Multi-mode Operation of Combined Cycle Gas Turbines with Increasing Wind Penetration

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***Abstract*—As power systems evolve to incorporate greater penetrations of variable renewables, the demand for flexibility within the system is increased. Combined Cycle Gas Turbines (CCGTs) are traditionally considered as inflexible units but those which incorporate a steam bypass stack are capable of open-cycle operation. Facilitating these units to operate in open-cycle mode is shown to improve system reliability and reduce emissions. It also yields benefits for the generators themselves via increased revenues (in some circumstances) and reduced cycling.**

***Index Terms*—Thermal Power Generation, Wind Power Generation, Power System Modeling.**

I. Introduction

COMBINED cycle gas turbines (CCGTs) are a type of power generating unit that achieve high efficiencies (up to 60%) by recapturing the waste heat from a gas turbine in a heat recovery steam generator (HRSG) and using it to produce steam to drive a steam turbine [1]. The high efficiencies achieved, combined with their ease of installation, short-build times and relatively low gas prices has made the CCGT a popular technology choice [2]. In the Republic of Ireland for example, 40% of installed thermal plant is combined-cycle and this is set to rise to 46% by 2010 [3].

The operational flexibility of a CCGT unit is limited by the steam cycle, which contains many thick-walled components, necessary to withstand extreme temperatures and pressures. To avoid differential thermal expansion across these components and the subsequent risk of cracking, these components must be heated slowly resulting in slower start-up times and ramp rates for the unit overall [4]. As CCGT units traditionally run base-loaded, this is not a major concern for plant operators. However, by incorporating a bypass stack at the design stage, CCGT units have the option to bypass the steam cycle and run in open-cycle mode, whereby exhaust heat from the gas turbine is ejected into the atmosphere via the bypass stack [4]. This would reduce the power output and efficiency of the plant but give greater operational flexibility. Running in open-cycle mode, the simple gas turbine has a short start-up time of 15 to 30 minutes and is capable of changing load quickly. However, these bypass stacks are not always incorporated due to the additional capital costs involved and leakage losses which could also result in reduced output and efficiency.

As international energy policy drives ever greater penetrations of renewable energy, wind power is set to represent a larger portion of the generation mix [5]. This is driving a greater demand for flexibility within power systems in order to deal with large penetrations of variable and intermittent energy [6]. Storage, interconnection and responsive demand are commonly cited as options for dealing with intermittency issues however these options have considerable costs associated with them. Facilitating open-cycle operation of CCGT units that have the technical capability to run in open-cycle mode (i.e. those with a bypass stack) can also deliver much needed flexibility to a system with a large wind penetration and this resource is often readily available, but can sometimes be limited by market rules.

This could also have benefits for the generators. Studies have shown that CCGT units will experience significant decreases in running hours with greater levels of wind and thus will receive less revenues from the market [7]. Due to it's almost zero marginal cost, wind will be dispatched ahead of all other generation when it is available, resulting in thermal generators being displaced down the merit-order. Base-load generators such as CCGTs are particularly affected by an increase in cycling operation. Increases in start-stop cycling, ramping and part-load operation for a CCGT unit, which have been shown to be correlated with greater levels of wind [7], result in serious physical deterioration of a CCGT plant's components and consequently reduces the reliability and lifetime of the plant [8]. By facilitating CCGT units to operate in open-cycle mode, cycling of the gas turbine may be reduced and these units may have a new opportunity to capture revenues from increased operation, during hours when it would otherwise be off-line.

