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Analysis of Coal Conversion to Biomass as a Transitional Technology

Derek W. Bunn⁽¹⁾, Jorge Redondo-Martin⁽²⁾, José I. Muñoz-Hernandez⁽²⁾, Pablo Diaz-Cachinero⁽²⁾

⁽¹⁾ London Business School, Sussex Place, Regent's Park, London NW1 5SA, UK

⁽²⁾ Universidad de Castilla-La Mancha, INEI, PEARL, 13071 Ciudad Real, Spain

ABSTRACT

The dominant transitional path towards a low carbon electricity industry for systems which have been heavily dependent upon coal is through its replacement by large scale wind farms and the widespread emergence of distributed solar. In this pathway, maintaining resource adequacy in the context of increased intermittency in generation has become a major concern. This paper examines this requirement to maintain resource adequacy and compare the costs and carbon impacts for new gas turbines or biomass conversions to achieve this in an expedient transitional way. This is formulated as a policy optimization in which the imperative is to replace existing coal with a renewable alternative (in this case study, wind) and to maintain the system security at the existing level, and thereby find the optimal subsidies, either as energy credits ("green certificates" or "contracts-for-differences") or capital benefits ("capacity payments" or tax allowances). In a model of the GB system, the results show that that biomass-conversion outperforms investment in peaking gas turbines to deal with the transitional economic externality of extra reserve costs. In particular, the results suggest benefits of 10% lower costs of subsidies, 70% lower implied costs of carbon, and a reduction of 18% in wholesale power prices.

Keywords: Renewable Energy, Biomass, Investment, Security, Carbon Price

1. Introduction

Managing the transition of a carbon-intensive electricity industry towards low, or zero, carbon emissions has become a delicate balance of policy initiatives and long-term commitments. Whilst substantial subsidies have been provided to support the early stage innovations of renewable energy technologies, wind and solar in particular, a consequence of these subsidies has been a structural change in the wholesale market economics leading to lower revenues and asset impairments for incumbent fossil fuel generators [1, 2, 3]. As a consequence, further subsidies, usually in the form of capacity payments, have been required to ensure that sufficient generators remain operational and to incentivize the extra reserves that are needed to cope with the intermittency of wind and solar production [4, 5, 6, 7, 8]. The sum of these subsidies, both for stimulating the innovation in new, clean technologies and maintaining resource adequacy, together with the associated network infrastructure upgrading, are inevitably subject to government budgets and considerations of consumer impact (e.g. the Levy Control Framework in the UK [9], and the Energiewende in Germany [10]). Within a framework for medium or longer term decarbonisation of the sector, e.g. by 2030 or 2050, policy support for

42 decarbonisation therefore reflects, implicitly or explicitly, a dynamic policy optimization
43 of subsidy design subject to costs, resource adequacy and carbon mitigation constraints.

44 In the context of this, investment in gas turbine facilities to provide extra reserve
45 capacity, as intermittent wind and solar replace coal, is often regarded as a viable
46 transitional process, notwithstanding its carbon emissions [11, 12]. The "open cycle gas
47 turbines" (OCGTs) are relatively low capital cost, easy to install and with the low load
48 factors associated with peaking facilities, they are usually presumed to be the best
49 economic option to provide the extra capacity. Indeed, the OCGT "levelised" cost is
50 widely used a reference price for capacity payments and auction parameters, for example
51 when governments are seeking to procure firm capacity to meet annual resource adequacy
52 targets [13]. Nevertheless, gas generation is not low carbon, and more reserve is required
53 as intermittent renewable resources replace the firm coal facilities.

54 In contrast, whilst the conversion of existing coal facilities to biomass, via burning
55 wood pellets, is also a low-carbon initiative attracting policy subsidies [14], it has not
56 been considered in the same way as OCGTs for providing reserve. But these coal-to-
57 biomass conversions have a number of attractions: the biomass cycle, if implemented in
58 a fully compliant way, is low carbon; the conversion costs are substantially smaller than
59 new build; new sites and new infrastructure connections are not required and the business
60 model for those incumbent coal generating companies does not have to change
61 substantially. Furthermore, with the extensive global coal reserves and worldwide coal
62 generation expected to remain substantial through to 2040 [15], biomass conversion has
63 an appealing role to play in gradually moderating the emissions from the large stock of
64 coal plants in operation. Nevertheless, it is clearly transitional and inferior to a complete
65 low-carbon solution, to the extent that the full supply-chain, carbon-footprint for wood
66 pellets can be significant depending upon the mode and distance of transportation.

67 In the future, on the other hand, it has been well-recognized that allied to carbon
68 capture and storage (CCS), if indeed CCS were to fulfill the long-standing aspirations of
69 commercialization [16], biomass coal conversion would offer the possibility of being a
70 net reducer of carbon emissions [17]. But that remains speculative, as do several other
71 new technology solutions to maintain reserve adequacy. Storage is developing rapidly, as
72 well as the aggregation of demand side response into "virtual power plants", but not yet
73 at a scale to keep pace with, and thereby provide the reserve support for, the penetration
74 of new wind and solar. In the longer-term, renewable energy allied to storage is a desirable
75 end-stage, but the transition is not immediate. Thus, in the meantime, new-build gas
76 turbines continue to be advocated as the transitional peaking technology.

