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Carbon savings in the UK demand side response programmes

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HIGHLIGHTS

- We model carbon emissions and savings in DSR programmes with Smart interventions.
- We consider STOR, Triad, Fast Reserve programmes, and Irish Smart Metering project.
- We model reserve energy generation by conventional OCGT and CCGT power plants.
- DSR interventions are diesel generators, hydro-pump storage, demand reduction and shift.
- Carbon savings are difference between business-as-usual and intervention emissions.

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ABSTRACT

We quantify carbon (CO_2) savings in the demand side response (DSR) programmes. We consider Short Term Operating Reserve (STOR), Triad, Fast Reserve and Smart Meter roll-out, with various types of smart interventions involved (using diesel generators, hydro-pumped generation and use of tariffs). We model CO_2 emissions in each of the DSR programmes with appropriate configurations and assumptions used in the energy industry. This enables us to compare carbon emissions between the business-as-usual (BAU) solutions and the smart intervention applied, thus deriving the carbon savings. Whether such DSR produces positive CO_2 savings or not depends on the used technologies, as well as the scale of the interventions, which we illustrate in examples.

1. Introduction

The UK national energy system experiences increasing demand and load on the infrastructure, as well as uncertainty in energy consumption (variable heating in colder seasons, addition of green generators without storage facilities, etc.). Because of their low cost and the possibility to postpone large-scale upgrades of the network infrastructure, DSR programmes have been receiving large attention in the context of reducing energy usage and costs [1,2]. According to U.S. DoE [3], DSR is defined as alterations in electric usage by consumers from the BAU consumption patterns in response to alterations in the price of electricity, or the incentive based schemes designed to force the lower electricity usage during high wholesale market prices or system stress. The DSR does not concentrate on power production side, rather DSR acts as an ancillary service in balancing the energy across the grid. Wang et al. [4] studied the role of DSR in mitigating electricity shortage in the current energy market in China. Boait et al. [5] proposed a novel DSR-based scheme that allows an aggregator to corroborate relationship between a consumer and the electricity market. A signal is provided to a 'Smart Home' control unit that manages electrical usage to address the consumer's needs and preferences. A similar concept is elaborated in the paper by Marwan et al. [6], where a DSR model is developed that aids the electrical consumers in managing air-conditioning during peak electricity demand. Consumers participating in the DSR programme developed by Marwan et al. [6] are exposed to the fluctuations of the market prices. The DSR model is simulated through numerical optimisation in finding the set of air-conditioning temperatures that satisfy the constraints and provide minimum energy costs. The DSR model has successfully forced consumers to shift energy and reduce costs when there is a potential of high electricity prices. Stözer et al. [7] used a novel DSR approach to analyse the load shifting potential in the residential and commercial sectors in Germany. The most recent paper by Ceseña et al. [8] presented a comprehensive techno-economic DSR

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Nomenclature

BAU	business-as-usual	GHG	greenhouse gases
BM	Balancing Mechanism	HH	half hourly
CCGT	combined cycle gas turbine	IHEM	in-home electricity monitor
CHP	combined heat and power	Non-BM	Non-Balancing Mechanism
CO	carbon monoxide	OCGT	open cycle gas turbine
CO_2	carbon dioxide	STOR	Short Term Operating Reserve
DSM	demand side management	TD	transmission and distribution
DSR	demand side response	TNUoS	Transmission Network Use of System
FFES-2	Ffestiniog plant fleet number two	ToU	time of use

methodology focusing on small (below 100 kW) residential and commercial end-users.

However, DSR implementation is still at rather low level. Main barriers are insufficient marketing strategies and low awareness of DSR in promoting energy and cost savings [4,9]. According to Palensky and Dietrich [1], Strbac [9], the specific challenges of the DSR implementation are the lack of interoperability, algorithm stability, metering, information security infrastructure, as well as high competition with traditional approaches, increase in the complexity of system operation and inappropriate market incentives. Case studies of DSR in 15 companies were investigated by Lindberg et al. [10] who showed very low implementation of DSR due to complications in reaching a stable production after a 'parking' state of power plants, and expensive and fixed price contracts for electricity in Sweden.

Although DSR programmes are widely promoted for their cost-effectiveness and greater energy system efficiency [see 11–15], only a few attempts to quantify related CO_2 emissions in DSR programmes were made. Cooper et al. [16] analysed the impact on the emissions of heat pumps and micro-cogenerators participating in DSR programmes. The results suggested that DSR programmes may enable the large deployment of heat-pumps and cause significant reduction in CO_2 emissions. It is important to note that this study was technology-specific and small-scale.

The assessment of CO_2 emissions in DSR programmes is very important in the context of environmental impact and identification of the preferable directions of development of technologies. While DSR programmes ensure the grid stability of the energy system, it is also necessary to remember that CO_2 emissions may be counter-intuitive when one compares BAU and smart interventions. At particular operational stages, balancing of energy demands may require 'peaking' of power plants, which may be highly polluting. However, the similarly polluting replacement solutions may still lead to CO_2 savings. Additionally, the use of green generations does not guarantee the stability and reduction of CO_2 emissions of the energy system due to its intermittency in generations.

It is important to meet not only energy requirements but also address the environmental targets. Following the European Union legislations on carbon (CO_2) emissions (the so-called "20-20-20 target", which requires 20% reduction of CO_2 emissions by 2020 [17]). The UK has committed to reducing CO_2 emissions by at least 15% across national industries.

In this paper, we model and quantify CO_2 emissions and savings under various DSR programmes with smart solutions that act as the ancillary service in the energy system. We apply the novel framework of assessment of CO_2 savings with modelling of operational profiles of reserve power stations. National Grid [18] and Ward et al. [19] bridged the DSR across the balancing services which range from STOR and Triad to Fast Reserve and demand management. In this paper, DSR programmes including STOR, Triad, Fast Reserve and use of tariffs (demand management) under the smart metering programme are modelled. The framework integrates the electrical energy data with corresponding DSR programmes, which in turn enable the assessment of CO_2 emissions and the associated savings. The novelty of the present study is the focus on short-term DSR interventions, which become increasingly used in the UK energy market because of the rapid response to peak demands. While the operational cycle of the common industrial power plants is well known, the adequate modelling of the carbon emissions for comparison with DSR interventions has not been introduced before. The merit of this modelling framework is strengthened by the increasing use of such DSR layouts in the UK energy market, and the present paper is based on the joint work with UK industrial partners who provided real data for the assessment. Therefore, the proposed approach combines rigorous modelling of the operational cycle of the power plants with realistic DSR interventions.

In principle, this framework may be implemented at the level of the UK National Grid (the transmission operator), the energy suppliers and distribution network operators. The framework allows the network operators develop an optimal operating strategy for greener control of DSR fleet usage in order to ensure environmental sustainability and minimal environmental impact in power systems.

The paper is organised as follows: Section 2 reviews DSR programmes. Section 3 defines CO_2 emissions and savings. Section 4 reviews the DSR interventions. Section 5 shows the formulation of CO_2 emissions and savings in DSR programmes. Section 6 presents the results of CO_2 emissions and savings in DSR programmes. Section 7 concludes.

2. Overview of DSR programmes

2.1. STOR

The STOR programme allows National Grid to balance power generation during the time of demand 'stress' (for instance, sudden generation losses, unpredictable changes in demand and intermittent renewable energy generation) [20,21]. National Grid allocates and utilises a number of reserve resources to cope with uncertainties in electrical demand, either through generation or demand reduction [21]. National Grid tenders for STOR twice a year and the reservations are procured at different availability windows in competitive tender rounds [20,21].