II. Multi-mode operation of CCGTs

CCGTs typically have large minimum loads. This is one of the key reasons they are shut-down frequently with large wind penetrations as they cannot reduce output sufficiently to accommodate the wind [7]. Online CCGT units which have bypass stacks can instantaneously switch to open-cycle operation, while remaining online, by opening the bypass damper to release exhaust gases through the bypass stack. This could allow the gas turbine to remain online during periods when the CCGT would otherwise be shut-down, thereby reducing start-ups for the gas turbine. Likewise, offline CCGT units

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This work was conducted in the Electricity Research Centre, University College Dublin, Ireland, which is supported by Airtricity, Bord Gais, Bord na Mona, Cylon Controls, the Commission for Energy Regulation, Eirgrid, Electricity Supply Board (ESB) International, ESB Networks, ESB Power Generation, Siemens, SWS Group and Viridian. This research is funded by a Charles Parsons Energy Research Award from the Department of Communications, Energy and Natural Resources administered by Science Foundation Ireland.

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with bypass stacks can start-up in open-cycle mode and the steam unit can be warmed slowly to be brought into operation at a later point. Thus on occasions when a CCGT unit has been forced offline by a large amount of wind on the system it could have the opportunity to run as a peaking unit.

The Single Electricity Market or SEM is the electricity market of Northern Ireland and the Republic of Ireland. This is a mandatory gross pool market where generators submit day-ahead, complex bids and the cheapest generators are dispatched until the demand is met [9]. The current market rules allow generators to change their bids for a given trading day up to 10am on the previous day, but bids cannot be changed within day. This implies CCGT units which are capable of open-cycle operation can bid into the market as either a CCGT or an OCGT for any given day, but they cannot submit bids for both CCGT and OCGT operation within the one day or at the same time. Therefore, CCGT generators typically only bid as an OCGT into the market if the steam unit is out on maintenance.

This paper examines if facilitating CCGT units to operate in open-cycle mode, when technically feasible and economically suitable, can benefit the integration of wind power on a power system, reduce cycling and also improve revenues for these generators. The all-island Irish 2020 system is used as a test system as it contains both a large share of wind power and CCGT plant.

III. Test System

The test systems used in this study are based on those developed in the All Island Grid Study [10]. This study investigated the feasibility of various generation portfolios for the Irish system in 2020, with each incorporating significant portions of wind power. Portfolios 1, 2 and 5 from this study are used here. These incorporate 2000 MW, 4000 MW and 6000 MW wind, which provide 11%, 23% and 34% of the energy demand respectively. These portfolios are shown in detail in Table I and the fuel prices are given in Table II. The total system demand for the year is 54 TWh with a winter peak of 9.6 GW and a summer night valley of 3.5 GW.

TABLE I
Installed Capacity (MW) by Fuel Type

Generation Type	Portfolio 1	Portfolio 2	Portfolio 5
Coal	1324	1324	1324
Base-load Gas	4047	3953	3953
CHP	166	166	166
Peat	343	343	343
Mid-Merit Gas	1754	1579	1155
Gasoil	388	388	388
Pumped Storage	292	292	292
Base Renewables	182	182	360
Hydro	216	216	216
Tidal	72	72	72
Wind Power	1999	4003	6000

There is 1000 MW of HVDC interconnection assumed to be in place between Ireland and Great Britain and it is scheduled on an intra-day basis i.e. it can be rescheduled in every rolling planning period. A simplified model of the British power system is included, with no integer variable for generators and where wind and load is assumed to be perfectly forecast.

TABLE II
Fuel Prices (€/GJ) by Fuel Type

Fuel	Fuel Price
Coal - Republic of Ireland	1.75
Coal - Northern Ireland	2.11
Base-load Gas	5.91
Mid-merit Gas	6.12
Peat	3.71
Gasoil - Republic of Ireland	9.64
Gasoil - Northern Ireland	8.33
Base Renewables	0

The test system included four CCGT units with bypass stacks, that can run in open-cycle mode. The characteristics for these units in combined-cycle mode are given in Table III. Limited data was available for these units in open-cycle mode so each was modelled as a typical OCGT unit with characteristics as shown in Table IV. As CCGT 1 and CCGT 4 were comprised of two gas turbines connected to one steam turbine, these units were modeled as having two individual open-cycle units available for dispatch when the CCGT is operated in open-cycle mode. CCGTs 1 and 2 are located in Northern Ireland, whilst CCGTs 3 and 4 are located in the Republic of Ireland.