77 The starting point for this paper is therefore the basic observation that the dominant
78 path towards a low carbon electricity industry for systems which have been heavily
79 dependent upon coal is through its replacement by large scale wind farms and the
80 widespread emergence of distributed solar [15]. In this respect, whilst their introduction
81 has been driven by policy determination and subsidies [18], an externality of both of these
82 intermittent technologies is the need for extra reserve. This paper examines this
83 requirement to maintain resource adequacy and compare the costs and carbon impacts for
84 new gas turbines or biomass conversions to achieve this in an expedient transitional way.
85 This is formulated as a policy optimization in which the imperative is to replace existing

86 coal with a renewable alternative (in this case study, wind) and to maintain the system
87 security ("outages") at the existing level, and thereby find the optimal subsidies, either as
88 energy credits ("green" certificates or "contracts-for-differences") or capital benefits
89 ("capacity payments", grants or tax allowances). Further, the analysis does not presume
90 risk-neutrality on the part of investors but aversion to downside risk, as manifest by the
91 metrics of rating agencies (e.g. [19, 20]). Apart from the social welfare costs, the analysis
92 computes the full supply chain implied cost of carbon for the various alternatives. The
93 model reveals that that biomass-conversion outperforms investment in OCGTs to deal
94 with the economic externality of extra reserve costs. In particular, the results suggest
95 benefits of 10% lower costs of subsidies, 70% lower implied costs of carbon reduction,
96 and a reduction of 18% in wholesale power prices.

97 This paper therefore makes several research contributions. From an analytical
98 perspective it develops a methodology to analyze the subsidy costs over time to replace
99 coal with wind and at the same time maintain a reserve margin expressed as a loss of load
100 probability (an expectation of 3 hours per year is the UK target). Furthermore, the
101 financial viability of the replacements investments is ensured by a risk constraint on the
102 capital coverage ratio. Therefore, the formulation involves a dynamic, multistage
103 optimization with probabilistic risk constraints. From this model, a new comparison of
104 energy versus capacity subsidy schemes is provided and concludes in favor of the latter.
105 In terms of technological context, this research is the first to compare biomass
106 conversions and gas turbines as transitional alternatives within this optimized policy
107 framework. It concludes that the former is beneficial in terms of lower subsidies, lower
108 wholesale prices and a lower implied cost of carbon reduction.

109 The next section presents the formulation for the investment simulation. This is
110 applied to a realistic case study based up the British system which has indeed been
111 characterized by policy support for large scale offshore wind to replace an accelerated
112 retirement of coal facilities. Whilst being a particular application, the policy insights are
113 generalizable. Subsequent sections consider the comparisons of biomass and gas for
114 complementing the wind replacements with their extra reserve requirements. The analysis
115 computes the implied cost of carbon reduction, and also considers a variation in which
116 policy-makers are somewhat risk averse in optimizing the costs of subsidy design against
117 the twin constraints of a decarbonisation pathway and resource security. Final
118 observations and comments conclude the paper.

119

120 **2. Model Formulation**

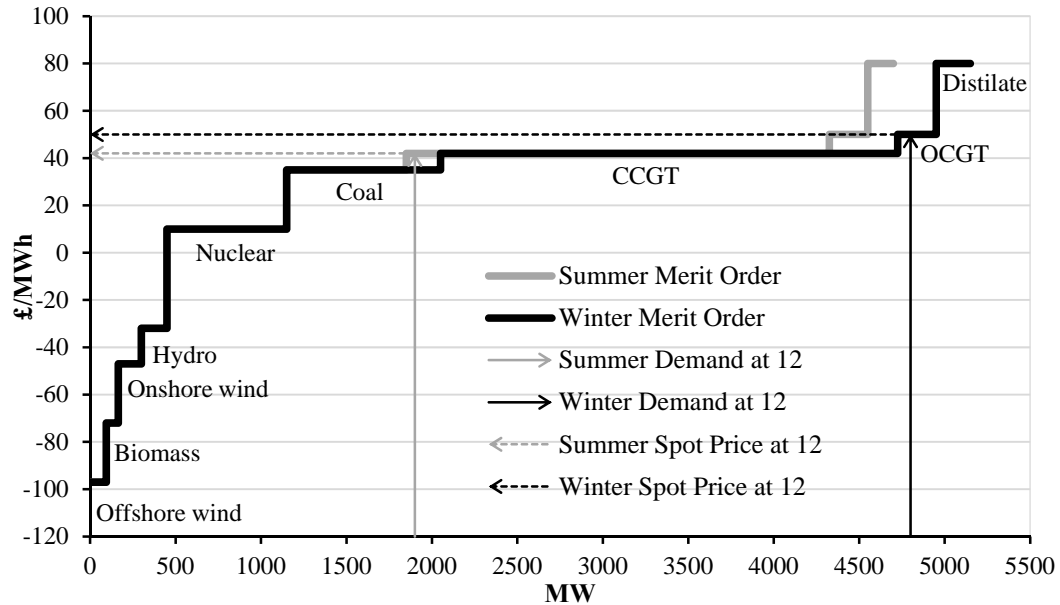
121 The stylized setting is an electricity industry (e.g. in Britain) seeking to replace its
122 existing coal generation with offshore wind, at minimum cost of subsidies, whilst
123 maintaining a constant security of supply margin. The analysis is a comparative static one
124 in the sense that no forecasts are presumed for future events and parameters, rather a
125 power industry as it exists in a target year (2016/17) is systematically varied by the
126 replacement of coal by wind, plus the addition of either gas or biomass to maintain the
127 same level of security. Its economic performance is determined by a market price
128 formation model which is simulated by Monte Carlo variation of all uncertain variables.

129 In other words, it provides a focus on the effects of key variables and current risks for a
130 set of target year variations, without speculation on future scenarios.

