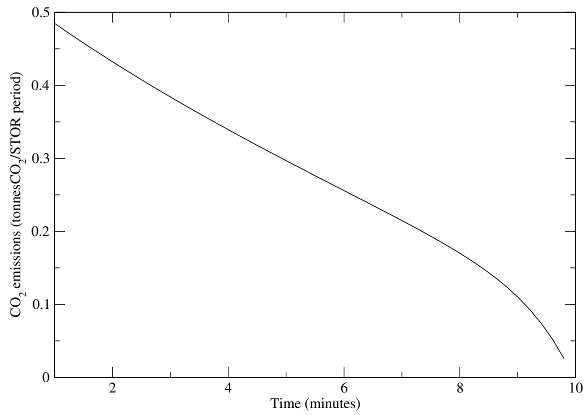


Figure 16: Carbon emissions for the shutdown period.