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 are traditionally considered as relatively inflexible units, but those which incorporate a steam bypass stack are capable of open-cycle operation. Facilitating these units to also operate in open-cycle mode can benefit the power system via improved system reliability, while reducing the production needed from dedicated peaking units. The utilization of the multi-mode functionality is shown to be dependent on the flexibility inherent in the system and the manner in which the system is operated.**

***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 capturing the waste heat from a gas turbine in a heat recovery steam generator (HRSG) and using it to produce superheated 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 have made the CCGT a popular technology choice [2], [3]. In the Republic of Ireland, for example, 43% of the installed thermal capacity is CCGT technology, whilst in the markets of Texas (ERCOT) and New England (NEPOOL), CCGTs represent 37% of the total installed capacity.

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 [4], [5]. To avoid differential thermal expansion across these components and the subsequent risk of cracking, these components must be brought up to temperature slowly, resulting in slower start-up times and ramp rates for the unit overall [6]. However, by incorporating a bypass stack upstream of the HRSG at the design stage, a CCGT unit has the option to bypass the steam cycle and run in open-cycle mode, whereby exhaust heat from the gas turbine is ejected directly into the atmosphere via the bypass stack [6]. This reduces the power output and efficiency of the plant but offers greater operational flexibility. Running in open-cycle mode, the gas turbine has a short start-up time of 15 to 30 minutes and is capable of changing load quickly. However, bypass stacks are not always incorporated because they can potentially lead to leakage losses, thus reducing plant efficiency, while also introducing additional capital costs [1].

As international energy policy drives ever greater penetrations of renewable energy, wind power is set to represent a larger portion of the generation mix [7]. This is driving a greater demand for flexibility within power systems in order to deal with high penetrations of variable and difficult to predict energy sources [8], [9]. Storage, interconnection and responsive demand are commonly cited as flexible options for dealing with variability issues [10]–[12], 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 high wind penetration. This resource is often technically available, but inaccessible due to market arrangements.

In order to derive the greatest benefits from a CCGT unit that can run in open-cycle mode, it is necessary for the scheduling algorithm to explicitly consider both modes of operation for the unit, i.e. open-cycle and combined-cycle [13]. These will have greatly different technical and cost characteristics and so need to be declared individually. Currently most markets do not facilitate CCGT units to submit multiple bids representing different modes of operation, thus presently open-cycle operation of a CCGT unit is typically limited to periods when the steam section is undergoing maintenance. However, some US systems have begun addressing this issue to varying degrees, with ERCOT and CAISO seeking to implement configuration based modeling of CCGTs [14], [15].

The option to run in open-cycle mode could also provide benefits for the generators. Renewable integration studies have shown that CCGT units will experience significant decreases in running hours and thus will receive less revenue from the market as they are displaced by greater levels of wind generation which has an almost zero marginal cost [16]–[20]. Due to their high minimum loads CCGTs are shut down frequently with high wind penetrations as they cannot reduce output sufficiently to accommodate the wind power output [16]. By facilitating CCGT units to operate in open-cycle mode, these units may have a new opportunity to capture revenue from increased operation during periods when they might otherwise be offline. For example, if a CCGT unit has been forced offline by high wind generation on the system, it may have the opportunity to run as a peaking unit.

This paper builds on preliminary work in [21] and includes

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improved modeling of CCGTs from that in [21] to examine if a power system with a high wind penetration can benefit from the additional flexibility introduced when these units are facilitated to operate in open-cycle mode, when technically feasible and economically suitable. The all-island Irish 2020 system [22] is considered here as it is expected to contain both a large share of wind power and CCGT units. In addition, as it is a small, island system that is weakly interconnected, the challenges of maintaining the supply/demand balance with a high wind penetration are exacerbated, and so the solutions found can hold insights for other systems pursuing large-scale wind power. Section II describes the modeling tool used in this study and also the changes that were made to model multi-mode operation of CCGTs. Section III outlines the test system used. Section IV describes the results of the study and Section V concludes the paper.

II. Modeling Tool

The Wilmar Planning Tool is a stochastic, mixed integer unit commitment and economic dispatch model, originally developed to model the Nordic electricity system and later adapted to the Irish system as part of the All Island Grid Study [22]–[25]. The main functionality of the Wilmar Planning Tool is embedded in the Scenario Tree Tool and Scheduling Model.

The Scenario Tree Tool utilizes historical wind power or wind speed data, load data and wind and load forecasts for different time horizons to identify an Auto Regressive Moving Average (ARMA) series which can then simulate wind and load forecast errors for various time horizons [26]. These simulated wind and load forecasts errors are paired in a random way before a scenario reduction technique, following the approach of [27], is applied. The wind and load forecast errors are combined with scaled up wind and load time series to produce wind power production and load forecast scenarios. For each scenario the demand for replacement reserve (activation time >5 minutes) is calculated based on a comparison of the hourly power balance considering perfect forecasts and no forced outages with the power balance considering scenarios of wind and load forecast errors as well as forced outages. A percentile of the deviation between the compared power balances must be covered by replacement reserves; in this case the 90^{th} percentile is chosen based on current practice [23]. A forced outage time series for each unit is also generated by the Scenario Tree Tool using a semi-Markov process based on historical plant data of forced outage rates, mean time to repair and scheduled outages.

The model can also be run in deterministic and perfect foresight modes whereby only one wind generation and load scenario is planned for. In deterministic mode, this scenario is the expected value of wind and load. The expected value of wind is found by summing, for all (post-reduction) scenarios, the product of the wind power forecasts and their probability of occurring. The expected value of load and replacement reserve is found similarly [24]. Consequently, the scenario planned for will differ from the realized scenario. This mode is typical of the scheduling process currently practiced by most system operators, i.e. only one scenario is planned for and it will contain some level of forecast error. Perfect foresight mode contains no forecast error for wind generation or load but forced outages still occur, as with all other modes.

The Scheduling Model minimizes the expected costs for all scenarios, subject to system constraints for reserve and the 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 fuel costs (always assumed to be hot starts). In addition to replacement reserve, one category of spinning reserve, namely tertiary operating reserve (TR1), is modeled, which has a response time of 90 seconds to 5 minutes and is only supplied by online units. Enough spinning reserve must be available to cover an outage of the largest online unit occurring concurrently with a fast decrease in wind power production over the TR1 time frame, as described in [28].

