Vertical integration, recycling mechanism, and disadvantaged independent suppliers in the renewable obligation in the UK

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Abstract

Under the Renewable Obligation (RO) scheme implemented in the UK, electricity suppliers are required to present a certain number of RO certificates (ROCs) depending on the quantity of electricity they sold. Insufficient availability of ROCs, guaranteed by the amendment of headroom, helps boost investors' confidence about their values, but we observe that there was a large variation in compliance by suppliers. Using data from 17 reporting years from 2002-03 to 2018-19, our estimation results show that compliance of subsidiaries of the big six energy companies was 15.46% higher than that of independent suppliers. We trace the movement of ROCs from six generators to show that they prefer to sell ROCs to suppliers within the vertical integration. We develop scenarios and a theoretical model to show that, when the recycling mechanism is in place, integrated generators have the motivation to sell ROCs to integrated suppliers, rather than independent suppliers, while holding spare ROCs is the least favourite option. These predictions are consistent with observations that (i) integrated suppliers have better compliance than independent suppliers, and (ii) nearly all issued ROCs were presented. Therefore, we suggest that, when both vertical integration and the recycling mechanism exist, independent suppliers were disadvantaged in accessing ROCs given insufficient supply. Nonetheless, as a way of refunding unjustified penalties due to insufficient supply of ROCs, the recycling mechanism can promote competition among suppliers for ROCs, compared with a simple refunding method.

Keywords: Vertical integration, Recycling mechanism, Compliance, Renewable obligation, Insufficient supply

JEL Codes:

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1. Introduction

The EU Directive 2001/77/EC set a target of 12% of energy consumption from renewables for the EU-15 by 2010, and then the target was raised to 20% by 2020 in the EU Directive 2009/28/EC. The Directives gave a legally binding specific target of 15% to the UK, where the Renewables Obligation (RO) scheme was introduced in 2002 to support large-scale renewable electricity projects. The RO scheme is an obligation for electricity suppliers that a certain proportion of their sales comes from electricity generated using renewable sources by presenting adequate RO certificates (ROCs). The scheme allows renewable generators to receive additional revenue from selling awarded ROCs, to compete with low-cost fossil fuel power stations.

The Renewable Obligation is a quota-based scheme, which originated from the Renewable Portfolio Standard (RPS) in the United States. RPS is a state-mandated program establishes renewable energy targets, first introduced in Iowa in 1983 and then followed by more than half of states, with large variations in elements such as RPS targets and resources eligible to meet requirements (Berry and Jaccard, 2001). Positive impacts of RPS on renewable energy deployment are found by Carley (2009) and Yin and Powers (2010), but Upton and Snyder (2017) suggest similar increases in renewable energy in both RPS states and non-RPS states. A similar quota-based scheme known as the Renewable Energy Target (RET) was introduced in Australia in 2001 (Kent and Mercer, 2006). Valentine (2010) argues that RET has structural flaws that undermine its effectiveness of stimulating technological change in the electricity sector. Nelson et al. (2013) suggest that the uncertainty surrounding the RET prevents the market for certificates from operating efficiently.[2]

In the UK, partially contributed by the RO scheme, the proportion of electricity generated from renewable sources increased from 2.9% in 2002 to 37.1% in 2018 (DBEIS).[3] However, in its early stages, the RO scheme was criticised for lack of effectiveness by the literature. First, the RO scheme was designed to be technology-neutral to promote competition across different technologies. Specificity, all technologies received one ROC for each megawatt-hour (MWh) of electricity generated. Therefore, less developed technologies such as offshore wind and wave and tidal stream were disadvantaged, as they did not receive sufficient incentives from the RO scheme to cover their relatively higher costs. (Foxon et al., 2005; Foxon and Pearson, 2007; Woodman and Mitchell, 2011). Second, developers of any renewable project faced both a volume risk and a price risk. While there was no guarantee of contracted output from any supplier, the price of ROCs might drop to zero when there was no demand after all suppliers had met their obligations. Given these uncertainties, it was difficult to predict the return on investment of renewable energy projects (Mitchell et al., 2006; Woodman and Mitchell, 2011).

Consequently, two major amendments were adopted to overcome these issues. First, banding was introduced in 2009-10 to provide more support to less developed technologies. For example, in 2019-10, solar PV and offshore wind received 2 ROCs and 1.5 ROCs, respectively, for each MWh of electricity generated. Second, to increase investors' confidence about the value of ROCs, guaranteed headroom was added in 2010-11 to increase the obligations imposed on suppliers. This revised way of calculating obligations ensures excess

[2] Similar schemes were also implemented in other countries, such as Belgium (Jacobsson et al., 2009; Verbruggen, 2009), Norway (Finjord et al., 2018), Sweden (Jacobsson, 2008; Bergek and Jacobsson, 2010).