131 Within this target year model, revenues from the market simulation model provide
132 the basis for determining the amount of subsidies needed for the investments in new
133 capacity to be viable. Whilst the conventional NPV of a facility gives the economic value,
134 it is well-observed that a positive NPV is often not sufficient by itself to motivate
135 investment in practice. Often, an incentive to invest will only occur if the debt service
136 coverage ratios required by senior lenders can be maintained [21]. The debt service
137 coverage ratio is defined as the total cash flow available to service debt divided by the
138 debt repayments in a given period, usually one year, as in [20]. A new investment is
139 therefore considered to be feasible, in the sense of being financeable, if this coverage risk
140 is below a critical level. Specifically, a proxy criterion of 1.2 is used for capital coverage
141 at 90% probability, implying that in any year the risk of the annuitized capital costs not
142 being covered operational earnings plus 20%, should be less than 10%. Various wind farm
143 financings corroborate these numbers [22, 23, 24, 25]. However, it is recognised that
144 although such financial metrics tend to be idiosyncratic in practice, the particular values
145 are less important to this analysis than the general principle of such a metric being applied
146 in a consistent way across the policy variables. In particular, such a metric requires a risk
147 simulation element to the market modelling.

148 Three different case studies have been considered, which are detailed below. All
149 of them have the same purpose (to fully remove the installed capacity of coal plants and
150 replacing with offshore wind), and for that, two different approaches are analysed:
151 replacing the total productive capacity of coal, or just the actual production in the base
152 year. Moreover, extra reserve capacity is required to prevent the increase of unserved
153 energy (outages), due to wind intermittency. Extra capacity can be provided by a peak
154 technology, the "open cycle gas turbines" (OCGTs), or a flexible baseload technology,
155 biomass (in this case, from the conversion of existing coal facilities, via burning wood
156 pellets). These two alternatives are evaluated for each scenario.

157 The research questions are analyzed in this paper with reference to the British
158 wholesale power market when, *ceteris paribus*, the installed capacity of coal plants is
159 progressively replaced by offshore wind, taking 2016 as the base year. The simulation
160 proceeds as follows. Random exogenous variables are simulated. These include the
161 demand (hourly), the availability of each generating unit, including wind facilities, each
162 fuel (inter-correlated), and the carbon emissions price. Hourly demand distributions are
163 obtained from the actual historical half-hourly data available from National Grid.



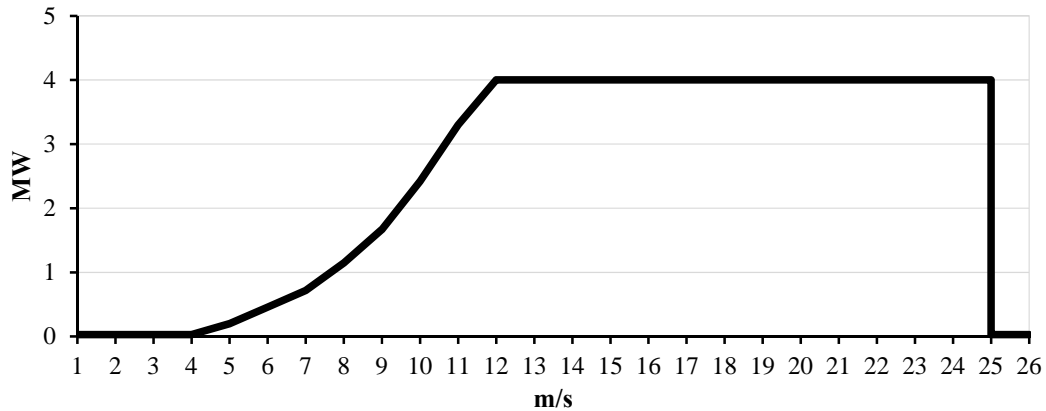
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Fig. 1. Average British Merit Order in 2016.

166 The merit order supply stack is constructed from all 320 generating units available in
 167 2016 ordered in ascending order of marginal cost (from least to most expensive). For
 168 market price formation, nuclear is always assumed to be at the bottom of the stack,
 169 although its marginal cost is higher than wind. This ensures that nuclear output is not
 170 curtailed. The market, as indicated in Figure 1, is cleared by having all active players take
 171 the price of the most expensive active generating unit needed to meet demand. If the
 172 demand is higher than the cumulative available capacity, an “outage” is recorded.

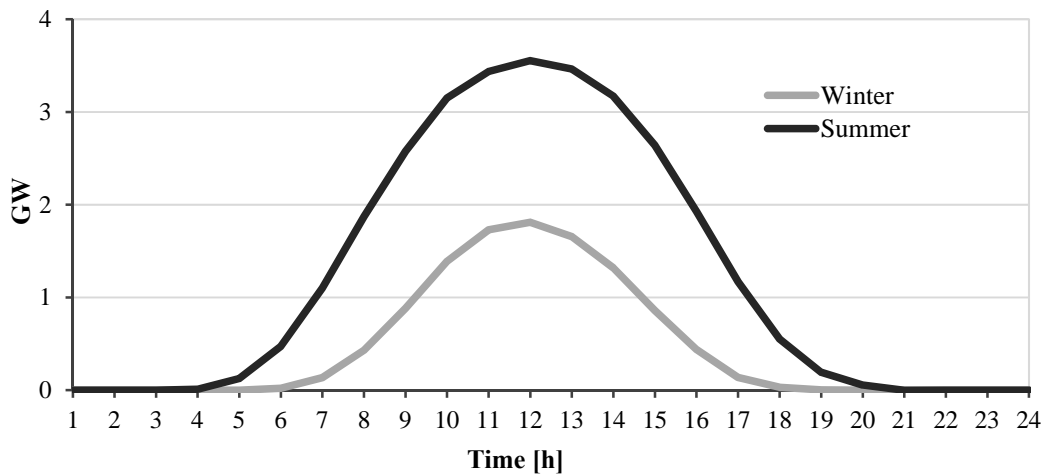
173 Production uncertainty of each technology is simulated from binomial distributions,
 174 wind speed (used for estimating wind production) is represented by Weibull probability
 175 distribution functions, and fuel prices are specified by lognormal distributions. Wind
 176 speed is converted to power according to a typical wind-power nonlinear transfer
 177 function, as Figure 2, following [26,27,28]. The portfolio averaging of extensive wind
 178 farm penetration is modelled by considering two regions in GB, north and south. From
 179 studies on wind speeds in geographic locations [29] an output correlation index of 0.7 is
 180 taken for plants in the same geographic areas within the north or south, and an index of
 181 0.1 is used as the output correlation coefficient between the north and south plants. New
 182 offshore wind generation is assumed to be distributed evenly between north and south.