Generator constraints such as minimum down times, synchronization times, minimum operating times and ramp rates must also be obeyed. Rolling planning is employed to re-optimize the system as new wind generation and load information become available. Starting at noon each day, the system is scheduled over 36 hours until the end of the next day. The model steps forward with a three hour time step and reschedules the units based on information from new forecasts. The model produces a year-long dispatch at an hourly time resolution for each individual generating unit. Further detail on the model and formulation of the unit commitment problem can be found in [23]. The Generic Algebraic Modeling System (GAMS) is used to solve the unit commitment problem using the mixed integer feature of the Cplex solver (version 12). For all simulations in this study the model was run with a duality gap of 0.5%. A year-long simulation takes >3 hours when run in deterministic mode or >24 hours in stochastic mode, on an Intel core quad 3 GHz processor with 4 GB of RAM.

Modeling multi-mode operation of CCGTs

In order to examine the potential for multi-mode operation of CCGT units a set, 'ccgt', of all CCGT units capable of prolonged open-cycle operation, i.e. those with bypass stacks, was defined. The set '$ccgt_a^{open}$' corresponds to these CCGT units when run in open-cycle mode. CCGT units comprised of two or more gas turbines will have multiple '$ccgt_a^{open}$' units, as indicated by index 'a'. The relation 'multi-mode' is defined to pair each member of 'ccgt'with the corresponding member(s) of '$ccgt_a^{open}$'. To ensure the mutually exclusive operation of these 'ccgt' units and the corresponding '$ccgt_a^{open}$' units, the constraint shown in (1) was added to the model, where V^{Online} is the state binary variable which describes the online status of the unit. This allows the model to dispatch, when economically optimal, either the 'ccgt' (combined-cycle mode) or any/all of the corresponding '$ccgt_a^{open}$' units (open cycle mode), for all scenarios 's' and time steps 't', but not both simultaneously as they are in reality the same unit.

$$\begin{aligned} & V_{s,t,ccgt}^{Online} + V_{s,t,ccgt_a^{open}}^{Online} \leq 1, \\ & \forall\ s,\ t,\ multi-mode(ccgt, ccgt_a^{open}) \end{aligned} \tag{1}$$

Equation 2, taken from [29], sets the state binary variables $V_{s,t,i}^{Start}$ or $V_{s,t,i}^{Shut}$ equal to 1 for all units 'i', when a unit is started up or shut down respectively.

$$V^{Start}_{s,t,i} - V^{Shut}_{s,t,i} = V^{Online}_{s,t,i} - V^{Online}_{s,t-1,i} \quad (2)$$

When modeling multi-mode operation of CCGT units two new circumstances arise when calculating the start-up fuel consumption, $\mathrm{Fuel}^{Start}_{s,t,i}$, which must be explicitly represented. Firstly, when a 'ccgt' unit transitions from conventional combined-cycle operation into open-cycle operation no start-up fuel is consumed by the '$\mathrm{ccgt}^{\mathrm{open}}$' unit as represented by inequality (3), where $\mathrm{Startfuel}_i$ is the start-up energy used by each unit (measured in MWh). When the '$\mathrm{ccgt}^{\mathrm{open}}$' unit starts from zero production ($\mathrm{V}^{Start}_{s,t,ccgt^{open}_a}$ = 1 and $\mathrm{V}^{Shut}_{s,t,ccgt}$ = 0), the first term on the right hand side of inequality (3) determines the fuel used by the unit whilst the second term equals zero. Alternatively, when the unit switches from combined-cycle to open-cycle operation ($\mathrm{V}^{Start}_{s,t,ccgt^{open}_a}$ = 1 and $\mathrm{V}^{Shut}_{s,t,ccgt}$ = 1) the second term causes the right hand side of (3) to equal zero. Setting $\mathrm{Fuel}^{Start}_{s,t,i}$ as a positive variable and using an inequality condition ensures that when a 'ccgt' unit is shutting down and the corresponding '$ccgt^{open}$' unit is not starting up $\mathrm{Fuel}^{Start}_{s,t,ccgt^{open}_a}$ will be 0.

$$\begin{aligned} Fuel^{Start}_{s,t,ccgt^{open}_a} \geq &\ (Startfuel_{ccgt^{open}_a} * V^{Start}_{s,t,ccgt^{open}_a}) \\ &- (Startfuel_{ccgt^{open}_a} * V^{Shut}_{s,t,ccgt}) \end{aligned} \quad (3)$$

The second circumstance relates to the unit transitioning from open-cycle to combined-cycle operation. In this case the start-up fuel consumed is less than the start-up fuel used in bringing the CCGT online from zero production, as some of this start-up fuel has already been used to bring the unit online in open-cycle mode and the gas section of the plant is in a hot state. As an approximation, the start-up fuel used to bring the unit into combined-cycle operation from open-cycle operation is the difference between the start-up fuel for the 'ccgt' and a fraction, α, of the start-up fuel for the '$ccgt^{open}$', as seen in (4). Based on the operating experience of generators, α was chosen to be 0.5 here. When the 'ccgt' unit is started from zero production ($\mathrm{V}^{Start}_{s,t,ccgt_a}$ = 1 and $\mathrm{V}^{Shut}_{s,t,ccgt^{open}_a}$ = 0), the first term on the right hand side of (4) provides the start-up fuel consumed whilst the second term equals zero. When the unit switches from open-cycle to combined-cycle operation the second term is included, thus approximating the start-up fuel consumed in this situation.

$$\begin{aligned} Fuel^{Start}_{s,t,ccgt} \geq &\ (Startfuel_{ccgt} * V^{Start}_{s,t,ccgt}) \\ &- (Startfuel_{ccgt^{open}_a} * V^{Shut}_{s,t,ccgt^{open}_a} * \alpha) \end{aligned} \quad (4)$$