[3] For comparison, in 2019, the proportion of electricity generated from renewable sources was 17.5% in the United States and 21% in Australia. (Sources: https://www.eia.gov/ and https://www.energy.gov.au/). Different progresses in renewable energy deployment can be caused by various factors, such as natural endowments, legislative framework, financial accessibility, and consumer preference.

demand (i.e., insufficient supply) for ROCs in the market, preventing a collapse of the ROC price. Although Wood and Dow (2011) indicate that significant doubt remains whether these changes would have obvious impacts, these two amendments unlocked the potential to build expensive large wind farms in particular. Bunn and Yusupov (2015) confirm the effectiveness of the RO scheme in promoting electricity generation from renewable sources.

Different versions of banding are also seen in other quota-based systems. In the United States, credit multipliers award more than one (or less than one) certificate for electricity produced by certain technologies, with large variations in different RPS states. In Australia, a multiplier scheme issues more certificates to support small electricity generators, but this may discourage the development of large-scale renewable projects (Valentine, 2010). In contrast, the design of headroom in the UK is unique. In the United States, the supply of certificates has always been greater than the demand for it. For example, in 2018, in terms of percentage of U.S. retail electricity sales, the aggregate RPS demand was 5% while the supply was 12%, for renewable sources excluding hydro (Barbose, 2019). In Australia, in the calculation of the obligation level, two main elements are pre-specified renewable energy target and estimated sales of electricity, but the availability of certificates is not taken into account.[4] Therefore, a surplus of certificates is possible. For example, in February 2019, 7.1 million certificates remained available in the market at the end of the reporting year (Clean Energy Regulator, 2019). From the economic arguments for the headroom amendment, when there is excess supply of certificates in the market, the price of certificates is unlikely to be stable. Indeed, volatilities in the prices of certificates were observed in both the United States and Australia (Barbose, 2019; Clean Energy Regulator, 2019). Last but not least, another unique feature of the RO scheme is the recycling mechanism, which redistributes unjustified penalties resulted from insufficient supply back to suppliers. Suppliers pay a buy-out price for each ROC missed into the buy-out fund, but they receive a recycle payment for each ROC presented, redistributed from the buy-out fund. In contrast, fixed penalties were set in the United States and Australia. For example, the shortfall charge was A$65 per certificate missed in Australia in 2019.

While the literature has been focused on the impacts of the RO scheme (or other quota-based systems) on the generation sector, there is limited research on the behaviours of sellers and buyers in the certificates market. First, compared with fixed penalties, the recycling mechanism has profound impacts on the market. Zhou (2012) constructs a model to show that this mechanism allows generators to restrict the sales of certificates to maximise their profits. But as unsold ROCs were not observed in reality, Li et al. (2020) develop a theoretical model to show the recycling mechanism induces strategic behaviour (Nash-Cournot type) of suppliers. They also show that generators can take suppliers' behaviour into account and then choose a specific price of ROCs that produces the maximum transfer payment and full compliance. Next, the introduction of headroom causes an insufficient supply of ROCs, bringing additional impacts to the market. The insufficient supply of ROCs implies that some suppliers will miss their targets, but others may benefit from that due to the recycling mechanism. As a result, the key issue that needs to be addressed is whether any supplier had a disadvantage of accessing ROCs in the market with insufficient supply, instead of why full compliance was not achieved. Moreover, the dynamics are further complicated by the market structure in the UK electricity market, as there were six large vertically integrated energy companies (the Big Six), having subsidiaries in both the

[4] The renewable power percentage in RET was explained on the website of the Clean Energy Regulator in Australia.

generation sector and the retail sector.[5] This paper is the first to empirically examine the large variations in compliance by suppliers given the insufficient supply of ROCs, the recycling mechanism, and the existence of vertically integrated companies.