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Fig. 2. Generation Output for a Typical Turbine as a function of Wind speed.



188
189

Fig. 3. Average Daily Solar Generation in 2016.

190 The hourly photovoltaic production distribution functions are obtained
191 analogously, using the 2015 historical data [30]. In Figure 3, PV generation obtained from
192 these distribution functions is represented. This PV production is subtracted from the
193 demand in this modelling procedure.

194 In the model, all (320) generating units offering into the market are included from
195 the very small biomass, onshore and offshore wind facilities to the large nuclear stations.
196 Installed capacities, capital costs, annual fixed costs, lifetimes, availabilities, carbon
197 intensities and heat rates were consistent with various sources [13,14,31,32,33,34,35] and
198 hourly demand for 2015/16 was taken from the National Grid¹. The basic fuel cost
199 parameters were specified by lognormal distributions with the follow mean and standard
200 deviations: coal (\$/tonne 80, 8); gas (p/therm 45,5); oil (£/bl 43, 4); ROC (£/ROC 45,4);
201 and EUA carbon price floor (£/tonne 18,0). The within year correlations were estimated
202 empirically as 0.6 for Gas and Oil; 0.6 for Gas and Coal; 0.8 for Coal and Oil.

203 No allowances were made for start-up costs. Transmission constraints do not
204 factor into wholesale market prices, as they are part of the real-time system balancing

¹ <http://www.nationalgrid.com/UK>

205 activities. No demand elasticity is assumed. Unplanned outages are simulated according
 206 to binomial distributions based upon average availabilities. Finally marginal cost clearing
 207 prices as simulated for the whole year were given a 15% mark-up to provide a good
 208 calibration to actual 2016 data.

209 Using the above annual price simulation model, the analysis proceeds by
 210 optimising the amount of extra reserve capacity needed to maintain the same security as
 211 in 2016 whilst replacing the coal with offshore wind. More precisely, the objective
 212 function (OF), which is minimised in the optimisation, is the mean value of the total
 213 subsidies required in the process of removing coal generation (1), subject to constraints.
 214 Total cost of subsidies (*TS*) is calculated as the sum of subsidies to new offshore wind
 215 and extra capacity. The subsidies can be either green certificates or capital grants.

$$\min\{OF = \text{mean}(TS)\} \quad (1)$$

216

217 It is subject to a constraint (2), to maintain the security of supply. To do so, the
 218 limit on outages during the process is set as the risk of outages in the base year, based on
 219 the simulation of the model with 5,000 iterations to ensure a stable value. We found from
 220 the simulations that the appropriate base mean outage value (expected energy unserved)
 221 was 1050 MWh. Note that the precise British reliability standard of 3 hrs Loss of Load
 222 Expectation, has not been used, but the model maintains consistency with the status quo
 223 in 2016. The actual value of this expected energy unserved is not crucial to this analysis
 224 as the key results relate to the changes from a base level.

$$\text{mean}(\text{outg}) \leq 1050 \text{ [MWh]} \quad (2)$$

225

226 The objective function is also subject to an investment constraint (3), to ensure an
 227 adequate profitability to investors in extra reserve capacity. In this case, a capital coverage
 228 ratio (CR) of 1.2 with a 90% confidence is considered.

$$\text{percentile}_{10\%}(CR) \geq 1.2 \quad (3)$$

229

230 Capital coverage ratios are calculated as the as shown in (4), where *PR* refers to
 231 annual profits, *G* refers to annual capital grants, and *PAY* refers to the annuitized capital
 232 payments (*ACP*) and fixed payments related to O&M, calculated as shown in Eq. (5),
 233 where *C* refers to installed capacity. The associated data are displayed in Table 1. In order
 234 to avoid issues of gearing, it is assumed for simplicity that the capital coverage ratio
 235 covers both debt and equity and this is discounted at a cost of capital to account for both.

$$CR = \frac{PR + G}{PAY} \quad (4)$$

$$PAY = (ACP + O\&M) \cdot C \quad (5)$$

236

TECHNOLOGY	Capital Costs (CC) [£/kW]	Interest rate [%]	Lifespan (Y) [Years]	ACP [£/kW]	O&M Costs [£/kW]
Offshore wind	2,800.00	7	20	264.30	48.00
OCGT	440.00	7	25	37.76	9.50
Biomass (conversion)	321.00	7	20	30.30	22.00

237

Table 1. Data to calculate annuitized payments.

238 Two types of subsidy mechanisms are considered. "Green Certificates" are an energy
 239 credit, widely used internationally and provide a supplement to the market prices for
 240 producers of renewable energy. They are known as Renewable Obligation Certificates
 241 ("ROCs") in the UK. An alternative to an energy payment is a capital payment on the
 242 investment. This can take the form of a fiscal benefit or a capacity payment. This as a
 243 "grant" in this analysis. Biomass could receive either an energy subsidy, ROC, or a
 244 capacity grant; but OCGTs can only receive capacity payments. In both cases, this model
 245 optimises the levels to ensure that constraint (3) is achieved.