In the Wilmar model any unit can contribute to the target for replacement (non-spinning) reserve, provided that an offline unit can come online in time to provide reserve for the hour in question and the reserve available from an online unit is not needed to meet spinning reserve targets. In Wilmar, the contribution from online and offline units to the replacement reserve target, $\mathrm{P}^{Off}_{s,t,i}$ (MW), are calculated individually. In this case the 'ccgt' units cannot provide offline replacement reserve as they have long start-up times, but the corresponding '$ccgt^{open}$' units can, given their fast start-up times. The constraints shown in (5) and (6), where cap^{Min}_i is a unit's minimum stable operating level (MW) and cap^{Max}_i is a unit's maximum capacity (MW), ensure that if either the 'ccgt' unit or the '$ccgt^{open}$' unit is online, then the '$ccgt^{open}$' unit cannot contribute to the portion of replacement reserve that is provided from offline units. This is necessary to avoid the situation where a 'ccgt' unit is online and the model allows the corresponding '$ccgt^{open}$' unit to contribute to offline replacement reserve.

$$P^{Off}_{s,t,ccgt^{open}_a} \leq cap^{Max}_{ccgt^{open}_a} * (1 - V^{Online}_{s,t,ccgt}) \quad (5)$$

$$P^{Off}_{s,t,ccgt^{open}_a} \leq cap^{Max}_{ccgt^{open}_a} * (1 - V^{Online}_{s,t,ccgt^{open}_a}) \quad (6)$$

Improved modeling of plant start-ups was also implemented following the formulation given in [29]. This allows for those units with start-up times greater than 1 hour to be block-loaded over the course of their start-up time. In earlier versions of the Wilmar model, units remained at zero production for the duration of start-up process. The addition of this feature significantly increased the computation time, so only the start-up process of the CCGT units was modeled in detail. Other units with a start-up time greater than 1 hour, namely the coal-fired units, typically have fewer starts over the year and lower minimum operating levels relative to the CCGTs and so modeling their start-up process in detail would have little impact on the results.

When the bypass stack is utilized to switch from combined-cycle to open-cycle operation, the transition is automatic and occurs without shutting down the gas turbine or reducing its power output. However, the transition from open-cycle to combined-cycle operation is dependent on the temperature state of the boiler. Therefore, if the CCGT unit has been operating for a period of time in open-cycle mode and is then scheduled to switch to combined-cycle mode, its output must adjust in order to achieve the correct HRSG inlet temperature, as depicted in Figure 1. This was implemented by setting the allowable power output ($P_U(i)$ from [29]) for each interval of the CCGT's start-up process, which begins at hour 0 in Figure 1, such that the appropriate soak time is achieved.

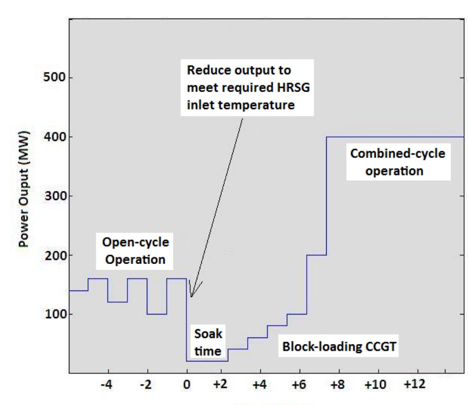

Fig. 1. CCGT start-up from open-cycle mode

Scheduled outages for each unit, determined from historical experience [22], are inputted in time-series format to the Wilmar model. In this case, CCGT units with the capability to operate in open-cycle mode are considered to be available to run in open-cycle mode for a portion of their scheduled outage. Given that gas turbine equipment is more accessible and compact in comparison with the steam turbine equipment, it was assumed that one third of the maintenance period was sufficient for the gas turbine.

III. Test System

The test system used is the Irish 2020 system, based on portfolio 5 from the All Island Grid Study [22], [30]. Four 103.5 MW OCGT units were removed from the original grid study portfolio as recent generation adequacy reports would indicate they are unlikely to be built by 2020 [31]. Table I shows the number of units, installed capacity and average operating cost (fuel) by generation type. (The multi-mode capable CCGT units in open-cycle mode are shown on the last row.) Three different levels of installed wind power were examined: 2000, 4000 and 6000 MW, which supply 15%, 29% and 44% of the total energy demand respectively. Fuel prices are as given in Table II. Base-load gas generators (i.e. CCGTs and CHP) are assumed to have long-term fuel contracts and therefore pay a cheaper fuel price compared to mid-merit gas generators (i.e. OCGTs, ADGTs and legacy CCGTs). Differences in the fuel price for coal and gasoil in the Republic of Ireland and Northern Ireland reflect varying delivery costs. The original demand profile from [22] with a 9.6 GW peak and 54 TWh total demand was scaled down to a profile with a 7.55 GW peak and 42 TWh total demand to reflect a reduction in predicted demand, seen in recent long term forecasts [31].

TABLE I
Generation Mix of Test System

Generation Type	Capacity (MW)	No. Units	Avg. Operating Cost (€/MWh)
Wind power	2000/4000/6000		0
CCGT	4012	10	39.79
Coal	1324	5	18.45
OCGT	414	4	61.16
Gasoil	383	8	121.26
Other renewables	360		10
Peat	343	3	36.32
Pumped storage	292	4	0
Hydro	216	15	0
Legacy CCGT	215	2	47.97
CHP	166	2	37.94
ADGT	111	1	47.85
Tidal	72		0
$CCGT^{Open}$	1441	7	55.24

The test system assumes that there is 1000 MW of HVDC interconnection in place between Ireland and Great Britain and it is scheduled on an intra-day basis, i.e. it can be rescheduled in every 3 hour rolling planning period. A simplified model of the British power system is included, with aggregated units, no integer variables for generators and where wind generation and load are assumed to be perfectly forecast. The total demand in Britain is assumed to be 370 TWh with a peak of 63 GW and the installed wind capacity is assumed to be 14 GW. A carbon price of €30/tonne was assumed.