TABLE III
Characteristics of CCGT units (capable of multi-mode operation)

	CCGT 1	CCGT 2	CCGT 3	CCGT 4
Max Output (MW)	480	404	340	480
Min Output (MW)	232	260	220	280
Average Efficiency (%)	46	54	54	51
Min Operating Time (Hours)	4	6	4	4
Min Down Time (Hours)	2	4	4	2
Synchronization Time (Hours)	1	1	2	4
(Hot) Start-up fuel (GJ)	2000	1080	1732	2000

TABLE IV
Characteristics of CCGT units in open-cycle mode

Max Output (MW)	160
Min Output (MW)	20
Average Efficiency (%)	36
Min Operating Time (Hours)	0
Min Down Time (Hours)	0
Synchronization Time (Hours)	0
(Hot) Start-up fuel (GJ)	8

IV. Modeling Tool

The modelling tool used in this study was the Wilmar Planning Tool, a stochastic, mixed integer unit commitment and economic dispatch model. Wilmar was originally developed to model the Nordic electricity system and was later adapted to the Irish system as part of the All Island Grid Study [10]. The main functionality of the Wilmar Planning Tool is embedded in the Scenario Tree Tool and the Scheduling Model.

The scenario tree tool generates stochastic scenario trees containing three inputs to the scheduling model: wind, load and demand for replacement reserve, with each branch having a probability of occurrance associated with it. The Scenario Tree Tool uses an ARMA approach to generate possible wind forecast errors considering the historical statistical behavior of wind at individual sites. These are then transformed to wind power forecast scenarios. Load forecast scenarios are generated in a similar manner. A scenario reduction technique similar to that in [11] is employed to reduce the large number of possible scenarios generated. A forced outage time series for each unit is also generated by the Scenario Tree Tool using a Semi-Markov process based on given data of forced outage rates, mean time to repair and scheduled outages.

The Scheduling Model minimises the expected costs for each scenario, subject to system constraints for reserve and a minimum number of units online (6 units in the Republic of Ireland and 2 units in Northern Ireland). These costs include fuel, carbon and start-up costs. In the modeling tool reserve is categorized as primary or replacement. Primary reserve, which is needed in short time scales (less than five minutes), is supplied only by synchronized units. The system should have enough primary reserve to cover an outage of the largest online unit occurring at the same time as a fast decrease in wind power production. The demand for replacement reserve, which is reserve with an activation time greater than 5 minutes, is determined by the total forecast error which is defined according to the hourly distribution of wind power and load forecast errors and the possibilities of forced outages. Any unit that is off-line and can come online in under one hour can provide replacement reserve.

Generator constraints such as minimum down times (the minimum time a unit must remain off-line following shut-down), synchronization times (time taken to come online), minimum operating times (minimum time a unit must spend online once synchronized) and ramp rates must also be obeyed. Rolling planning is used to re-optimize the system as new wind and load information becomes available. Starting at noon the system is scheduled over 36 hours until the end of the next day. The model steps forward with a three hour time step with new forecasts used in each step. The model produces a year-long dispatch with hourly time resolution for each individual generating unit so that their specific operation can be examined. The Generic Algebraic Modeling System (GAMS) was used to solve the unit commitment problem using the mixed integer feature of the Cplex solver. For all the simulations in this study the model was run with a duality gap of 0.01%.

A. Modeling multi-mode operation of CCGTs

In order to examine the potential for multi-mode operation of feasible CCGT units an additional constraint was added to the Wilmar model. Firstly, a set of all CCGT units with bypass stacks was defined. A set of open-cycle gas turbines or (OCGTs) which corresponded to each of the CCGT units when run in open-cycle mode was then included. The following constraint was added to the Wilmar code to allow the model dispatch either the CCGT (in combined-cycle mode) or the CCGT in open-cycle mode, but not both simultaneously, when this was economically optimal:

$$[online(CCGT_i) + online(OCGT_i)] \leq 1, \forall\ i,\ hours \quad (1)$$

In Equation 1 online is a binary variable which is 0 if a unit is off-line or 1 if a unit is online, CCGT is the set of CCGT units capable of open-cycle operation, OCGT is the corresponding set of CCGTs operating in open-cycle mode and hours corresponds to all hours in the optimization period.