In this paper, using data collected from RO annual reports from 2002-03 to 2018-19, we find that subsidiaries of the Big Six had better compliance, with 15.46% higher than that of independent suppliers. We also find that independent suppliers had better compliance when more ROCs were available, but this only happened after subsidiaries have met their obligations already. Then we collect information from the Ofgem Renewables and CHP Register and use six examples of generators to show that they prefer to sell or transfer ROCs to suppliers shared the same parent company. Next, to understand the reason for this preference, we illustrate four simple scenarios to show that, given the recycling mechanism, this preference helps maximise the net gain of the vertically integrated company. We further develop a theoretical analysis in a more realistic setting and find that the integrated generator has the following preference: (i) selling ROCs to the integrated supplier when the latter has not met its obligation, (ii) selling ROCs to independent suppliers after the integrated supplier has met its obligation and a comfortable price range for the ROC transaction was derived, and (iii) holding ROCs as spare ones. These predictions are consistent with what we observed in reality: integrated suppliers had better compliance than independent suppliers, and nearly all issued ROCs were presented. Last, we show that the recycling mechanism helps refund unjustified penalties resulted from insufficient ROCs in the market. Compared with a simple refunding method, the recycling mechanism may be more attractive for two reasons. First, it promotes competition among suppliers for ROCs as a higher refund is given to the supplier who presents more ROCs. Second, it allows the regulator to follow a hands-off approach as all penalties are redistributed back to suppliers.

The paper will be constructed in the following way. Section 2 explains the RO scheme and compliance at the aggregate level. Section 3 conducts econometric analysis for compliance by suppliers at the disaggregated level. Section 4 shows the movements of ROCs, discuss the economic reasoning of ROC transactions, and compare two ways of refunding. Section 5 concludes the paper.

2. The RO scheme and compliance at the aggregate level

This section explains the features of the RO scheme. In the first three reporting years, from 2002-03 to 2005-06, the RO scheme was implemented in England and Wales and Scotland. From 2005-06, the scheme was extended to include Northern Ireland. We first explain the obligation level and the impact of the headroom amendment. In particular, the calculation with headroom creates an insufficient supply of ROCs to increase the market confidence about the price. Next, we show that full compliance at the aggregate level was not achieved in most years, but we explain that this was caused by insufficient issuance. The example of 2015-16 shows that full compliance was achieved when there was sufficient supply. Indeed, suppliers were willing to purchase and present ROCs, as nearly all issued ROCs were presented in most years. We finally explain the recycling mechanism, which helps redistribute unjustified penalties resulted from the insufficient supply of ROCs in the market.

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[5] The Big Six were Centrica, EDF Energy, E.ON, RWE Npower, Scottish Power, and SSE.

2.1. Setting the obligation level

Under the RO scheme, it is an obligation for electricity suppliers that a certain proportion of their supply comes from electricity generated using renewable sources. This proportion is known as the obligation level, which was announced by the regulator six months before a reporting period. The obligation level determines the number of ROCs that suppliers are required to present for each megawatt-hour (MWh) of electricity they supply to customers. Table 1 shows that the obligation level was initially set at 0.03 ROCs/MWh when the scheme was introduced in 2002-03, that means, for each MWh of electricity sold, the supplier should present 0.03 units of ROCs.

Given concerns that the value of ROCs may decrease dramatically when all suppliers have met their obligations, guaranteed headroom was introduced in 2010-11 to allow extra demand (insufficient supply, equivalently) for ROCs to prevent crashed in ROC prices. The revised calculation first estimates the potential amount of ROCs to be generated from existing stations and new-build and then add 10% as headroom to calculate expected total obligation. Next, by dividing the expected total obligation by the expected total electricity supply, the obligation level is calculated.[6] This revised way of calculation partially explains the large increase in the obligation level since 2010-11. In 2018-19, the obligation level was 0.468 ROCs/MWh for Great Britain and 0.158 ROCs/MWh for Northern Ireland (DBEIS). It is worth mention that, as expectations are used in the calculation, the actual gap between the number of ROCs generated and the number of ROCs required may deviate from 10%.

Obligation period (1 April - 31 March)	The obligation level for England & Wales and Scotland (ROCs/MWh)	The obligation level for Northern Ireland (ROCs/MWh)	Total obligation (total ROCs required)	Total ROCs presented	Percentage of obligations met by ROCs	Area
2002-03	0.030		9,261,568	5,451,449	58.9%	GB
2003-04	0.043		13,627,412	7,610,144	55.8%	GB
2004-05	0.049		15,761,067	10,855,848	68.9%	GB
2005-06	0.055	0.025	18,032,904	13,699,317	76.0%	UK
2006-07	0.067	0.026	21,629,676	14,612,654	67.6%	UK
2007-08	0.079	0.028	25,551,357	16,466,751	64.4%	UK
2008-09	0.091	0.030	28,975,678	18,948,878	65.4%	UK
2009-10	0.097	0.035	30,101,092	21,337,205	70.9%	UK
2010-11	0.111	0.043	34,749,418	24,969,364	71.9%	UK
2011-12	0.124	0.055	37,676,829	34,404,733	91.3%	UK
2012-13	0.158	0.081	48,915,432	44,773,499	91.5%	UK
2013-14	0.206	0.097	61,858,174	60,757,250	98.2%	UK
2014-15	0.244	0.107	71,922,000	71,276,525	99.1%	UK
2015-16	0.290	0.119	84,439,465	84,384,727	99.9%	UK
2016-17	0.348	0.142	100,748,885	90,214,078	89.5%	UK
2017-18	0.409	0.167	117,842,123	103,220,879	87.6%	UK
2018-19	0.468	0.185	127,623,995	107,643,960	84.3%	UK

Table 1: Obligation levels and compliance. Source: Renewable Obligation Annual Reports, Ofgem.