TABLE II
Fuel Prices by Fuel Type

Fuel	Fuel Price (€/GJ)
Renewables	0
Coal - Republic of Ireland	1.75
Coal - Northern Ireland	2.11
Peat	3.71
Base-load gas	5.91
Mid-merit gas	6.12
Gasoil - Northern Ireland	8.33
Gasoil - Republic of Ireland	9.64

Five (of the ten) CCGT units on the Irish system include bypass stacks and therefore can run in open-cycle mode. Each of these units is currently installed and operational. The characteristics of 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 given characteristics similar to a typical open-cycle gas turbine (OCGT) unit, as shown in Table III. As CCGT 2 and CCGT 5 are comprised of two gas turbines connected to one steam turbine (2+1 configuration), these units were modeled as having two identical open-cycle units available for dispatch when the CCGT is operated in open-cycle mode. CCGTs 2 and 3, located in Northern Ireland and CCGTs 1, 4 and 5, located in the Republic of Ireland contribute to the minimum units online constraint in their respective regions.

TABLE III
Characteristics of CCGT units (capable of multi-mode operation) in combined- and open-cycle modes

CCGT	1	2	3	4	5
Configuration	1+1	2+1	1+1	1+1	2+1
	Characteristics in combined-cycle mode				
Max output (MW)	445	480	404	343	480
Min output (MW)	240	232	260	220	280
Max efficiency (%)	57.6	58.9	53.9	52.9	52.3
Min up time (Hours)	4	4	6	4	4
Min down time (Hours)	1	2	4	4	2
Start-up time (Hours)	2	1	1	2	4
Hot start-up fuel (GJ)	2600	2000	1080	1732	2000
Max spinning reserve contribution (MW)	42	37	40	25	40
Efficiency at max spinning reserve (%)	57.4	58.1	52.8	52.2	51.3
	Characteristics in open-cycle mode				
Max output (MW)	280	160	256	265	160
Max efficiency (%)	39.5	38	39.3	39.3	38
Min up time (Hours)	0	0	0	0	0
Min down time (Hours)	0	0	0	0	0
Start-up time (Hours)	0	0	0	0	0
Hot start-up fuel (GJ)	14	8	13	13	8
Max spinning reserve contribution (MW)	20	20	20	20	20
Efficiency at max spinning reserve (%)	39.3	37.5	39.1	39.2	37.5

IV. Results

A number of model runs were conducted to investigate the potential for multi-mode operation of CCGT units. The Wilmar model was run in deterministic mode as this is more representative of current scheduling practice. A year long dispatch was produced for each of the three wind power

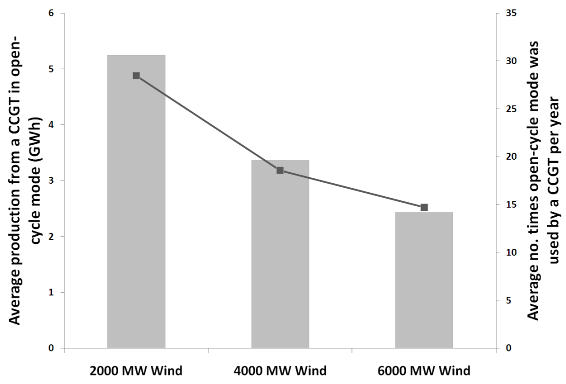

Fig. 2. Average production from a CCGT in open-cycle mode (line) and average number of instances generators utilized open-cycle operation (grey column), shown for various levels of installed wind capacity

penetrations outlined in Section III, when (i) multi-mode operation of CCGT units is not allowed and (ii) when multi-mode operation of CCGT units is allowed.

A. Usage of the multi-mode function

The average number of times a CCGT unit with multi-mode capability was run in open-cycle mode and the average production from a CCGT in open-cycle mode over the year, at each of the wind penetrations examined, is shown in Figure 2. Despite increasing wind penetration being correlated with an increased demand for flexibility, be it fast starting or ramping, Figure 2 shows the multi-mode function is used less frequently as wind penetration on the system increases.

As more wind power, with an almost zero marginal cost, is added to a system, the production from thermal plant is increasingly displaced and as such there is an increased likelihood of generators operating at part-load. To illustrate, Table IV gives the annual utilization factor (ratio of actual generation to maximum possible generation during hours of operation) averaged for the coal, CCGT and peat units on the system with 2000, 4000 and 6000 MW wind power. Therefore, as wind penetration increases, online part-loaded units are more often available to ramp up their output to meet unexpected shortfalls in production, avoiding the need to switch on fast-starting units, such as the CCGTs in open-cycle mode.

TABLE IV
AVERAGE UTILIZATION FACTORS WITH INCREASING WIND PENETRATION

Installed Wind	2000 MW	4000 MW	6000 MW
Coal	0.90	0.87	0.82
CCGT	0.83	0.79	0.80
Peat	0.75	0.55	0.51

The trend seen in Figure 2 is consistent with the production from peaking plants as wind penetration increases. Table V shows the drop in production from the most utilized OCGT unit, with increasing wind penetration when multi-mode operation is and is not allowed. Reduced production from peaking plants due to increased wind penetration has also been observed in other wind integration studies such as [17], however, it is also likely that systems with base-load units that have slower ramp rates than those examined in this study will rely on fast-starting units (such as CCGTs in open-cycle mode) more often as wind penetration increases. [All units on the test system are assumed to be capable of ramping from minimum to maximum output in one hour or less.] The average production from the CCGT units in open-cycle mode, as seen in Figure 2, is comparable with average production levels from dedicated OCGT peaking plants on the system when multi-mode operation of CCGTs is not enabled.

TABLE V
OCGT PRODUCTION (GWH) WITH INCREASING WIND PENETRATION

Installed Wind	2000 MW	4000 MW	6000 MW
Multi-mode not allowed	8.5	3.9	3.4
Multi-mode allowed	2	0.2	0.3

As wind penetration increases so too will the demand for replacement reserve, due to the increased forecast error. The replacement reserve target can be met by fast-starting offline units or from excess spinning reserve if available. If sufficient excess spinning reserve is not available to meet the replacement reserve target, the model must ensure a number of fast-starting units are offline and available for operation to maintain a secure system. Consequently, as a result of maintaining the replacement reserve target, production from fast-start units (such as the multi-mode units in open-cycle mode) is reduced. Additional simulations were conducted for the various wind penetrations with no replacement reserve target, to investigate the extent that maintaining replacement reserve suppressed the multi-mode units from running in open-cycle mode. For many systems, such as the Irish system, this is more representative of current practice, where no replacement reserve target formally exists. Table VI shows the difference in the average open-cycle production from multi-mode units that results when no replacement reserve targets are enforced.