V. RESULTS

A number of model runs were conducted to investigate the potential for multi-mode operation of CCGT units. A year long dispatch was produced for each of three test systems outlined in Section III, when (i) multi-mode operation of CCGT units is not allowed and when (ii) when multi-mode operation of CCGT units is allowed. A sensitivity was also conducted investigating how the amount of peaking capacity on the system affected the usage of the multi-mode function. This was done for the highest wind system, i.e. 6000 MW installed wind capacity, which contained eight new OCGT units with a capacity of 160 MW each.

Increasing power system flexibility is considered essential to the integration of wind power [6], thus the first result examines the change in wind curtailment when multi-mode operation of CCGTs is allowed. Table V shows the amount of wind curtailment on the system with 6000 MW installed wind capacity when multi-mode operation of CCGT units is not allowed and when multi-mode operation is allowed. As can be seen in Table V a slight increase in wind curtailment arises from the introduction of multi-mode CCGT operation. However, Figure 1 shows the reduction in CO_2 emissions on the systems with 2000 MW, 4000 MW and 6000 MW installed wind capacity. This shows that although multi-mode operation of CCGT units results in a slight increase in wind curtailment, the changes to operation of other units yields a more significant reduction in CO_2 emissions relative to the case when multi-mode operation is not allowed.

TABLE V
WIND CURTAILMENT ON SYSTEM WITH 6000 MW INSTALLED WIND CAPACITY

Wind Curtailment	Multi-mode CCGT not allowed	Multi-mode CCGT allowed
MWh	11,674	12,079
% of Total Wind	0.063	0.066

Table VI shows the number of hours that the hourly replacement reserve target could not be met. It is clear that the extra fast-starting generation available to the system when multi-mode operation of CCGT units is allowed greatly reduces the

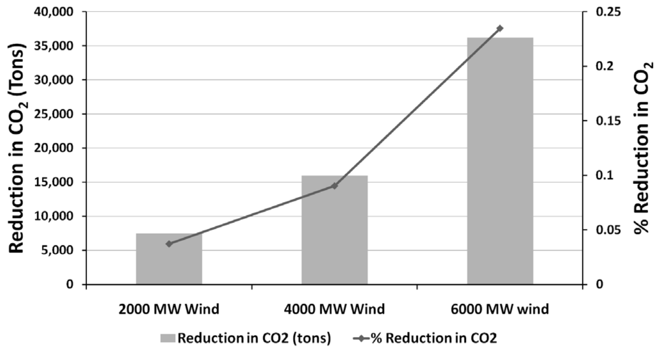

Fig. 1. Reduction in CO_2 emissions resulting from facilitation of multi-mode CCGT operation, shown for various generation portfolios

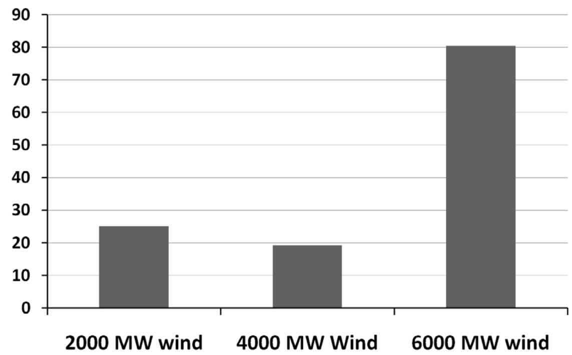

Fig. 2. Average number of instances generators switched between combined-cycle and open-cycle operation and vice-versa, shown for various levels of installed wind

number of hours that there is insufficient replacement reserve. Thus the system benefits from increased security and is more likely to meet system adequacy targets.