According to National Grid [21], there are two main STOR schemes: Balancing Mechanism (BM) and Non-Balancing Mechanism (Non-BM). BM participants have large enough supply of energy generation that can be connected directly to the UK Transmission System. On the other hand, the Non-BM participants are represented by smaller providers connected to the lower voltage

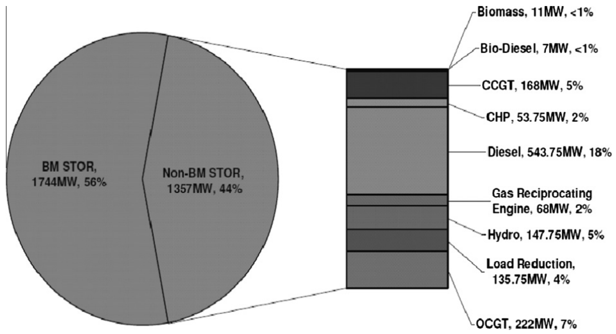

Fig. 1. Fuel type composition of Non-BM STOR providers. Adapted from National Grid [21].

distribution networks. Both categories are often referred to as "demand side providers". A Non-BM aggregator combines smaller loads into STOR units of ⩾3 MW and provides the aggregated energy volume to National Grid. Fig. 1 shows an example of fuel type composition of Non-BM STOR providers.

A STOR provider supplies National Grid with sufficient operating reserve for at least two hours in real time, and a large proportion of generating units are made available within 20 min with the minimum load reserving capacity of 3 MW [19,20,22] as a requirement. The STOR contracts vary according to different seasons. For instance, a total of 3101 MW of STOR contracts were accepted for the season 7.3 (19/08/2013–23/09/2013), and 3149 MW for the season 7.5 (28/10/2013–03/02/2014) [21,23]. As soon as the STOR instruction is received, a STOR provider will have the following options to run the DSR intervention: standby generation; load reduction; combined heat and power (CHP) generation.

However, it may happen that some STOR providers have insufficient amount of generation to meet the minimum STOR contract (⩾3 MW). In order to mitigate the limitations, there are several companies known as Aggregators that merge the smaller loads from participating companies (supermarkets, schools, universities and hospitals) into STOR units that are larger than 3 MW minimum STOR capacity. The aggregated volumes contribute to the overall proportion of STOR tendered for the particular availability window and presented to National Grid [21].

2.2. Triad

The Triad programme comprises three settlement periods of maximum energy demand within one financial year in winter (usually from November until the end of February), particularly in the evening periods. Determination of the Triad charges is achieved with the first Half-hourly (HH) system peak demand and the other two HHs of the next highest demand, which have to be different from the system peak demand and from each other by at least ten clear days [24]. The average of the three highest demand periods is used to calculate the Transmission Network Use of System (TNUoS) charges according to different zonal tariffs in the UK [25,26]. Unlike other energy balancing services available at National Grid, Triad charges are calculated when the Triad season is over, for the licensed suppliers of National Grid [19,24]. According to Ward et al. [19], the minimum load for reserving is 1 MW. The licensed suppliers subscribe for the Triad programme with forecasting the potential peak demand during the active periods. Triad warnings (or Triad avoidance) are sent to consumers that allow instant actions to be taken. According to Ward et al. [19], the action based on Triad warnings includes on-site standby generation and demand reduction. 10–40 Triad warnings can be issued annually, depending on the nature of forecasts by participating companies.

During the Triad period, generators (used for replacement of energy supply) will usually operate for an hour at winter peaks from 5 pm to 6 pm [19] – instead of drawing from the UK energy grid operated by reserve power plants controlled by National Grid that are switched off if Triad programme is running. It is cheaper to use in-house diesel generators for energy generation than purchase it from the UK energy grid (only due to the reduction in TNUoS charges seen as the result of hitting all three Triad peaks).

2.3. Fast Reserve

The Fast Reserve programme is the reserve service providing rapid and reliable delivery of active power through a range of demand changes from generation to demand reduction, following acceptance of an electronic despatch instruction from National Grid [20,27]. Fast Reserve service is highly important in responding to very rapid changes in demand at the same instant such as TV pick-ups, boiling water and watching a live event (sport event). Fast Reserve service can be triggered at any time of the year, and can be announced on a daily basis, particularly to accommodate the rapid rate of changes in demand [19]. Fast Reserve is procured by National Grid through a monthly contracted process with each contract containing technical information of power plants by the Fast Reserve provider [20,27].

In order to participate in the Fast Reserve service, a typical provider must be capable of despatching power delivery within two minutes following the instruction by National Grid, with the requirement of minimum run up and run down rates of 25 MW/min [19,20,27]. System documentation [19,20,27] states that supply of energy for Fast Reserve should be sustainable for at least 15 min. Similarly to STOR, a Fast Reserve provider should supply a minimum of 50 MW, or can be aggregated by merging smaller units to achieve the total volume of minimum 50 MW [27]. Pump-based storage for electrical generation is the most common technology in the Fast Reserve service.

2.4. Smart Meter project: the Irish case study

The Irish Smart Meter pilot project explores the impact of smart interventions (the time-of-use (ToU) tariffs in combination with demand side management (DSM) stimuli) on the consumer behavioural response in Ireland [28]. The smart metering trial aims to discover the willingness of consumers to shift the electrical usage to low peak tariff rates. The energy data is recorded every 30 min (in kW h). According to Ireland [28], the trial begins with establishment of benchmarking level of electricity usage (01/07/2009–31/12/2009) and later tests various ToU tariffs with DSM stimuli (01/01/2010–31/12/2010). At the end of the benchmark state, consumers in the trials are divided into two groups: consumers with ToU tariffs and DSM stimuli intervention (test group) and the BAU consumers (BAU group). The main finding of this big trial is that there are overall reduction of electricity usage by 2.5% and peak usage by 8.8%. The ToU tariffs are shown in Table 1. Four different ToU tariffs are established for the behavioural trial programme.

The ToU tariffs are combined with specific DSM initiatives:

(1) Monthly detailed energy bill.
(2) Bi-monthly detailed energy bill.
(3) In-home electricity monitor (IHEM).
(4) Overall load reduction incentive.

The BAU group performed non-controlled energy usage and this was compared with the test group implementing smart interventions.

Table 1
Residential ToU bands and tariffs (cents per kW h). *Source:* CER11080a [28].

Timeband	Morning-afternoon rate 8 am–5 pm	Peak rate 5 pm–7 pm	Night rate 7 pm–11 pm	Midnight-morning rate 11 pm–8 am
Tariff A (cents per kW h)	14.0	20.0	14.0	12.0
Tariff B (cents per kW h)	13.5	26.0	13.5	11.0
Tariff C (cents per kW h)	13.0	32.0	13.0	10.0
Tariff D (cents per kW h)	12.5	38.0	12.5	9.0

3. Carbon emissions and savings

DSR programmes were introduced in order to provide continuous delivery of power in the uncertain conditions of the modern UK power system, and also to reduce the network load during the demand peaks. DSR programmes create revenue and rewarding opportunities for participating companies and consumers. However, the environmental impact due to the energy intervention, such as GHG emissions, have not been estimated before. In this paper, we quantify the amount of CO_2 emissions generated due to the interventions from DSR. The equivalent CO_2 is thus far the most practical presentation of GHG [29,30]. Hill et al. [31] from the UK Department of Energy and Climate Change (DECC) presented the methodology in converting other GHG to CO_2 equivalent based on the Global Warming Potential. According to Wiedmann and Minx [30], the long-scale projections (at least 50 years) for other GHG are needed due to insufficient availability of current GHG data. Therefore, the assessment of the CO_2 equivalent in the current situation is sufficient.