[6] 8% was used in the first year of introducing the headroom, 2010-11. In the calculation, the expected number of ROCs to be generated by operational stations were 30.95m, and then raised to 33.43m (33.1m in England and Wales and Scotland (EWS), 0.33m in Northern Ireland (NI)) after adding 8% of headroom. Meanwhile, the estimate of electricity to be supplied across the UK was 305.83 TWh (298.18 TWh in EWS, 7.65 TWh in NI). Therefore, the obligation level was calculated as 0.111 ROCs/MWh for WES and 0.043 ROCs/MWh for NI in 2010-11.

2.2. Compliance at the aggregate level

The total obligation is the total number of ROCs required for all electricity suppliers. It is calculated by multiplying the annual total electricity supplied (MWh) to customers in the UK by the obligation level (ROCs per MWh) in a given year. Table 1 shows that the total obligation increased from 9.26 million in 2002-03 to 127.62 million in 2018-19 (Ofgem).

Suppliers need to present ROCs purchased from renewable generators to meet their obligations. Total ROCs presented by all suppliers increased from 5.45 million in 2002-03 to 107.64 million in 2018-19. The ratio of total ROCs presented to total ROCs required is referred to as the percentage of obligation met by ROCs. This is known as compliance at the aggregate level. This ratio was relatively low before 2010-11, ranged from 55.8% to 76%, but was higher afterwards, ranged from 84.3% to 99.9%, as Table 1 shows. A value of less than 100% indicates that some suppliers did not fully meet their obligations, but it is misleading to conclude that the RO scheme is ineffective as suppliers were not willing to purchase and present ROCs. To have the full picture of compliance, we need to look at the number of ROCs issued each year.

2.3. Issuance of ROCs

At the beginning of each reporting year, ROCs were issued to accredited renewable generators according to their expected electricity output. Initially, all technologies received one ROC for each megawatt-hour (MWh) of electricity generated. Banding was introduced in 2009-10 to provide more support to less developed technologies, which were previously disadvantaged. For example, from 2009-10, solar PV received 2 ROCs/MWh and offshore wind received 1.5 ROCs/MWh, but the highest value was awarded to small wave and tidal stream projects (under 30 MW) as 5 ROCs/MWh from 2012-13 (DECC). Total number of ROCs issued increased from 5.6 million 2002-03 to 105.9 million in 2018-19, indicating that more renewable generators have been accredited. In particular, rapid increases from 2011-12 confirm that the two amendments, banding and headroom, stimulated investment in renewable generation projects.

Table 2 shows that the number of ROCs issued was less than the number of ROCs required in most reporting years. Insufficient supply was observed before the introduction of headroom, but this amendment helps improve the market confidence about the value of ROCs by making the insufficient supply to be a built-in feature of the RO scheme. Table 2 also shows that nearly all ROCs issued were presented by suppliers in most of the reporting years. Therefore, insufficient presentations of ROCs were caused by insufficient issuance, instead of suppliers' unwillingness to purchase ROCs. As a result, the key issue that needs to be addressed is whether any supplier had a disadvantage of accessing ROCs in the market with insufficient supply, instead of why full compliance was not achieved.

Compliance from 2013-14 to 2015-16 was particularly satisfactory, but this might send unexpected signals to the market as the insufficient supply disappeared. We take 2015-16 as an example to understand why this happened when headroom was in place to secure the insufficient supply and the stability of ROC prices. First, when calculating the obligation level, the expected number of ROCs from existing stations and new build was 78.9 million, and then raised to 86.8 million with 10% headroom. Meanwhile, projection of electricity expected to be supplied was 303.8 TWh, so the obligation level was set at 0.290 ROCs/MWh in England, Scotland and Wales, and 0.119 ROCs/MWh in Northern Ireland (DBEIS). Later from Annual Report, total ROCs actually issued was 90.4 million, exceeding the expected supply (86.6 million). Total electricity supplied was 295.8 TWh, less than the expected value, reducing total obligation to 84.4 million (Ofgem). Therefore, higher-than-expected supply and lower-than-expected demand jointly changed the situation from undersupply to oversupply in the ROC market. Nonetheless, this example confirmed that suppliers were willing to purchase ROCs if they were available.