TABLE VI
NUMBER OF HOURS REPLACEMENT RESERVE TARGET CANNOT BE MET, SHOWN FOR VARIOUS LEVELS OF INSTALLED WIND

	Multi-mode not allowed	**Multi-mode allowed**
2000 MW Wind	78	2
4000 MW Wind	111	7
6000 MW Wind	118	4

Figure 2 shows the average number of instances the CCGTs with multi-mode capability switched between combined-cycle and open-cycle operation. As seen in Figure 2, this multi-mode operation is employed more frequently at the highest wind penetration examined. This is due to the CCGT units being off-line more frequently as more wind is installed on the system and as such they have more opportunity to utilize open-cycle operation when the CCGT is off-line.

It was seen, however, that CCGT 1 and 2 rarely utilized the multi-mode function, even in the highest wind scenario. These units are located in Northern Ireland and therefore contribute to meeting the minimum number of units online constraint in that region (necessary to maintain a sufficient level of inertia). As there are less generators available to contribute to the constraint in Northern Ireland relative to the Republic of Ireland, CCGT 1 and 2 spend a much greater number of hours online relative to CCGT 3 and 4 and therefore do not have as much opportunity to operate in open-cycle mode.

Figure 3 shows the change in the average number of hours online for CCGT 3 and 4, when operating as a combined-cycle only and when operating as a combined-cycle or open-cycle unit, with varying levels of peaking capacity on the system. As seen in Figure 3, the number of hours the units operated as a combined-cycle is reduced when multi-mode operation is allowed. However, when the hours in which the unit operates in open-cycle mode are included, the facilitation of multi-mode operation shows an increase in the total number of hours online for a CCGT unit. Figure 3 shows that as the amount of peaking capacity on the system is reduced, CCGT units with multi-mode capability will spend more hours online due to the unit running in open-cycle mode more frequently.

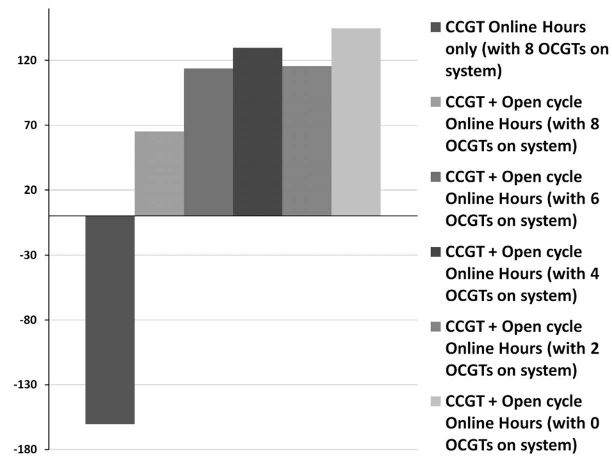

Fig. 3. Change in average number of online hours for CCGT 3 and 4 resulting from facilitation of multi-mode CCGT operation, shown for various generation portfolios

Figure 4 shows the change in revenue earned for each of the CCGTs, in each of the wind scenarios examined. Revenues were calculated as:

$$\sum_{hour=1}^{hours} Plant\ Production_{hour} * System\ Marginal\ Price_{hour} \tag{2}$$

It can be seen from Figure 4 that each of the CCGTs benefit from increased revenue when multi-mode operation is allowed, with the exception of CCGT 3 and 4 on the system with 6000 MW wind. The reduction of over €300,000 and almost €2,000,000 seen by CCGT 3 and 4 respectively on the system with 6000 MW wind, represents 0.6% and 4.7% of overall income for these units. Although these units spend more hours online when multi-mode operation is allowed, they capture less revenue during the increased hours of open-cycle operation as the output of the plant is much smaller. However, given the benefits to system reliability that arise when multi-mode operation is allowed, it is likely these units would receive an additional ancillary services payment for having multi-mode capability.