246

247 3. Replacement of Coal by Offshore wind

248 In this transition scenario, total available production capacity of coal (*COA*) is replaced
 249 by offshore wind (*WOF*), following the formula described in Eq. (6), where *af* refers to
 250 the availability factor of each technology (coal, 87%; offshore wind, 45%; OCGT: 94%;
 251 biomass: 87%).

$$C_{100\%}^{WOF} = C_{0\%}^{WOF} + (C_{0\%}^{COA} - C_{100\%}^{COA}) \cdot \frac{af^{COA}}{af^{WOF}} = 4,705 + (13,737 - 0) \cdot \frac{0.87}{0.45} = 31,263 \quad (6)$$

252

253 Extra capacity requirements, either biomass or OCGT, are also optimised to satisfy the
 254 probabilistic security constraint. Installed capacity [MW] of coal, offshore wind, and
 255 OCGT or biomass, under 0% and 100% coal replacement are shown in Table 2.

TECHNOLOGY	0%	100%
Coal	13,737	0
Offshore wind	4,705	31,263
Biomass	2,226	4,653
OCGT	2,020	4,296

256

Table 2. Case 1: Capacities in MW for coal replacement based upon installed availability.

257 The above replacement is based on installed capacity adjusted by technical availability
 258 factors. However, with a high carbon floor price of £18/tCO₂, the load factor of the coal
 259 plant in 2016 is low and so it would be appropriate to also consider the working hours
 260 (load factor) replacement of coal by offshore wind. In this second scenario therefore, coal
 261 energy production is replaced by offshore wind, following the formula described in (7),
 262 where *wh* refers to the 2016 working hours of each technology (coal: 1,200 hours, and
 263 offshore wind: 8,760 hours), again adjusted by technical availability factors. Installed
 264 capacities [MW] are detailed in Table 3. Evidently much less wind is installed but more
 265 peaking plant is required to maintain the same security.

$$C_{100\%}^{WOF} = C_{0\%}^{WOF} + C_{0\%}^{COA} \cdot \frac{af^{COA} \cdot wh_{0\%}^{COA}}{af^{WOF} \cdot wh^{WOF}} \quad (7)$$

266

TECHNOLOGY	0%	100%
Coal	13,737	0
Offshore wind	4,705	8,343
Biomass	2,226	11,318
OCGT	2,020	12,541

267

Table 3. Case 2: Capacities in MW for coal replacement based upon load factor.

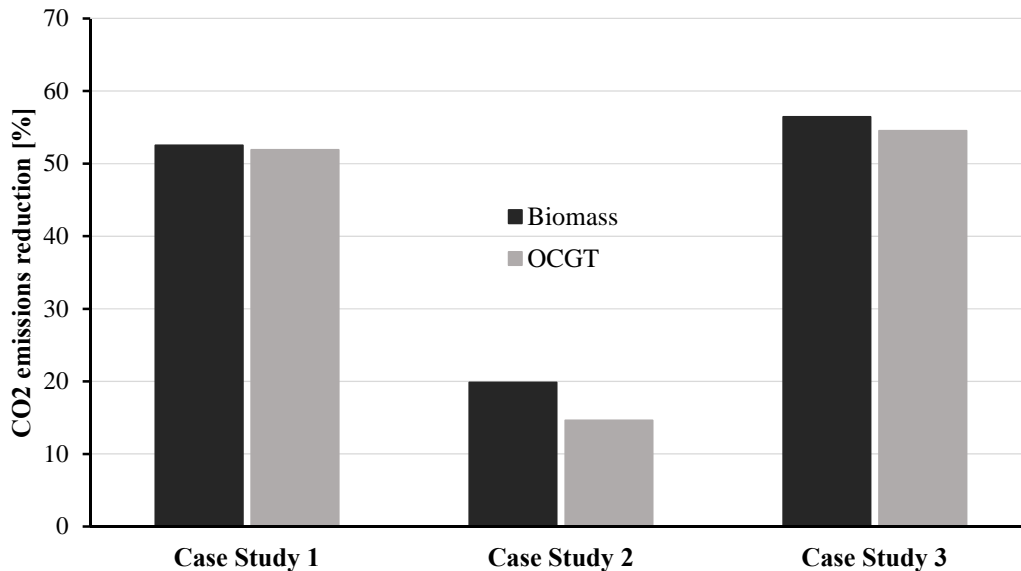
268 To see the effect of the carbon floor at £18/tCO₂, the above scenario is repeated using an
 269 EU ETS market price average of £5/tCO₂. This reduces the coal generators' marginal costs
 270 to below those of the CCGTs and accordingly the average operational hours go to 5,379
 271 from 1,200 hours, previously. Therefore, its production is higher in the base year, and
 272 more offshore wind is needed. Installed capacities [MW] are detailed in Table 4.

TECHNOLOGY	0%	100%
Coal	13,737	0
Offshore wind	4,705	21,013 (16,308 new)
Biomass	2,226	8,023 (5,797 new)
OCGT	2,020	7,616 (5,596 new)

273

Table 4. Case 3: Capacities in MW for coal replacement based upon load factor with low carbon price.