TABLE VI
DIFFERENCE IN OPEN-CYCLE PRODUCTION (GWH) FROM MULTI-MODE UNITS WITH NO REPLACEMENT RESERVE TARGET ENFORCED

Installed Wind	2000 MW	4000 MW	6000 MW
$\triangle$ Production	16.9%	7.2%	-0.5%

As seen, in the absence of a target for replacement reserve, open-cycle production from the multi-mode units is utilized substantially more for the 2000 MW and 4000 MW wind power scenarios. However, with 6000 MW wind power, due to more frequent part-loading of units, there is more frequently an excess of spinning reserve on the system, as well as off-line fast-starting units (as per Table V) which can contribute to the replacement reserve target. Thus with 6000 MW wind power, the replacement reserve target has little effect on the open-cycle operation of multi-mode units. Table VII shows the average surplus spinning reserve available and the average replacement reserve target per hour for each of the wind cases examined.

Figure 3 shows the capacity factor for each CCGT in combined-cycle mode and its production over the year in open-cycle mode for the 2000 MW wind power scenario. An inverse

TABLE VII
AVERAGE HOURLY SURPLUS SPINNING RESERVE (MW) AVAILABLE AND REPLACEMENT RESERVE TARGET (MW)

Installed Wind	2000 MW	4000 MW	6000 MW
Surplus spinning reserve	65	120	240
Replacement reserve target	500	580	700

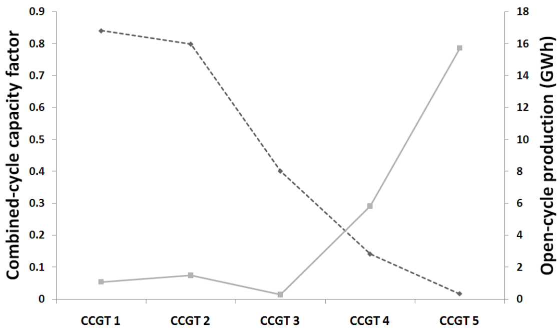

Fig. 3. Combined-cycle capacity factor (dashed line) and open-cycle production (solid line) for each CCGT with multi-mode capability for the 2000 MW wind power system

TABLE VIII
PERCENTAGE CHANGE IN TOTAL PRODUCTION WHEN MULTI-MODE IS ENABLED, SHOWN FOR EACH WIND PENETRATION

Installed Wind	2000 MW	4000 MW	6000 MW
CCGT1	5.5	5.4	-7.5
CCGT2	0	0.1	-0.1
CCGT3	-3.3	5	-2.5
CCGT4	-1.4	-7.3	-37.1
CCGT5	13.3	38.5	11.1

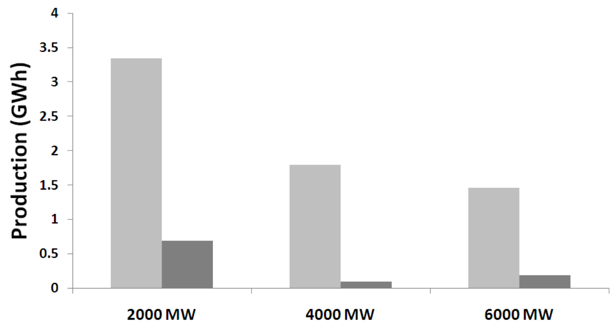

Fig. 4. Average production from OCGT peaking units in each wind power scenario, with multi-mode operation of CCGTs not allowed (light grey) and allowed (dark grey)

relationship is evident between the open-cycle production from a CCGT and the capacity factor of the CCGT, which indicates that usage of the multi-mode function is related to the amount of time the CCGT is offline. The more often a CCGT is not in operation but available for dispatch, the more opportunities it has to run in open-cycle mode and this relationship would be expected regardless of the plant portfolio.

The percentage change in total production (combined-cycle plus open-cycle) that results when multi-mode operation of CCGTs is enabled is shown in Table VIII, for each of the wind penetrations examined. Multi-mode operation increased production for CCGT5, the lowest merit CCGT which was seen to utilize the function most frequently, across all the wind penetrations examined. Total production from CCGT3 and CCGT4, which are mid-merit CCGTs, is reduced in all cases but one. There is a risk, (particularly for CCGTs that are frequently the marginal unit on the system such as CCGT3 and CCGT4) when offering open-cycle operation, of being dispatched from combined-cycle to open-cycle operation at times of low net demand (demand minus wind generation) to alleviate minimum load issues and then losing out to another generator that can come online faster/cheaper, when the net demand increases again. However, it is also likely that in a market environment, generators would strategise when they would offer this multi-mode capability to avoid losing out on production. CCGT1, the highest merit CCGT, benefits from increased production when multi-mode operation is enabled on the system with 2000 MW and 4000 MW installed wind power. This is due to increased exports and reduced production from the other CCGTs, as opposed to increased production in open-cycle mode.

B. Benefits arising from multi-mode operation

The efficiencies of the OCGT peaking units on the system are comparable with the CCGT units in open-cycle mode. However, the CCGT units running in open-cycle operation are assumed to have a lower gas price, to reflect the advantage of long-term contracts. Their open-cycle capacity (as seen in Table III) is also larger than the capacity of the OCGTs (103.5 MW each) and they benefit from avoided start-up costs when transitioning from combined-cycle mode. Thus, when multi-mode operation of CCGTs was enabled, production from OCGT peaking plant tended to be substituted by production from the CCGTs in open-cycle mode. Figure 4, which shows the average production from OCGTs for each wind penetration level when multi-mode operation of CCGTs is allowed and not allowed, illustrates this point. Assuming open-cycle production from CCGTs is more economic than production from OCGTs, as is the case here, it is possible that by enabling multi-mode operation of CCGTs sufficient flexibility could be extracted from a systems portfolio of plant to avoid building additional peaking units, or equally that OCGT units would no longer be able to cover their costs and so would be forced to retire from service. Both situations may then lead to increased production from CCGTs in open-cycle mode.