The amount of CO_2 emissions generated due to the DSR interventions are further compared with the BAU conventional reserve plants. Thus, CO_2 savings are estimated as the difference between these quantities (positive in case of real savings and negative if the CO_2 emissions increase due to the intervention). We apply the methodology from Hill et al. [32] and Lau et al. [33,34] to quantify the amount of CO_2 emissions and the associated savings for DSR programmes.

The CO_2 emissions resulting from the energy generated/consumed are calculated as:

$$\mathcal{E} = \sum_{t=1}^{N_t} E(t) \times C(t), \quad (1)$$

where $\mathcal{E}$ denotes CO_2 emissions with units kilogramCO_2 (kgCO_2), tonneCO_2 (tCO_2) or kilotonneCO_2 (ktCO_2), E is the amount of energy generated/consumed (kW h), $C(t)$ is the CO_2 factor, t denotes the time step, N_t is the total number of time steps.

The $C(t)$ for electricity generation and consumption are parameters estimated using the Life Cycle Assessment [35] and measured in units of equivalent CO_2 mass (kgCO_2, tCO_2 or ktCO_2) per unit of energy (kW h). Calculation of the national CO_2 footprints in the UK is performed annually by Ricardo-AEA [36]. For the energy consumption from the UK energy grid, we calculate the dynamical grid CO_2 factor (denoted as $G_{UK}(t)$) that is derived from the fuel mix, as described in Lau et al. [34,37]. Monte Carlo simulations are used for quantification of uncertainties. In the case of energy consumption from the UK energy grid, the $G_{UK}(t)$ in this case replaces the $C(t)$ in Eq. (1).

The CO_2 factor $G_{UK}(t)$ [34,37] in Eq. (1) is calculated at temporal resolution of the fuel mix data (the HH scale):

$$G_{UK}(t) = \frac{\sum_{m=1}^{N_m} \left(F_m \times E_m^g(t)\right)}{\sum_{m=1}^{N_m} E_m^g(t)}, \quad (2)$$

where F_m are the CO_2 factors (kgCO_2/kW h) for different fuels m, $E_m^g(t)$ is the amount of energy generated (kW h) at time step t, m is the fuel type index at $m = 1, 2, \ldots, N_m$, N_m is the number of fuels.

We calculate $G_{UK}(t)$ using the available fuel mix data from Elexon [38]. Transmission and distribution (TD) losses reported as 7.7% by Digest of United Kingdom Energy Statistics [39] are included in this report for further estimations. Uncertainty estimation is performed for those individual fuels used in electricity generations in specific power plants, using publicly available national average data.

The CO_2 savings S are determined as the difference of CO_2 emissions between the BAU $\mathcal{E}_B$ and those in the optimised/improved interventions $\mathcal{E}_I$:

$$S = \mathcal{E}_B - \mathcal{E}_I. \quad (3)$$

4. DSR interventions

Types of interventions considered in each of the DSR programmes are as follows: (1) in STOR – standby diesel generators; (2) in Fast Reserve – pump-storage hydroelectricity; (3) in Triad – standby diesel generators; (4) in smart metering trial – ToU tariffs in combination with DSM stimuli.

4.1. Standby diesel generators

The standby diesel generation is one of the STOR [18] and Triad management [19] instruments. Therefore, both STOR and Triad programmes include the intervention by switching from conventional BAU fuelled production to diesel generators.

We estimate the reduction of CO_2 emissions resulting from the use of generators (diesel–fuel powered) as compared with a reserve BAU plant based on the balancing mechanism controlled by National Grid. The CO_2 emissions of diesel generators are compared with BAU plants, that are open cycled gas turbine (OCGT) and combined cycled gas turbine (CCGT) plants.

4.1.1. CCGT plant – operational profile

A CCGT plant must be warmed up to reach the base load level as necessary to operate in stable conditions before it can generate energy [40].

Due to the inflexibility of instantaneous energy generation in responding to unpredictable energy demand, CCGT plants should be operated at base-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 common that CCGT plants undergo complete warm-up process but eventually may or may not actually be used [26].

Warm-up. A conventional CCGT plant burns additional fuel for a few hours throughout the warming up period to full-load before it is capable of generating electricity (for instance, a 380 MW CCGT plant may take 3 h to reach the full-load condition [41]). 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 [40], Boyle et al. [41] for the detailed explanation of warming up of conventional CCGT

Table 2
Percentage increase of CO_2 emissions at various loads for CCGT plants. Adapted from [26].

Part load point (%)	Percentage increase of CO_2 emissions (%)
25	79
50	20
75	10

plants). Since CCGT plants are expected to operate at part-loaded level, we assume that the warm-up duration of CCGT plants is approximately 35 min, excluding the standby period [42]. Due to the requirement to sequentially warm up CCGT plants at different part-loading points, such a plant will consume additional fuel and consequently the CO_2 emissions. Table 2 shows the percentage increase of CO_2 emissions for CCGT plants at different part-loads. The data in Table 2 is derived based on the percentage increases of the fuel consumption from Flexitricity [26] corresponding to different part-loads. Martin [43] further denoted the percentage increases of fuel consumption data from Flexitricity [26] as the part-loading heat rate. According to Korellis [44], as one percent of heat rate is equivalent to one percent of CO_2 emissions, the percentage increase of fuel consumption or heat rate can be expressed as the percentage increase of CO_2 emissions.

Operation. CCGT plants will generate the required level of energy when all stages of the warm-up sequence have been completed (except the 'hot-standby' period when awaiting a despatch instruction from National Grid). In this study, we assume that a single CCGT plant is assumed to operate at 50% part-loaded (a group of part-load CCGT plants will generate the required level of energy) throughout the DSR programmes. Such policy is important in order to provide the right source of plant margin that maintains the security of energy supply [26]. It is stated in regulations of electricity supply that 'plant margin' of at least 20% is strictly needed to avoid power failures [45]. More details on plant margins are available in Flexitricity [26], National Grid [45].

As CCGT plants are assumed to operate at 50% of full load, there will be short term increase of fuel consumption (15–20%) and CO_2 emissions as shown in Table 2.

Shutdown. The shutdown time for a CCGT plant is the interval from the initiation of shutdown starting at base load (approximately 55%) to the 'flame-off' signal of the gas turbine [46]. CCGT plants have negligible emissions at standstill following the complete shutdown sequence [46]. CCGT plants can also 'park' at certain part-load levels instead of 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 CO_2 emissions [40]. We assume there is a short-term increase of CO_2 emissions about 8–10% before CCGT plants shut completely after the flame-off phase.

4.1.2. OCGT – operational profile

In order to cope with increasing uncertainty of the energy system (for instance, wind generation intermittency and variable consumer demand) within short time intervals, National Grid allocates a large number of 'peaking' power plants (in particular, OCGT plants) for providing standing reserve energy supply [21,47]. An OCGT plant is very flexible in providing standing reserve and often referred as 'peaking plants' due to its shorter duration of start-up time and higher efficiency when operating at various part-loads [47,48].

Warm-up. We assume that OCGT plants will always operate at above 50% load in order to avoid the increase of emissions [49] and also to operate in a stable state before it can generate energy. There will be short-term increase in fuel consumption at different part-loading points during the start-up sequence, thus increasing the CO_2 emissions. Table 3 shows the percentage increase of CO_2 emissions for OCGT plants at different part-loads.

Table 3
Percentage increase of CO_2 emissions at various part-loads for OCGT plants. Adapted from Macak [49].