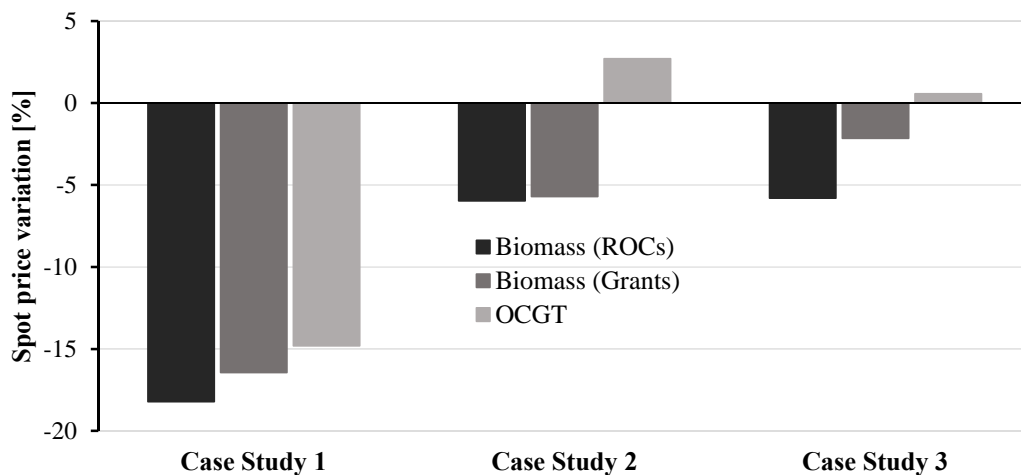
274 To assess the decarbonisation achieved in each of the three scenarios, the percentage of
 275 CO₂ emissions reduced is calculated. Estimates are used of the full supply chain carbon
 276 emissions per MWh generated, i.e. carbon emission intensities of 1.00 tCO₂/MWh for
 277 coal, 0.53 tCO₂/MWh for OCGT and 0.28 tCO₂/MWh for biomass. These are different
 278 from the carbon intensities used in the market price simulations (which are not based upon
 279 the full supply chain). This in the market, biomass is considered carbon neutral, but in the
 280 overall accounting, included are the total emissions from the cultivation, harvesting,
 281 processing and transport of the biomass feedstocks. And to follow the same criterion for
 282 coal and OCGT, final emission intensities of these two technologies are increased by 10%
 283 over their usual market levels to account for transport. Results for each scenario and
 284 alternative are represented in Fig. 4.



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Fig. 4. Percentage of CO₂ emissions reduced according to replacement assumptions.

287 Replacing coal by offshore wind typically leads to a drop of wholesale electricity prices.
 288 However, when the amount of offshore wind introduced is small and a peaking
 289 technology with high marginal costs is used to provide extra capacity, spot prices might
 290 consequently remain at the same level or even increase. Moreover, the subsidy scheme
 291 used to pay the subsidies also affects prices. For that reason, in the following chart,
 292 biomass is divided into two groups: “ROCs”, for energy subsidies, and “Grants”, for
 293 capacity payments. The variation of daily average electricity prices is shown in Fig. 5.
 294 There is a beneficial effect on reducing prices for using biomass, and indeed against the
 295 background of the high carbon price floor of £18/tCO₂ in Case 2, the use of OCGTs to
 296 maintain security actually increases prices slightly.

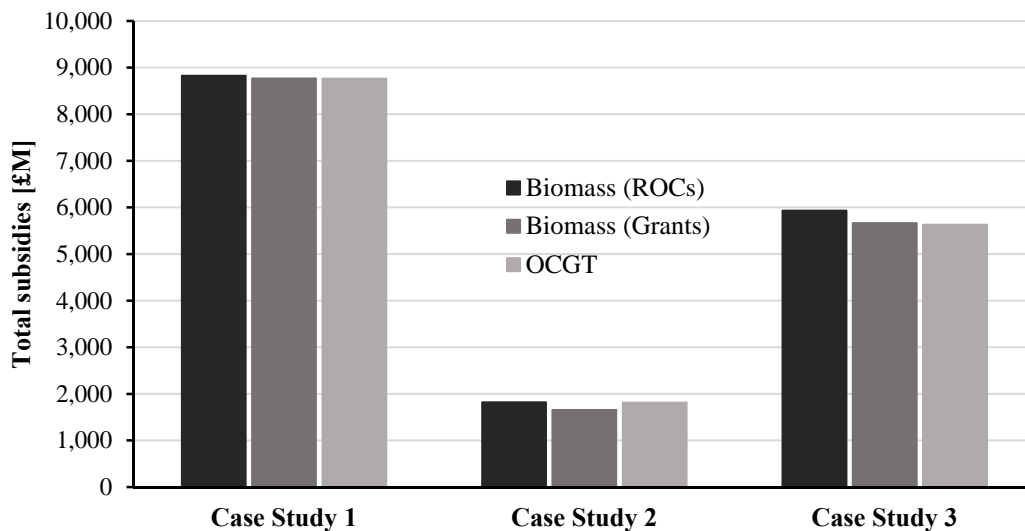


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Fig. 5. Daily average spot prices variation.

299 In all scenarios, ROCs and grants for biomass and OCGT are optimised. However, the
 300 amount of subsidies to offshore wind is maintained at the same 2016 level (1.8