Table IX shows the total shortfall in replacement reserve over the year and the number of hours in which this occurred, for each of the wind penetrations examined, when multi-mode operation of CCGTs is and is not allowed. The additional fast-starting generation available to the system when multi-mode operation of CCGT units is allowed significantly reduces the shortfall in replacement reserve. This contributes to a more secure system by preventing capacity shortfalls when wind forecasts prove to be overly optimistic and also indicates that, depending on the market structure, the generators may benefit from an additional revenue stream, via ancillary services payments for the replacement reserve provided.

In addition to enhanced system security, the additional flexibility available to the system when multi-mode operation

TABLE IX
MAGNITUDE AND FREQUENCY OF REPLACEMENT RESERVE SHORTFALL, SHOWN FOR VARIOUS LEVELS OF INSTALLED WIND

Installed Wind	Multi-mode CCGT not allowed		Multi-mode CCGT allowed	
MW	MWh	No. hours	MWh	No. hours
2000	1688.7	13	861.4	3
4000	2972.9	17	880.2	5
6000	609.9	13	7.6	1

of CCGT units is allowed will also yield production costs savings. Table X shows the total system operating cost savings achieved by enabling multi-mode operation of CCGTs. The total system cost is made up of fuel, carbon and start-up costs for the Irish and British system combined, as they are co-optimized. In this case, these savings were achieved at no additional cost as each of the CCGTs is currently capable of multi-mode operation.

TABLE X
TOTAL SYSTEM COST SAVING (M€) RESULTING FROM MULTI-MODE OPERATION OF CCGTS

Installed Wind	2000 MW	4000 MW	6000 MW
Reduction in costs	1.55	0.51	2.65

A modest reduction in plant start-ups for multi-mode units (in combined-cycle mode) was also observed ($\approx$10% averaged over the three wind power scenarios), relative to the case when multi-mode operation is not allowed, which would indicate benefits for the steam equipment via avoided wear-and-tear.

C. Sensitivity studies

Usage of the multi-mode function is dependent on many factors, particularly the amount of flexibility already present in the system. A sensitivity study was conducted to examine the usage of the multi-mode function when the system was less flexible to meeting demand. This involved running the model with 2000 MW wind power (as this level of wind generation greatest usage of CCGTs in open-cycle mode) and power exchange across the interconnector fixed day-ahead as opposed to intra-day. Examining the usage of the multi-mode function when the interconnector is scheduled day-ahead versus intra-day illustrates how a less flexible system will utilize this flexible resource more frequently. Figure 5 shows the average production from a CCGT in open-cycle mode and the average number of instances CCGTs utilized open-cycle operation, with the interconnector scheduled day-ahead and intra-day on the 2000 MW wind power system. The average production from CCGTs in open-cycle mode on the system with day-ahead scheduling of the interconnector is seen to be more than three times greater than the system with intra-day scheduling of the interconnector. By fixing the power exchange between the Irish and British systems day-ahead, when there is greater uncertainty in the expected wind generation and demand, the system is forced to dispatch generators such as the multi-mode CCGT units, as opposed to reschedule imports/exports, to compensate for wind and load forecast errors. Likewise, systems with seasonal hydro restrictions may see greater usage

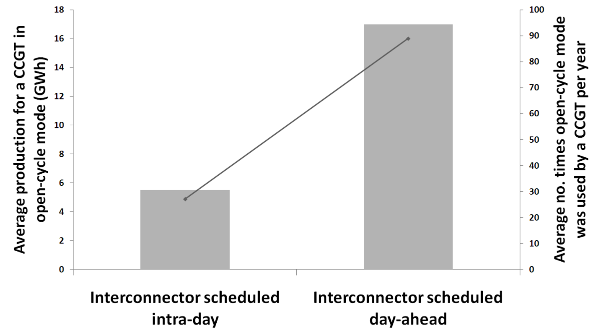

Fig. 5. Average production from a CCGT in open-cycle mode (line) and average number of instances generators utilized open-cycle operation (grey column), with interconnector scheduled day-ahead and intra-day on 2000 MW wind system

of multi-mode CCGT operation during these periods when the operating flexibility of the system is reduced.

In addition, the type of wind and load forecasts employed by a system will also determine the usage of the multi-mode function. Additional simulations were completed running the model in stochastic and perfect foresight mode. These represent different means of including load and wind forecasts in the scheduling process; whereby stochastic optimization can be considered to represent a system employing ensemble forecasts, deterministic optimization is representative of a system utilizing a single forecast and the perfect forecast scenario is a hypothetical case where no forecast error exists. The robust solutions obtained by stochastic optimization showed less deployment of the multi-mode function compared with the deterministic results. The stochastic solution, optimized for several wind and load scenarios, typically has more units online to cover all scenarios and therefore is more prepared to deal with unforseen shortfalls in wind generation or increases in demand without the need for starting peaking plant. The capacity factors of the CCGT units are also higher for the stochastic case compared to the deterministic case indicating that there was also less opportunity for these units to run in open-cycle mode when the system is optimized stochastically. Running the Wilmar model with perfect foresight of the system demand and wind profile also reveals even less open-cycle operation from CCGTs as in this case, with no forecast errors on the system (except forced outages of generators), fast starting units are in less demand relative to the deterministically optimized solution. Figure 6 compares the average open-cycle operation from the multi-mode CCGTs, on the system with 2000 MW wind power, when optimized with perfect foresight, stochastically and deterministically. The average open-cycle production from a CCGT unit is seen to be 11% less on the stochastically optimized system and 35% less on the system with perfect forecast compared to the deterministic case.