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

The OCGT profile is adapted from Macak [49]. Initially, the emissions corresponding to different part-loads are specified as carbon monoxide (CO) equivalent. The ordinary CO emissions at different part-loads are further converted into CO_2 equivalent emissions.

Based on Table 3, the percentage increases of CO_2 emissions reduce as load increases. In our approach we follow the method of Macak [49] 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/Triad capacity). This configuration is compatible with most of OCGT plants operated in the UK.

An OCGT plant has ability to reach full load in 10 or 30 min [42,49,50]. We assume that the duration from start-up to full load for OCGT plants is approximately 30 min.

Operation. OCGT plants will generate the required level of energy as soon as the start-up sequence completes. Operating OCGT plants at base-load capacity throughout the DSR operations introduces additional 6.7% increase of fuel consumption and the resultant CO_2 emissions as shown in Table 3.

Shutdown. The shutdown sequence of OCGT plants can be achieved within 10 min [49] (almost instant shutdown). We assume there is a short-term increase of CO_2 emissions before OCGT plants shut completely.

4.1.3. Diesel generator – operational profile

Most diesel generators burn no fuel when waiting for peak demand or system failure [26]. Diesel generators have the ability to warm up very rapidly within 1–2 min [51] and shutdown instantly. However, most of the diesel generators have small size and low efficiency (35%) with heavily emitting fuel. Multiple diesel generators are required to generate the same amount of energy as one large-scale plant. Given such different operational features of reserve plants and diesel generators, it is necessary to compare the CO_2 emissions of the two energy generation scenarios in order to quantify possible carbon savings.

4.1.4. Technological parameters of CCGT, OCGT and diesel generators

Table 4 shows the parameters of CCGT/OCGT plants and diesel generators participating in STOR and Triad programmes, which we use to model energy generation and the resulting CO_2 emissions and savings. Apart from the parameters provided in Table 4, due to different technological cycles of plants and generators and duration of DSR programmes, the resultant CO_2 emissions and savings may vary.

4.2. Hydro-pumped storage – operational profile

Hydro-pumped storage plants are powered by water from an upper reservoir. Each of the conventional power stations may comprise of two-four generators/motor pumps. During the pumping

Table 4
Characteristics of CCGT, OCGT and diesel generators.

Parameters	CCGT	OCGT	Diesel generator
Warm-up duration	35 min	30 min	1 min
Shutdown duration	⩽one hour	10 min	None
Load condition	Part-load	Full-load	
Standby duration	30 min		None
Additional warm-up emissions	Yes, at different part loads		None
Additional operational emissions	15–20% at base-load	6.70% operating at nominal load	None
Additional shut down emissions	Yes, at different part loads		None
TD losses	7.7%		None
Efficiency	52–60%	35–42% (Lower heating value)	35%
Carbon intensity ($kgCO_2$/kW h)	0.365–0.400	0.460–0.480	0.710 (at 35% efficiency)

mode, the pump acts as a rechargeable battery by pumping the water at the foot of a hill to the upper reservoir during the night, when electricity tariffs are usually cheap [52]. The water is stored in the reservoir and is released as necessary to charge the turbines (generating mode) to meet peak demands [52]. The hydro-pumped storage is often regarded as the default mechanism in providing electricity in the Fast Reserve programme.

The high flexibility of the hydro-pumped storage allows one to achieve the full-load pumping speed within a few minutes. There are restrictions imposed in terms of the maximum number of utilisations (for instance, 300 MW h per operational day for a tendered unit). National Grid [53] provides detailed account of maximum utilisations corresponding to tendered units of hydro-pumped storage plants. There are also established restrictions on the total electricity generated by such plants due to the possible environmental effects from waste oils and also oil leakages [52]: for instance, Cruachan hydro plant with 705 GigaWatts hour (GW h) reduced amount of generated electricity in 2009 compared to 885 GW h in 2008.

In this study, the Ffestiniog pumped storage hydroelectricity plant participating in the Fast Reserve programme is selected for assessment of CO_2 emissions. The general specification of Ffestiniog pumped storage is given in Table 5.

5. Carbon emissions and savings methodology in DSR programmes

In the following sections, we outline the modelling of CO_2 emissions and estimation of CO_2 savings in the considered DSR programmes.

5.1. STOR

The STOR market information and tender round results are available in the National Grid website [22]. In this study, we use data of the contracted STOR period in order to match the timeline data provided by an aggregator. The total accepted power (MW) within the seasonal span is reported in National Grid [56]. The contracted capacity is shown in Table 6.

Table 5
Specification of Ffestiniog pumped storage. *Source:* First Hydro Company [54,55].

Number of turbines (units)	4
Number of pumps (units)	4
Total plant capacity	360 MW
Generating capacity (per unit)	90 MW
Pumping capacity (per unit)	75 MW
Cycle efficiency	72–73%
Total reservoir capacity	1.3 GW h
Duration of achieving full load generation	⩽5 min (from ‘standstill’) ⩾60 s (from ‘spinning’)

Table 6
Contracted STOR period with accepted capacity.

Season	Dates	Accepted MWs
8.1	01/04/14–28/04/14	2537
8.2	28/04/14–18/08/14	2648
8.3	18/08/14–22/09/14	2804
8.4	22/09/14–27/10/14	2819
8.5	27/10/14–02/02/15	3500
8.6	02/02/15–01/04/15	3498

The STOR data from Table 6 is used to estimate the energy generation and CO_2 emissions for the STOR programme.

Based on Fig. 1, we estimate the CO_2 emissions of a Non-BM aggregator. We assume that if there was no existing STOR programme, National Grid would request the reserved BAU plants (OCGT and CCGT plants) to provide the total capacity of STOR. In contrast, the aggregator substitutes proportional part of this capacity by generating the contracted power (diesel–fuelled) within the availability windows. This allows for the estimation of CO_2 emissions and savings from the replacement of the reserved BAU plants (hypothetical, as the plant does not operate during the STOR period) by diesel generators of aggregators at the same scale of generation.

The ratio of the aggregator's diesel-generated capacity to the full STOR capacity of the reserved BAU plants is:

$$k' = \frac{V_a}{V_o}. \tag{4}$$

The V_a is the volume provided by the aggregator, V_o is the overall STOR volume contracted to reserved BAU plants.

Through Eq. (4), we compare the emissions resulting from the reserved BAU plants $\mathcal{E}_B^{ik'}$ and diesel generators $\mathcal{E}_I^k$:

$$\mathcal{E}_B^{ik'} \sim \mathcal{E}_I^k, \tag{5}$$

where superscript k indicates the nominal amount of generation, k' is the rescaled energy generated from Eq. (4), i indexes the BAU (CCGT and OCGT) plants.

The CO_2 savings resulting from STOR programme is

$$S_S^i = \mathcal{E}_B^{ik'} - \mathcal{E}_I^k = \sum_{t=1}^{N_t} \left(E_B^{ik'}(t) \times C_B^i - E_I^k(t) \times C_D \right), \tag{6}$$

where $E_B^{ik'}$ indicates the energy generation (kW h) by the reserved BAU plants, E_I^k is the energy generation (kW h) resulting from the diesel generators, C_B^i is the CO_2 factor for BAU plants, C_D is the CO_2 factor for diesel generators, i indexes the reserved BAU plants.

Table 7
National Grid's accepted tenders for the Fast Reserve programme. *Source:* [53].