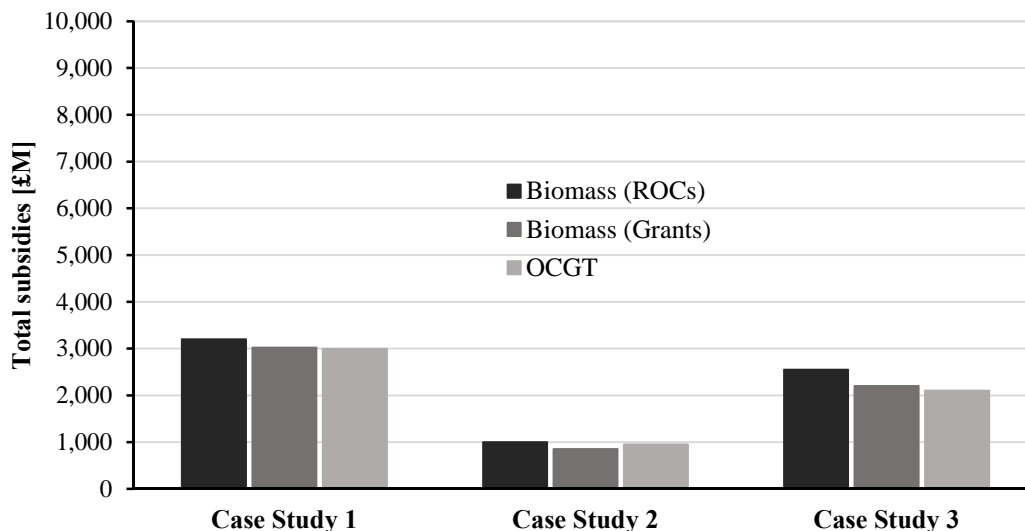
301 ROCs/MWh, i.e. about £80/MWh in addition to the wholesale price around £35/MWh),
 302 which is significantly higher than the optimised value of 0.3 ROCs/MWh for biomass).
 303 As a consequence, the larger the installed capacity of offshore wind, the higher the total
 304 subsidies. Although dominated by the cost of subsidising the wind with this base case of
 305 high ROCs, it is discernible in Case 2 that supporting biomass with capital grants can lead
 306 to a marginal saving compared to using green certificates, and compared to maintaining
 307 security via OCGTs.



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Fig. 6. Total subsidies.

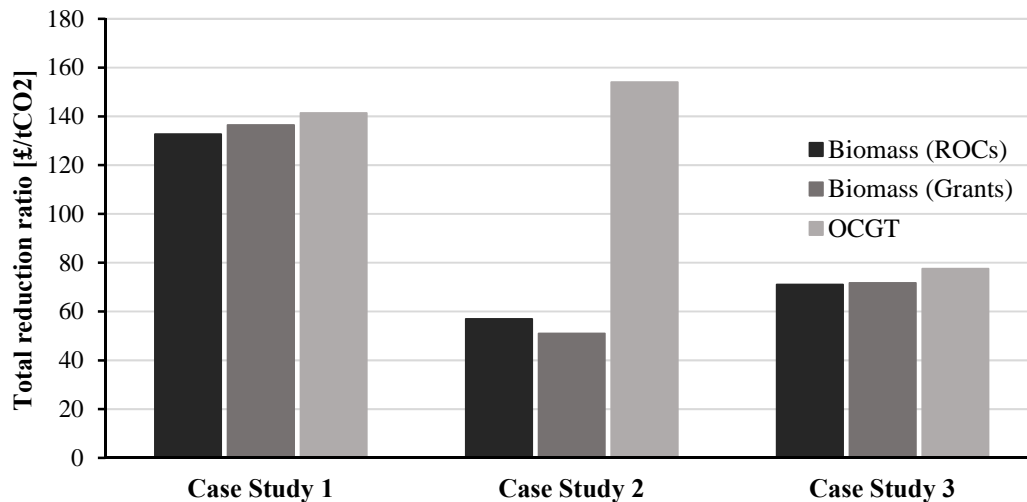
310 The base year 2016/17 was a year of rapid change in support levels for offshore wind. By
 311 September 2017, ROCs had been replaced for offshore investment by Contracts for
 312 Differences. These were determined by an auction which cleared at £57.5/MWh. Fig. 7
 313 shows the effect of this lower subsidy level, but note that the differences between the
 314 Cases do not change.



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Fig. 7. Total subsidies with CfD policy for offshore wind.

317 Finally, Fig. 8 shows the ratio between total subsidies at the 2016 level (in Fig 6) and the
 318 CO₂ emissions reduced to produce an implied cost of carbon (£/tCO₂) for the transition
 319 under the different cases. Evidently, there is a much higher implied cost of carbon for the
 320 transition if security is maintained with OCGTs compared to Biomass in all cases, but
 321 particularly against the background of the £18/tCO₂ carbon price floor. With biomass, the
 322 implied cost of carbon is around £59/tCO₂ if energy subsidies are used or about £55/tCO₂
 323 with capital grants compared to about £155/tCO₂ if gas is used for the security. Note that
 324 with the lower September 2017 CfD prices for offshore wind, these implied carbon costs
 325 would be reduced substantially to about a third.

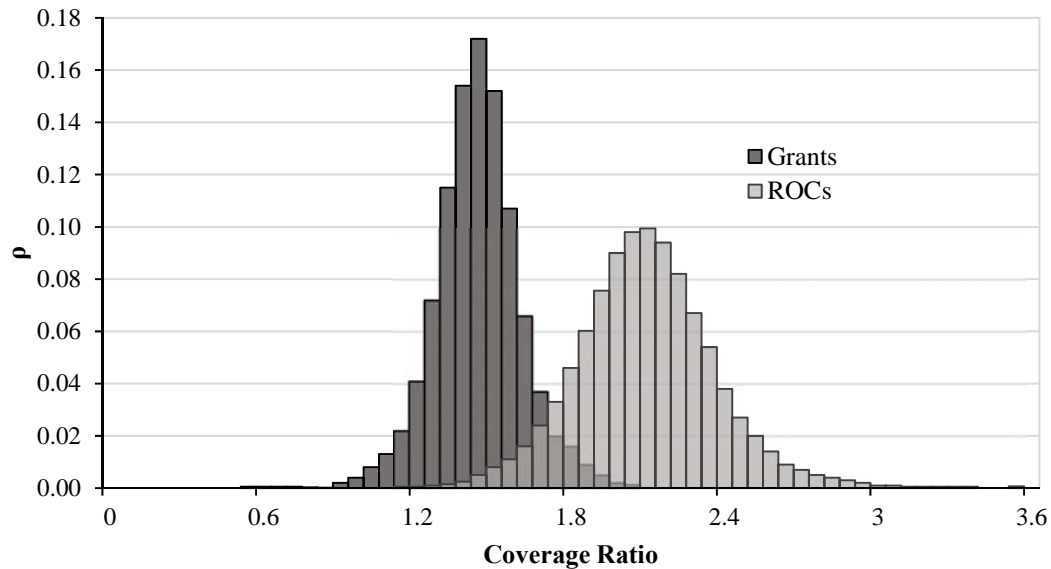


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Fig. 8. Cost of carbon reduction.