A sensitivity analysis was also conducted using a higher level of demand on the system. In this case the original demand profile from [22] with a 9.6 GW peak, discussed in Section III, was run for each wind scenario. The average production from a CCGT in open-cycle mode over the year is shown in Figure 7 to be six to eight times greater on the 9.6 GW peak demand system, where peaking capacity is in greater

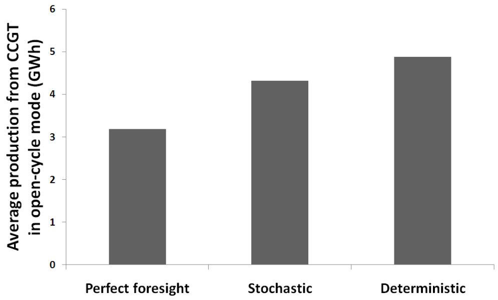

Fig. 6. Average production from CCGT in open-cycle mode (GWh), shown for different methods of optimization with 2000 MW wind power

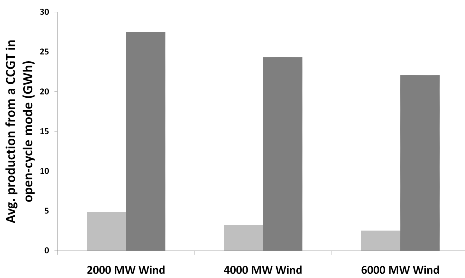

Fig. 7. Average production from a CCGT in open-cycle mode on the 7.55 GW peak demand system (light grey) and the 9.6 GW peak demand system (dark grey), shown for various levels of installed wind power

demand, compared to the 7.55 GW peak demand system, at each of the wind power penetrations examined. In addition to the increased demand resulting in increased open-cycle production from the multi-mode CCGTs (as well as combined-cycle production), the other main difference between the scenarios is the predominant direction of power transfer on the interconnector. With 2000 MW installed wind capacity the Irish system is a net importer of power from Britain, at both levels of demand examined. However, as more wind power is installed on the 7.55 GW peak demand system the marginal electricity price is reduced sufficiently with respect to the British system such that Ireland becomes a net exporter of power. Although increasing wind power penetration on the 9.6 GW peak demand system also reduces the marginal price it is still a net importer with 6000 MW installed wind power. Thus, on occasions when forecast wind is overestimated and the system is in need of fast-starting plant, the 7.55 GW peak demand system, being a net exporter, can more frequently choose to curtail exports or start up a unit to compensate. In contrast, the 9.6 GW peak demand system, being a net importer, more often only has the option to turn on fast-starting plant. Hence, this implies that a system which tends to be a net exporter is inherently more flexible, and has more options for dealing with variable wind power than a system that is a net importer of power. In this scenario with higher demand, each of the multi-mode CCGT units experienced increased total production (combined-cycle plus open-cycle) when multi-mode operation was allowed, suggesting that offering multi-mode capability may prove more profitable on a system with a smaller capacity margin.

Given the low deployment of the multi-mode functionality and the high capacity factor in combined-cycle mode for CCGT 1 and 2, as seen in Figure 3, it would appear that there is insufficient incentive for all CCGTs capable of multi-mode operation to offer this flexible capability. Thus, given that CCGTs 3, 4 and 5 have low capacity factors in combined-cycle mode, additional simulations were conducted to investigate the benefits yielded if these units alone, and if CCGT 5 alone, offered multi-mode capability. Table XI shows the total system cost (for Ireland and Britain) and the magnitude of the replacement reserve shortfall over the year for these configurations (in addition to other configurations examined in the paper). Examining the shortfall in the replacement reserve target for the different configurations reveals that the majority ($\approx$ 80%) of the reduction in replacement reserve shortfall due to multi-mode capability is attributable to CCGT 5, while CCGTs 1 and 2 are seen to have no impact on the replacement reserve shortfall. Thus CCGTs capable of open-cycle operation, which have very low output in combined-cycle mode, have value in providing replacement reserve.

As seen in Table VIII, the multi-mode CCGTs may experience a reduction in total production as a result of offering multi-mode capability to the market. This was also observed to be the case for CCGTs 3 and 4, when only three units offered multi-mode operation. This indicates that a system seeking to increase its flexibility via multi-mode operation of CCGTs, possibly to facilitate integration of variable renewables, may need to reward these units either through ancillary service payments or another market mechanism to restore their revenue to original levels (i.e. when multi-mode operation was not allowed). The subsidy or "top-up payment" required to restore the revenue of these units to their original level is estimated here as the loss in total production multiplied by the average electricity price. The average "top-up payment" required is shown in Table XI with the number of units requiring this payment shown in parenthesis. However, it should be noted that this represents the worst-case figure given that the multi-mode CCGT unit offered this capability in all time periods, rather than when it was profitable for them to do so, as would likely be the case in reality.

V. Conclusions

This paper examines if allowing CCGT units to operate in open-cycle mode, when this is technically feasible and cost optimal, could deliver benefits to a system with a high wind penetration or to the generators themselves. It is shown that the extra fast-starting capacity available from multi-mode operation of CCGTs can reduce the replacement reserve shortfall, indicating an opportunity for increasing system reliability. Low-merit CCGTs will utilize the multi-mode function more as they are frequently offline and available for dispatch, whilst the increased competition among generators, typical at higher levels of wind generation, results in multi-mode operation of CCGTs being utilized less frequently. Peaking production from CCGTs in open-cycle mode can displace peaking production from OCGTs, potentially reducing the need for such units to be built. Sensitivity studies reveal that usage of the multi-mode function is dependent on the level of flexibility inherent in a

TABLE XI

TOTAL SYSTEM COST, REPLACEMENT RESERVE SHORTFALL AND TOP-UP PAYMENT, SHOWN FOR VARIOUS MULTI-MODE CONFIGURATIONS

Configuration	**Total System Cost / Saving**	**Replacement Reserve Shortfall**	**Avg. Top-up Payment (and no. units)**
All cases with 2000 MW wind power	**M€**	**MWh**	**M€**
7.55 GW Peak, No Multi-mode	13372.03 / -	1688.7	-
7.55 GW Peak, 5 Multi-mode CCGTs	13370.48 / 1.55	861.4	1.36 (2)
7.55 GW Peak, 3 Multi-mode CCGTs (3, 4 & 5)	13368.99 / 3.04	861.4	0.49 (3)
7.55 GW Peak, 1 Multi-mode CCGT (5)	13371.73 / 0.3	1032.4	0
7.55 GW Peak, No Multi-mode, day-ahead interconnector trading	13384.64 / -	2197.9	-
7.55 GW Peak, 5 Multi-mode CCGTs, day-ahead interconnector trading	13382.98 / 1.66	798	1.66 (2)
7.55 GW Peak, No Multi-mode, stochastic	13371.23 / -	966.5	-
7.55 GW Peak, 5 Multi-mode CCGTs, stochastic	13371.27 / -0.04	394	0.91 (2)
7.55 GW Peak, No Multi-mode, perfect foresight	13370.87 / -	0	-
7.55 GW Peak, 5 Multi-mode CCGTs, perfect foresight	13369.38 / 1.49	0	0.45 (1)
9.6 GW Peak, Multi-mode not allowed	13997.24 / -	68345.9	-
9.6 GW Peak, 5 Multi-mode CCGTs	13996.16 / 1.08	63265.3	0

system. Optimizing the system stochastically or allowing intra-day trading on interconnectors reduces the need for flexibility to be extracted from generators and consequently results in less frequent deployment of the multi-mode function.