Tendered unit	Tendered period	Tendered window	
		Monday to Saturday	Sundays
Ffestiniog plant, FFES-2	01/04/13–31/03/14	0700–1230	1600–2230 0900–1300 1700–2230

5.2. Fast Reserve

For simplicity, we adopt the Fast Reserve tenders for the Ffestiniog plant at which the timeline is provided by National Grid [53], as shown in Table 7.

We follow the tendered window period as given by National Grid [53]. As the Fast Reserve programme can be despatched by the National Grid at any moment, we assume that the programme operates daily with maximum demand occuring in both morning and evening. The daily demand data is available publicly in National Grid [57]. It should be noted that the full capacity (360 MW) of Ffestiniog plant is not always utilised in the Fast Reserve programme. Despatching instruction of National Grid is only called based on the accepted tendered service period. Therefore, not all generating units are powered at the same time: some turbines may be preserved for other DSR programmes or for normal mode of electricity generation. As an example, we select the Ffestiniog plant fleet number two (FFES-2).

Additionally, the reservoir can be refilled when it is partly drained or at times of low peak periods. Utilisation restrictions/constraints are also imposed on the FFES-2 as maximum energy of 250 MW h per day and, additionally, the maximum of 30 utilisations per day [53]. The FFES-2 that refills the reservoir only operates during the night time, and we assume that the FFES-2 will draw/buy the energy from the UK grid based on Economy 7 tariffs. The refills of the reservoir will be initiated at 0130 British Summer time or 0030 Greenwich Mean Time. The duration for refilling the reservoir is estimated as

$$N_{t_\alpha} = \frac{C_r}{C_p}, \tag{7}$$

where C_r is the capacity of the reservoir (MW h) and C_p is the capacity of the pump (MW h).

Since FFES-2 draws electricity from the UK grid, this results in CO_2 emissions. In addition, there are CO_2 emissions produced when the FFES-2 is generating electricity [33]. It is due to energy losses during the rotation of turbines. By using Eqs. (1) and (2), the CO_2 emissions resulting from the FFES-2 are as follows:

$$\mathcal{E}_H = \sum_{t_\alpha=1}^{N_{t_\alpha}} (E_H(t_\alpha) \times G_{UK}(t_\alpha)) + \sum_{t_\beta=1}^{N_{t_\beta}} (E_H(t_\beta) \times F_H), \tag{8}$$

where E_H is the amount of energy consumed and generated by FFES-2 (kW h), G_{UK} is the CO_2 factor of the UK grid, F_H is the CO_2 factor of FFES-2, t_β is the time index for energy generating mode, t_α is the time index for pumping mode, N_{t_α} is the total pumping duration, N_{t_β} is the total generating duration.

For simplicity, the resultant CO_2 emissions for the Ffestiniog hydro plant considering the same duration and capacity of operations for the remaining fleets $\mathcal{E}'_H$ is calculated as:

$$\mathcal{E}'_H = \mathcal{E}_H \times N_H, \tag{9}$$

where $\mathcal{E}_H$ are CO_2 emissions from Eq. (8), N_H is the total number of fleets/units in the Ffestiniog hydro plant.

We further assume that National Grid would call reserved BAU plants to provide the total capacity for Fast Reserve if FFES-2 fail to provide the substitution of grid energy for consumers. The CO_2 savings for Fast Reserve resulting from the intervention by hydro-pumped is calculated as:

$$S_F^i = \left(\sum_{t_\beta=1}^{N_{t_\beta}} \mathcal{E}_B^i(t_\beta) \right) - \mathcal{E}'_H, \tag{10}$$

where $\mathcal{E}_B^i$ are the CO_2 emissions by reserved BAU plants, $\mathcal{E}'_H$ denotes the overall CO_2 emissions from Eq. (9), i indexes reserved BAU plants, t_β is the time index for energy generating mode, N_{t_β} is the total generating duration.

5.3. Triad

Since there is no standard Triad warning communicated to participants by National Grid, we model each period of Triad operation as of one hour. The Triad period can be represented by the unit step function. When a Triad warning is issued, the instantaneous operation of diesel generators starts.

Similarly to the STOR and Fast Reserve programme, we assume that National Grid would call the reserve BAU plants to provide the total capacity if Triad participants did not cut the loads from the main UK energy grid. We further assume that the capacities of diesel generators have the same scale as the reserved BAU plants during the Triad event by taking 1 GigaWatts (GW) of total generating capacity. This allows us to estimate CO_2 emissions and savings from the replacement of reserved BAU plants by diesel generators at the same scale of generation.

The CO_2 savings for Triad are calculated as follows:

$$\begin{aligned} S_T^i &= \mathcal{E}_B^i - \mathcal{E}_I \\ &= \sum_{t=1}^{N_t} \left(E_B^i(t) \times C_B^i - E_I(t) \times C_D \right). \end{aligned} \tag{11}$$

The $\mathcal{E}_B^i$ indicates the CO_2 emissions by reserved BAU plants, $\mathcal{E}_D$ are the CO_2 emissions resulting from operating diesel, $E_B^i(t)$ denotes the energy generated by reserved BAU plants, $E_I(t)$ is the energy generated by diesel generators, C_B^i is the CO_2 factor for reserved BAU plants, C_D is the CO_2 factor for diesel generators, i indexes reserved BAU plants, t is the time step, N_t is the total time steps.

5.4. Irish smart metering

We adopt the electricity consumption data (kW h) of the BAU ($E_B(t)$) and test ($E_I(t)$) group based on datasets from Irish smart grid. We intend to quantify the overall CO_2 emissions reductions within the two distinct groups. The CO_2 savings in the case of Irish smart grid can be estimated as follows:

$$S_{SM} = \sum_{t=1}^{N_t} (E_B(t) - E_T(t)) \times G_{UK}(t), \tag{12}$$

where $E_B(t)$ is the electrical consumption by the BAU group (kW h), $E_T(t)$ denotes the electrical consumption by the test group (kW h). The G_{UK} is calculated using Eq. (2). The element of F_m in $G_{UK}(t)$ is the datasets from Balancing Mechanism Reporting Systems [38]. We match the G_{UK} with the timeline trial experiment by the Irish smart grid. Such realisation is important, because G_{UK} is affected by various external conditions, such as seasonal and consumer usage patterns.

It is important to monitor and analyse the impact of smart initiatives during the peak (from 5 pm to 7 pm daily) and off-peak periods [28]. The finding in Section 2.4 presented the results of the percentage energy reduction based on large samples of the BAU and test group with considerations of all Smart initiatives. In our present study, our main interest is to evaluate the particular Smart initiative. Therefore the Tariff D in the combination with IHEM is considered in this study.

We consider Irish smart grid energy datasets recorded for 132 trial days in order to estimate CO_2 emissions and savings. We compare the BAU group with the test group (Tariff D + IHEM). Such comparison enables one to determine the effect of Smart interventions due to behavioural changes in response to smart meters roll-out.

6. Results

To model the DSR programmes, we use Matlab-based simulations of CO_2 emissions of reserve power plants. We apply the input profile data from Tables 2–4 to determine the nonlinear relationship between the various load conditions and the corresponding CO_2 emissions level during the warm-up and shutdown sequences of BAU plants. We apply least-square fit in the Matlab curve fitting tool and estimate CO_2 emissions for three types of data (warm-up, operation and shut down) for energy profiles of BAU plants and diesel generators.

We perform Monte Carlo simulations to randomly sample the carbon factors for gas and diesel fuels, DSR periods, and various intervals of parameters for BAU plants, generators, hydro-pumped storage plants and electricity grid across the ranges of the uniformly distributed variables. Monte Carlo simulations of $N = 100$ random samplings are performed in order to quantify the corresponding uncertainties for the resultant CO_2 emissions and savings for each operational day. All uncertainties in the present paper are computed as standard uncertainties. The percentage reduction of overall CO_2 emissions is also included in the result along with the percentage uncertainty. It is not the scope of this paper to compare the effectiveness of different DSR models (due to different projected timelines and trading purposes).