328 Whilst the main result of this modelling is with regard to the value of biomass
 329 conversions, compared to new OCGT facilities, for maintaining security during a coal
 330 phase-out, these results also show that subsidies need to be slightly higher if they are paid
 331 as energy benefits (green certificates, ROCs, feed-in tariffs or contracts for differences)
 332 compared to capital grants (capacity payments, fiscal benefits). This is explained by the
 333 intrinsic uncertainty of the energy-based subsidies, where dependence on the different
 334 parameters mentioned previously increases the volatility of the cash-flow received by
 335 generators. This effect can be observed in Fig. 9, where the coverage ratio probability
 336 distributions for the Grants and ROC cases are compared. Higher volatility produces more
 337 disperse coverage ratios from a wider distribution, so the tails are longer and a 10%
 338 percentile of 1.2 is more difficult to achieve. Thus, biomass requires higher subsidy with
 339 energy credits compared to capital benefits.

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341

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Fig. 9. Coverage ratio probability distributions.

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Furthermore, important results are obtained regarding optimal ROCs in this analysis: the ROCs required to get a coverage ratio of 1.2 is around 0.3 ROC/MWh, much less than the 1.5 ROC/MWh being paid in 2016.

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4. Conclusions

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This analysis points to positive considerations for biomass conversion if coal facilities are being phased out and replaced by intermittent renewable energy resources. The need for a transition to maintain resource adequacy at a constant level, as measured by the expected energy unserved, can be optimized by the methodology developed in this paper. An application to the British context indicates that using biomass conversion compared to gas turbines to maintain adequate reserve levels leads to lower costs (according to this analysis, they could be up to 9% lower), lower prices (they could drop by 16-18%) and a lower implied cost of carbon reduction (it could be a 70% lower).

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It should be emphasized that the analysis is a marginal one. It has looked at the operating reserve technology needed to maintain a system reliability target during an evolution in which a firm power source such as coal is replaced by a renewable facility such as wind or solar. The analysis is not about the widespread introduction of new-build biomass facilities for baseload, but instead, the conversion of the pre-existing coal plants, which are being decommissioned, to provide occasional reserve supplies. As such, the capital costs and supply chain implications are much less restrictive, and the practical feasibility of this analysis is plausible. Note in this context that some large coal facilities in Britain (over 2GW) have indeed been converted to biomass [36]. However, subsidies are required and the analysis shows that capacity payments rather than energy price premia are more efficient (the results suggest a benefit in the cost of subsidies of up to a

367 10%). This particular conclusion confronts conventional practice in many national
368 markets.

369 Whilst this analysis has been derived from a stylization of the British context, the key
370 indications are generalizable. The advantage of capacity payments over energy price
371 premia is driven mainly by considerations of financing risk, being the reduction in the
372 lower tail of the debt-coverage risk distribution. This is a general result, but presumes a
373 focus upon financial risk in the investment decision. The context is that of private
374 investors in a competitive power market, and this would not generalize to a public sector
375 decision for a national monopoly. The latter case is however becoming much less
376 common worldwide as competitive electricity markets mature.

377 Regarding the specific British case study of replacing coal by wind, it can be observed
378 that other European countries are also progressing in this way, given the EU Directives
379 for the low carbon and renewable energy transition. The scale varies however with, for
380 example, France having a smaller installed coal capacity of 3 GW (vs. 14 GW, in the UK)
381 and a slower development of wind [37, 38]. For Germany, however, coal is a major source
382 of fuel for electricity generation with around 25 GW and there has been an active
383 development program of wind, solar and biomass [39]. Subsidies for renewable energies
384 in both France and Germany have, however, been energy premia rather than capacity
385 payments [40, 47]. Similarly for Spain with 14% provided by coal-fired plants and 20%
386 coming from wind power [41, 42], and in The Netherlands with more than 30% produced
387 by coal [44] and substantial offshore wind [45]. In other words, the European context
388 presents various member states having substantial coal plant being imminently
389 decommissioned and an expansion of their wind resources. Elsewhere in the world, in the
390 United States, Australia and Asia, similar trends are evident.

391 Apart from the economic conclusions of the above analysis in favor of biomass
392 conversion to maintain reserve levels, not costed are the attractions of a re-purposing of
393 existing facilities. For asset owners, the attractions are clear [36]. Overall, however, one
394 might have expected biomass coal conversions to be more widespread. Concerns about
395 securing the supply chain are clearly very different to linking up with a pre-existing gas
396 infrastructure. This study does not speculate on the future sustainability of biomass
397 resources if biomass conversion were to become widespread, and these concerns may be
398 overstated [46], but in the context of providing reserve to support wind and solar, the
399 analysis does not envisage large-scale baseload demands upon the supply chain. It is clear
400 furthermore that gas turbine installations are well established, reliable and well supported;
401 whilst biomass power generation is more complicated by comparison. But with
402 appropriate policy support this analysis suggests that biomass conversion can play a cost-
403 efficient role in the energy transition.

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411 **5. References**

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