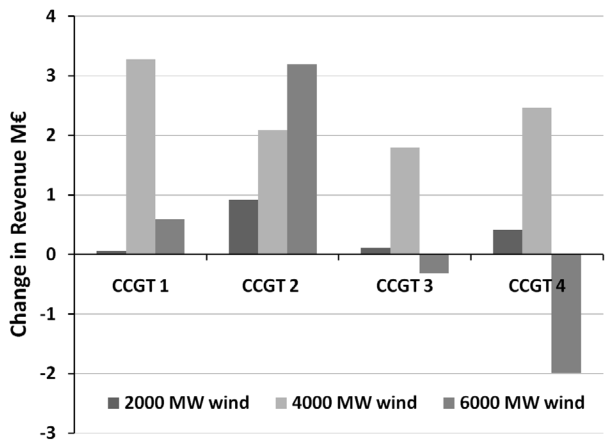

Fig. 4. Change in revenues received by CCGTs resulting from facilitation of multi-mode CCGT operation, shown for various levels of installed wind

However, as seen in Figure 5, despite a reduction in revenue, these units benefit from reduced cycling. Figure 5 shows the average change in start-ups for CCGT 3 and 4 when multi-mode operation is allowed. CCGT 3 and 4 see an average reduction of 25 starts each, or a 15% reduction in starts. In addition to the start-up fuel saving, a reduction in start-ups implies a significant reduction in plant wear-and-tear. It is difficult to estimate what a reduction in cycling is worth but some studies would indicate that an avoided start-up could save generators substantial amounts (up to $500,000) [12]. As hours online increase and start-ups decrease when multi-mode operation is allowed, the average length of an off-line period for a CCGT unit with multi-mode capability will decrease. This is shown for CCGT 4 in Table VII at various levels of installed wind. If the length of time spent off-line decreases the plant is more likely to be in a warmer state when it starts up, thus alleviating the level of creep-fatigue damage associated with start-ups [13].

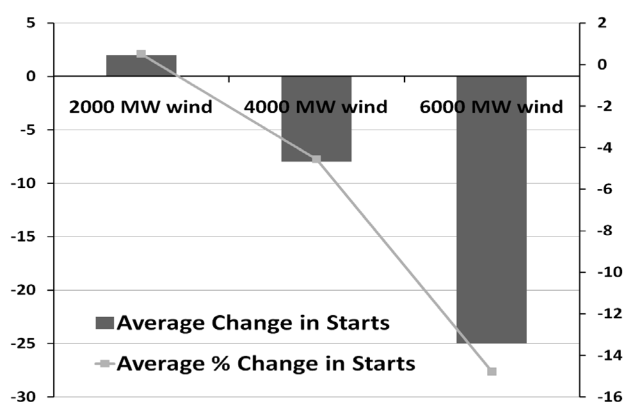

Fig. 5. Average change in start-ups for CCGT 3 and 4 resulting from facilitation of multi-mode CCGT operation, shown for various levels of installed wind

VI. Conclusions

This paper examined if allowing CCGT units to operate in open-cycle mode, when this is technically feasible and cost optimal, delivered any benefits to a system with a large wind penetration or to the generators themselves. Using the Irish 2020 system as a test system it was found that enabling multi-mode operation of CCGTs resulted in reduced CO_2 emissions and increased system security. Generators were seen to exploit the multi-mode function more frequently as the wind penetration increased, due to increased hours off-line and thereby increased opportunity for open-cycle operation. Open-cycle operation of the CCGTs was also seen to increase, as the amount of peaking plant on the system was reduced. The generators investigated benefited from increased revenues when multi-mode operation was allowed, with two exceptions. However, when the avoided wear-and-tear costs of start-ups are taken into consideration, these may likely have benefited overall.

TABLE VII
Average length of off-line period for CCGT 4, shown for various levels of installed wind

	Multi-mode not allowed	**Multi-mode allowed**
2000 MW Wind	17.01	14.46
4000 MW Wind	30.59	27.07
6000 MW Wind	44.55	28.98

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