6.1. STOR

We model each period of STOR operation as a total of 40 h with 50 runs of firing-up reserved BAU plants (CCGT and OCGT) and diesel generators. We assume that an average diesel capacity of 500 MW is reserved for the aggregators. Finally the capacity for reserved BAU plants in STOR can be determined using Eqs. (4) and (5). Three types of data (load factor, CO_2 emission level, and the resultant CO_2 emissions) are obtained in each warm-up and shutdown profiles for reserved BAU plants.

Fig. 2 shows the plot of CO_2 emissions for the reserved BAU plants (including warm-up and shutdown). We demonstrate the STOR operation as of two hours in Fig. 2 in order to illustrate the profile trend of the reserved BAU plants per STOR event. The warm-up sequence is completed in approximately 30–35 min. This is when the reserved BAU plants are assumed ready to generate energy (short-term 6.7% increase in fuel consumption) until the end of STOR operation. Based on Fig. 2, there is a slight increase of CO_2 emissions during the STOR operation (approximately between 0.4th h and 2.6th h). This happens due to the effect of TD losses.

In terms of the shutdown phase, we assume that the shut down duration is within 10 min for OCGT plant (note the sharp drop of CO_2 emissions for OCGT plants at 2.5th h). In contrast, CCGT plants will shut down completely (within one hour) instead of ‘parking’ at certain load, and the plant would emit negligible emissions after the flame-off phase.

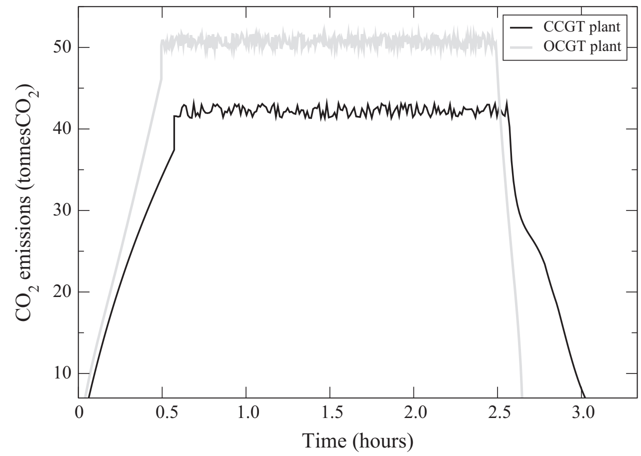

Fig. 2. CO_2 emissions of the 500 MW CCGT and OCGT plants in a single STOR period.

Table 8
CO_2 emissions and savings of diesel generators in comparison with **CCGT** plants, based on 50 STOR runs with 40 h of operations.

	CCGT	Diesel	CO_2 savings ($ktCO_2$)
Warm-up	3.73 ± 0.11	0.29 ± 0.01	3.44 ± 0.11
Operation	8.76 ± 0.27	14.10 ± 0.06	−5.34 ± 0.28
Shut-down	2.73 ± 0.08	0	2.73 ± 0.08
Total CO_2 savings ($ktCO_2$)			0.83 ± 0.31

Table 9
CO_2 emissions and savings of diesel generators in comparison with **OCGT** plants, based on 50 STOR runs with 40 h of operations.

	OCGT	Diesel	CO_2 savings ($ktCO_2$)
Warm-up	3.38 ± 0.04	0.29 ± 0.01	3.09 ± 0.04
Operation	11.22 ± 0.12	14.10 ± 0.06	−2.88 ± 0.13
Shut-down	1.05 ± 0.01	0	1.05 ± 0.01
Total CO_2 savings ($ktCO_2$)			1.25 ± 0.14

Using Eq. (6), the CO_2 savings through the intervention by diesel generators in comparison with reserved BAU plants are shown in Tables 8 and 9, respectively. We obtain the total amount of 0.83 ± 0.31 $ktCO_2$ saved with 5.45 ± 37.34% reduction of using diesel generators in comparison with CCGT plants in the layout of our experiment. Similarly, 1.25 ± 0.14 $ktCO_2$ is saved with 8.05 ± 11.20% reduced due to the substitution by diesel generators of the generation capacity in OCGT plants. The percentage uncertainty in this case is high due to randomised event and operating policies of plants and generators. The CO_2 emissions are estimated assuming that the National Grid would call reserved BAU plants to contribute the total capacity of STOR with the aggregator substitutes proportional part of total STOR capacity.

6.2. Triad

As in line with Ward et al. [19], the standard operation of a Triad event is one hour. We assume that up to 26 Triad warnings (26 h of Triad operations) for a year at different times of occurence are issued by the energy forecaster before the event. Those Triad warnings are used to signal the need for the intervention by diesel generators in providing back-up generation instead of buying the electricity from the UK energy grid. However, the actual reduction in TNUoS charges are only visible as the result of hitting all three Triad peaks as indicated by National Grid. As Triad warnings are issued when there are high peak demands, it is assumed that the energy grid is under 'stress' with high amount of emission intensity. Henceforth the Triad warnings may help in lowering the demand 'stress' in the grid by having standby diesel generators operating independently.

The complete profiles of CO_2 emissions for reserved BAU plants are similar to STOR (see Fig. 2), but with different durations of operations due to different timeline projections of DSR programmes. The reserved capacity for diesel generators is at the same scale as reserved BAU plants (1 GW of total generating capacity). Using Eq. (11), the CO_2 savings 26 Triad runs are shown in Tables 10 and 11 respectively.

We obtain the total amount of 13.14 ± 0.62 $ktCO_2$ ($41.29 \pm 4.72\%$ reduction) saved using diesel generators in comparison with CCGT plants. Marginal CO_2 savings of 0.89 ± 0.19 $ktCO_2$ ($4.55 \pm 21.35\%$ reduction) can still be achieved compared with OCGT plants.

The CO_2 savings achieved as shown in Tables 10 and 11 are based on the assumption that the grid is under 'stress' occuring at those 26 randomly occured Triad events with high peak demands.

In addition, we have analysed the possible extended duration of a Triad period to quantify the CO_2 savings and find out when they become negative. In this analysis we compare the emissions from diesel generators with CCGT plants. This result is shown in Fig. 3.

Table 10
CO_2 emissions and savings of diesel generators in comparison with **CCGT** plants, based on 26 Triad runs that last for one hour each.

	CCGT	Diesel	CO_2 savings ($ktCO_2$)
Warm-up	4.39 ± 0.12	0.31 ± 0.01	4.08 ± 0.12
Operation	24.18 ± 0.60	18.34 ± 0.07	5.84 ± 0.60
Shut-down	3.20 ± 0.09	0	3.20 ± 0.09
Total CO_2 savings ($ktCO_2$)			13.12 ± 0.62

Table 11
CO_2 emissions and savings of diesel generators in comparison with **OCGT** plants, based on 26 Triad runs that last for one hour each.