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REFERENCES

[1] R. Kehlhoffer, *Combined-Cycle Gas & Steam Turbine Power Plants*, 2nd edition, Oklahoma: PennWell Publishing Company, 1999.

[2] W.J. Watson, "The success of the combined cycle gas turbine," in *Proceedings of the IEEE Conference on Opportunities and Advances in International Electric Power Generation*, 1996, pp. 87 - 92.

[3] U.C. Colpier and D. Cornland, "The economics of the combined cycle gas turbine - an experience curve analysis," *Energy Policy*, vol. 30, issue 4, pp. 309 - 316, 2002.

[4] A. Shibli and F. Starr, "Some aspects of plant and research experience in the use of new high strength martensitic steel P91," *International Journal of Pressure Vessels and Piping*, vol. 84, pp. 114-122, 2007.

[5] F. Starr, "Background to the design of HRSG systems and implications for CCGT plant cycling," *Operation Maintenance and Materials Issues*, vol. 2, issue 1, April 2003.

[6] R. Anderson, H. van Ballegooyen, "Steam turbine bypass systems," *Combined Cycle Journal*, Fourth Quarter, 2003.

[7] European Wind Energy Association, "Winning with European Wind," Available: http://www.ewea.org, 2009.

[8] H. Chandler, "Empowering variable renewables, options for flexible electricity systems," International Energy Agency, Paris, France, 2008.

[9] F. Van Hulle, P. Gardner, "Wind Energy - the facts, Part 2 Grid Integration," Available: http://www.wind-energy-the-facts.org/, 2008.

[10] P. Brown, J. Lopes, M. Matos, "Optimization of pumped storage capacity in an isolated power system with large renewable penetration," *IEEE Transactions on Power Systems*, vol. 23, no. 2, pp. 523-531, May 2008.

[11] V. Hamidi, F. Robinson, "Responsive demand in networks with high penetration of wind power," in *Proceedings of IEEE/PES Transmission and Distribution Conference and Exposition*, 2008.

[12] L. Göransson, "Wind power in thermal power systems - large-scale integration," Licentiate Thesis, Dept. of Energy and Environment, Chalmers University of Technology, Goteburg, Sweeden, 2008.

[13] B. Lu and M. Shahidehpour, "Short-term scheduling of combined-cycle units," *IEEE Transactions on Power Systems*, vol. 19, issue 3, pp. 1616 - 1625, 2004.

[14] B. Blevins, "Combined-cycle unit modeling in the nodal design," ERCOT, Taylor, Texas, 2007.

[15] CAISO, "Multi-stage generating (MSG) unit modeling," Available: http://www.caiso.com/2078/2078908392d0.html, 2010.

[16] N. Troy, E. Denny and M. O'Malley, "Base-load cycling on a system with significant wind penetration," *IEEE Transactions on Power Systems*, vol. 25, issue 2, pp. 1088 - 1097, 2010.

[17] NYISO, "Growing Wind - Final Report of the NYISO Wind Integration Study," http://www.nyiso.com, 2010.

[18] California ISO, "Integration of renewable resources - operational requirements and generation fleet capability at 20% RPS," Available: http://www.caiso.com/2804/2804d036401f0ex.html, 2010.

[19] National Renewable Energy Laboratory "Western wind and solar integration study," Available: http://www.nrel.gov/wind/systemsintegration/wwsis.html, 2010.

[20] L. Göransson and F. Johnsson, "Dispatch modeling of a regional power generation system - Integrating wind power," *Renewable Energy*, vol. 34, issue 4, pp. 1040-1049, 2009.

[21] N. Troy and M. O'Malley, "Multi-mode operation of combined cycle gas turbines with increasing wind penetration", in *Proceedings of IEEE Power and Energy Society General Meeting*, 2010.

[22] All Island Renewable Grid Study - Workstream 2B, "Wind variability management studies," Available: http://www.dcenr.gov.ie, 2008.

[23] P. Meibom, R. Barth, B. Hasche, H. Brand and M. O'Malley, "Stochastic optimization model to study the operational impacts of high wind penetrations in Ireland," *IEEE Transactions on Power Systems*, vol. 26, issue 3, pp. 1367 - 1379, 2011.

[24] A. Tuohy, P. Meibom, E. Denny and M. O'Malley, "Unit commitment for systems with significant wind penetration," *IEEE Transactions on Power Systems*, vol. 24, no. 2, pp. 592-601, 2009.

[25] P. Meibom, "WILMAR - Wind Power Integration in Liberalised Electricity Markets," Available: http://www.wilmar.risoe.dk/Results.htm, 2006.

[26] L. Söder, "Simulation of wind speed forecast errors for operation planning of multiarea power systems," in *Proceedings of International Conference on Probabilistic Methods Applied to Power Systems*, 2004.

[27] J. Dupacova, N. Growe-Kuska and W. Romisch, "Scenario reduction in stochastic programming: An approach using probability metrics," *Mathematical Programming*, vol. 95, no. 3, pp. 493 - 511, 2003.

[28] R. Doherty and M. O'Malley, "A new approach to quantify reserve demand in systems with significant installed wind capacity," *IEEE Transactions on Power Systems*, vol. 20, no. 2, pp. 587-595, 2005.

[29] J. M. Arroyo and A. J. Conejo, "Modeling of start-up and shut-down power trajectories of thermal units," *IEEE Transactions on Power Systems*, vol. 19, no. 3, pp. 1562-1568, 2004.

[30] Commission for Energy Regulation, "Redpoint Validated Forecast Model and PLEXOS Validation Report 2010," Available: http://www.allislandproject.org, 2010.

[31] EirGrid, "Generation Adequacy Report 2010 - 2016," Available: http://www.eirgrid.com, 2009.

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