	OCGT	Diesel	CO_2 savings ($ktCO_2$)
Warm-up	3.61 ± 0.04	0.31 ± 0.01	3.30 ± 0.04
Operation	14.81 ± 0.17	18.34 ± 0.07	−3.53 ± 0.18
Shut-down	1.12 ± 0.01	0	1.12 ± 0.01
Total CO_2 savings ($ktCO_2$)			0.89 ± 0.19

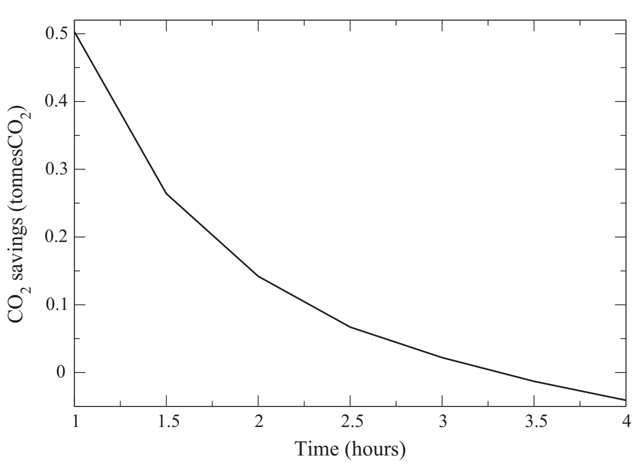

Fig. 3. CO_2 savings per Triad event as a function of the duration for the event. If the Triad event operates longer than 3.5 h, diesel generators produce more emissions than the reserve BAU plants.

The main aim of the sensitivity analysis performed in Fig. 3 is to show that continuous runs of diesel generators in a single Triad event do not guarantee CO_2 savings in case of long programme period duration. This happens when diesel generators are operating at longer scale, beyond the current energy policies and programmes. This shows that diesel generators are indeed beneficial in promoting CO_2 savings in short-term duration and unsuitable for long operations. In the normal mode of operations, BAU plants are most suitable for sustainable and reliable low-polluting energy generation.

6.3. Fast Reserve

We model the Fast Reserve operation as of total 365 days of the FFES-2 run. We apply the tendered Fast Reserve period (01/04/13–31/03/14) from Table 7 into our model by stochastically determining the randomly occured Fast Reserve events within the timeline intervals (occuring daily in mornings and evenings at various intervals). Therefore, the duration of the Fast Reserve events varies. The operating profile of the FFES-2 is modelled based on the specifications available in Table 5 with 90 MW generating size and 75 MW pumping capacity. The maximum energy utilisation for FFES-2 is limited to 250 MW h per operational day. It is assumed that the event duration is 15–30 min for a normal period (spring-summer) and 15–60 min for a critical period (autumn–winter). With the current 90 MW generating capacity of FFES-2, the FFES-2 is only allowed to operate for total durations of 2 h and 47 min per operational day. We compute the CO_2 emissions of FFES-2 ($\mathcal{E}_H$) using Eq. (8). The $\mathcal{E}_H$ of the FFES-2 in the Fast Reserve programme are shown in Table 12. Based on Table 12, we obtain the total $\mathcal{E}_H$ from FFES-2 as 21.07 ± 0.28 $ktCO_2$/year. Similar with STOR and Triad programmes, we apply the operating profiles of reserved BAU plants that enable us to compare the CO_2 emissions against the Ffestiniog hydro plant. If we further assume that the remaining three fleets in the Ffestiniog plant are operating with the same duration and reserved capacity of FFES-2, using Eq. (9) the resultant $\mathcal{E}'_H$ of the Ffestiniog plant are obtained as 84.32 ± 1.12 $ktCO_2$/year. We also compute the $\mathcal{E}^i_B$, assuming that the capacity of the reserved BAU plants is the same as the Ffestiniog hydro plant during the mode of generating electricity to consumers. The CO_2 savings based on the intervention by the Ffestiniog plant is calculated using Eq. (10). Tables 13 and 14 demonstrate the CO_2 savings of the hydro-plant in comparison to reserved BAU plants respectively.

We obtain the results of the total amount of saved 61.74 ± 2.85 $ktCO_2$ ($42.28 \pm 4.16\%$ reduction) using the hydro plant in comparison with CCGT plants. Similarly, 62.08 ± 1.68 $ktCO_2$ are

Table 12
CO_2 emissions of the FFES-2 under Fast Reserve programme for one year period.

FFES-2 mode	CO_2 emissions ($ktCO_2$/year)
Pump	20.89 ± 0.28
Generator	0.18 ± 0.04
Total CO_2 emissions ($ktCO_2$/year)	21.07 ± 0.28

Table 13
CO_2 emissions and savings of the Ffestiniog hyrdo-plant in comparison with **CCGT** plant for one year period.

Plant	CO_2 emissions ($ktCO_2$/year)
Hydro-pump	84.29 ± 1.14
CCGT	146.03 ± 2.61
Saved CO_2 emissions ($ktCO_2$/year)	61.74 ± 2.85

Table 14
CO_2 emissions and savings of the Ffestiniog hydro-plant in comparison with **OCGT** plant for one year period.

Plant	CO_2 emissions ($ktCO_2$/year)
Hydro-pump	84.29 ± 1.14
OCGT	146.37 ± 1.24
Saved CO_2 emissions ($ktCO_2$/year)	62.08 ± 1.68

saved with 42.41 ± 2.7% reduction achieved due to the substitution by the hydro plant of the generation capacity in OCGT plants. The CO_2 emissions are estimated assuming that the National Grid would call the reserved BAU plants to contribute the total capacity of Fast Reserve if the hydro-plant did not operate at the required event.

6.4. Irish smart metering trial

We compare CO_2 emissions and savings resulting from the BAU and test group. We use the BAU group as the baseline for the energy consumption and CO_2 emissions. As mentioned in Section 5.4, for simplicity we only adopt the test group with a particular smart initiative (Tariff D in combination of IHEM). The test group is then compared with the BAU group for CO_2 savings assessments using Eq. (12). To illustrate the results, the diurnal trend of average CO_2 emission values for the BAU and test group and its relative difference are shown in Fig. 4.

As can be seen in Fig. 4, at times of peak period (ToU rate of 38 cents/kW h) there is no distinct trend of the reduction in CO_2 emissions and the energy usage by the test group from 6 to 7 pm. However, the trend of emission reduction by the test group is quite visible from 5 to 6 pm. Additionally, there is a slight decrease of the CO_2 emissions by the test group from 8 pm until the 7 am next day. In contrast, there is a change of higher amount of the consumption and emission by the test group than the BAU group from 9 am to 11 am when morning-afternoon ToU rate is applied (12.5 cents/kW h). Overall, there is no clear trend in demand shift towards the cheapest tariff (midnight from 11 pm to 8 am next day). Additionally, there is only a small tendency of demand reduction based on the present study during the peak period.

Table 15 shows the CO_2 savings under smart metering within the 132 days (01/01/2010–12/05/2010) of trial runs.

The present study of 132 trial runs in Irish Smart Metering pilot project with the BAU group and test group (Tariff D + IHEM) in Table 15 shows the overall 0.09 ± 47.05% reduction (0.17 ± 0.08 $kgCO_2$ saved) in the peak period. The test group were not able to reduce the electricity usage during peak period. Additionally, there is no definite answer of the test group to shift the demand to particular period as the test group still use less energy than the BAU group that contributes to CO_2 savings in other off-peak period. The average CO_2 savings achieved by the test group is estimated as 29.20 ± 0.16 $kgCO_2$ (1.83 ± 0.54% reduction). Hence, the overall impact of the Smart interventions (Tariff D + IHEM) is very low.

Based on the overall CO_2 savings obtained, it can be further estimated that if there are 500,000 people in a large city, the overall CO_2 savings for 132 days would be 14.60 ± 0.02 $ktCO_2$.

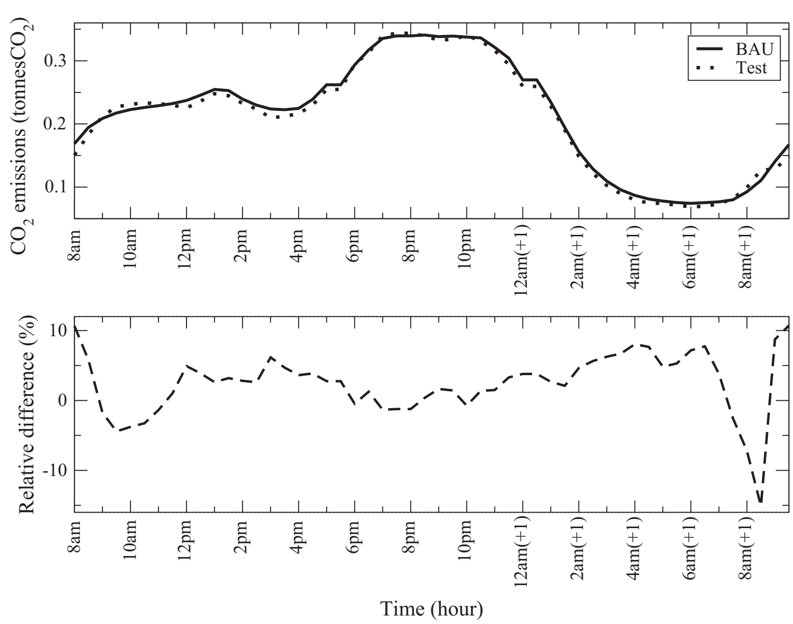

Fig. 4. Irish Smart Metering trial. Top: The average CO_2 emissions for the BAU and test group in a single day. Bottom: The relative difference of CO_2 emissions for the BAU and test group. Note that (+1) indicates the day after next. Negative values in the bottom panel indicate the additional CO_2 emissions by the test group (no CO_2 savings).

Table 15
CO_2 savings for 132 days (01/01/2010–12/05/2010) of smart metering trial, based on different imposed ToU Tariffs with the combination of IHEM initiative.

	Morning-afternoon rate 8 am–5 pm	Peak rate 5 pm–7 pm	Night rate 7 pm–11 pm	Midnight-morning rate 11 pm–8 am
CO_2 savings per consumer ($kgCO_2$)	12.80 ± 0.08	0.17 ± 0.08	4.59 ± 0.07	11.64 ± 0.09
Percentage reduction (%)	2.24 ± 0.63	0.09 ± 47.05	1.19 ± 1.53	3.79 ± 0.77

7. Conclusions

In this paper, we have quantified the amount of CO_2 emissions and savings under various DSR programmes. The considered DSR programmes include STOR, Triad and Fast Reserve. We have also included the Irish smart metering programme as an additional DSR programme (behavioural). Types of the smart interventions considered in each of the DSR programmes are as follows: (1) STOR – standby diesel generators; (2) Fast Reserve – pump-storage hydroelectricity plants; (3) Triad – standby diesel generators; (4) Irish smart metering trial – ToU tariffs in combination with DSM stimuli. We modelled each of the DSR programmes with required operational parameters and necessary assumptions. Smart interventions corresponding to DSR programmes are modelled as well. This enables the comparison of CO_2 emissions between the BAU and the smart solutions, with quantification of uncertainties.

The high amount of CO_2 emissions during the Fast Reserve event is mainly due to the hydro-pumped drawing electricity from the main grid to pump high volume of water to the reservoir. Large volumes of water from the reservoir are later released in order to provide high volume of electricity supply. The intervention by the hydro-pumped still results in CO_2 savings in this case as compared with the reserved BAU plants.

In the Irish smart metering trial study, through the ToU tariffs in combination with DSM stimuli, proportion of electricity demand is expected to be shifted to other periods, when those tariff rates are significantly lower than the peak rate. Consumers are aware of high peak rate and therefore are expected to avoid the electrical usage during the peak period. However, the present result indicates that the overall trend of demand shifts towards the cheapest tariff in one of the Smart initiative (Tariff D + IHEM) is unclear. One of the possible barriers to the savings may be due to the perception that it is not possible to reduce or shift the usage to other times (daily habitual activities). The 132 trial days of simulation indicate the overall $1.83 \pm 0.54\%$ reduction of CO_2 achieved per consumer. Additionally, 14.60 ± 0.02 $ktCO_2$ can be saved for the population of 500,000 people, in 132 days. As this study only limits to a particular Smart initiative, future work involving independent assessment of all Smart initiatives is required that would further determine the effect of smart interventions due to behavioural changes.

The need for demand reduction or demand shifting at the highest demand peak is very important in order to reduce the need to call additional BAU plants to standby which may or may not be needed for generations. The firing of additional BAU plants increases the overall CO_2 emission intensity in the network. Hence, demand reduction and shifting schemes are expected to reduce of demand 'stress' by reducing the number of BAU plants used for energy generation in the peak period. It can be argued that the demand shifting may increase the CO_2 emission intensity at other off-peak period. Therefore, averaging and smoothing techniques in profiling the energy usage pattern among consumers are needed. Such techniques already exist in the current electricity market with the potential of reducing CO_2 emissions in the developing energy market.

We also perform estimation of CO_2 emissions and savings of diesel generators compared with BAU plants (CCGT/OCGT plants) participating in the STOR/Triad event. The analysis is based on the comparison between the full allocated STOR/Triad capacity for both CCGT/OCGT plants and substituted STOR/Triad volume by aggregators using diesel generators. In both STOR and Triad programmes, by substituting diesel generators proportionate to energy generations from BAU plants respectively, significant amount of CO_2 savings can be achieved.

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. However, some greener fuel plants (for instance: nuclear plants) have limited flexibility in response to sudden peak demands and subsequently may only operate at base load [26]. Therefore, the 'peaking' plant such as OCGT may provide reserve to compensate for the peak demand problems but may produce high amount of emissions and also have higher fuel prices on generations compared to CCGT plants. Therefore, energy self-generation with diesel installations provides not only the security of supply but also reduction of CO_2 emissions.

Although diesel fuel is amongst the most polluting, the diesel generators in DSR programmes produce substantial amount of CO_2 savings. However, such CO_2 savings may not be achieved if the standard operating procedures for diesel generators (for instance, total reserve volume, hours of runs and efficiencies) are changed. Therefore, diesel generators are efficient for both energy generation and CO_2 savings only during reserve/contingency periods (short runs) and are not advisable to operate continuously. The unconstrained operation time from diesel generators will produce additional CO_2 emissions. Furthermore, emissions of small particles may lead to a potential threat of air pollution. In the normal mode of operation (where there is a steady demand), conventional gas-fired plants (e.g. CCGT) are most efficient and least polluting.

Overall, DSR programmes not only reduce the demand 'stress' but also generate CO_2 savings. The present study has successfully proved that even the polluting technology has the ability in saving the CO_2 emissions. It is not the scope of this paper to compare the effectiveness of various DSR programmes due to different projected timelines and trading purposes.

Currently, some National Grid installations prioritize balancing the cost and efficiency in supplying electrical energy to customers rather than their environmental impact. For instance, with the frequency control by demand management (FCDM), fast response (provide service within two seconds) is enabled in managing large deviations in frequency which can be caused by the loss of significantly large generation [58]. CO_2 emissions are therefore considered as secondary priority, especially in the current crisis environment. Installation of new efficient plants such as the thermal storage, CHP and the Carbon Capture and Storage technology may significantly improve CO_2 emissions. Due to the rapid developments in technology and efficiency of plants, we suggest that assessment of CO_2 emissions and savings should be performed regularly.

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