Obligation period (1 April - 31 March)	Total ROCs presented	Total ROCs issued	Percentage of ROCs issued being presented	Ratio of ROCs issued to ROCs required	Buy-out price per ROC (£)	Total penalty redistributed	Recycle value per ROC presented (£)	Area
2002-03	4,973,091	4,552,524	109.2%		30.00	79,251,930	15.94	E&W
2003-04	6,914,524	5,617,445	123.1%		30.51	158,466,502	22.92	E&W
2004-05	9,971,851	7,867,819	126.7%		31.39	136,169,914	13.66	E&W
2002-03	478,358	1,010,145	47.4%		30.00	11,267,124	23.55	Scotland
2003-04	695,620	1,929,342	36.1%		30.51	16,488,755	23.70	Scotland
2004-05	883,997	3,003,110	29.4%		31.39	17,668,392	19.99	Scotland
2002-03	5,451,449	5,562,669	98.0%	60.1%	30.00	90,519,054		GB
2003-04	7,610,144	7,546,787	100.8%	55.4%	30.51	174,955,257		GB
2004-05	10,855,848	10,870,929	99.9%	69.0%	31.39	153,838,306		GB
2005-06	13,699,317	13,767,375	99.5%	76.3%	32.33	139,815,195	10.21	UK
2006-07	14,612,654	14,964,170	97.7%	69.2%	33.24	234,439,091	16.04	UK
2007-08	16,466,751	16,151,978	101.9%	63.2%	34.30	307,180,739	18.65	UK
2008-09	18,948,878	18,996,453	99.7%	65.6%	35.76	352,651,576	18.61	UK
2009-10	21,337,205	21,227,618	100.5%	70.5%	37.19	323,668,318	15.17	UK
2010-11	24,969,364	24,884,608	100.3%	71.6%	36.99	358,308,373	14.35	UK
2011-12	34,404,733	34,753,771	99.0%	92.2%	38.69	123,116,772	3.58	UK
2012-13	44,773,499	44,298,719	101.1%	90.6%	40.71	164,420,029	3.67	UK
2013-14	60,757,250	62,819,706	96.7%	101.6%	42.02	42,372,844	0.70	UK
2014-15	71,276,525	71,310,673	100.0%	99.2%	43.30	24,714,120	0.35	UK
2015-16	84,384,727	90,431,090	93.3%	107.1%	44.33	0	0.00	UK
2016-17	90,214,078	86,170,351	104.7%	85.5%	44.77	459,957,270	5.10	UK
2017-18	103,220,879	100,581,303	102.6%	85.4%	45.58	604,116,946	5.85	UK
2018-19	107,643,960	105,948,003	101.6%	83.0%	47.22	841,941,647	7.82	UK

Table 2: ROCs issued, buy-out prices, and recycle values. Source: Renewable Obligation Annual Reports.

2.4. Buy-out price, buy-out fund, and recycle value

At the end of each reporting year, suppliers presented their ROCs to demonstrate that if they have met their obligations. If suppliers fail to meet their obligations, they must pay a penalty for the insufficient number of ROCs. The penalty for each ROC missed is known as the buy-out price. In 2002-03, the buy-out price was set at £30 per ROC and it was intended to act as a cap on the costs to be charged to consumers. Subsequently, the regulator set the buy-out price for each obligation period by taking the buy-out price from the previous obligation period and adjusting it in line with the change in the Retail Prices Index (RPI) during the previous year. In 2018-19, the buy-out price was £47.22, suggesting that suppliers needed to pay a penalty of £47.22 for each ROC missed.

When the number of ROCs issued was insufficient, it was impossible for all suppliers to meet their obligations fully, so penalties may be unjustified. Therefore, a recycling mechanism was incorporated to refund those unjustified penalties. Penalties from all suppliers are paid into the buy-out fund, which is then redistributed to suppliers in proportion to the number of ROCs they presented, after deducting the regulator's administration costs. The redistribution payment received for each ROC presented is known as the recycle value.

In the first three reporting years, the RO scheme was implemented in England and Wales and Scotland, but separate recycling mechanisms were used in these two regions, i.e., there were two separated buy-out funds and two recycle values. From 2005-06, the scheme was extended to include Northern Ireland, and a single recycling mechanism was used for all three regions.[7] Since then, the regulator redistributes the buy-out fund to suppliers using the single recycling mechanism, which means the regulator pays out the aggregate of the funds across the three obligations (England and Wales, Scotland, and Northern Ireland) to suppliers, in proportion to the amount of ROCs each supplier presented. For example, a supplier who presents 3% of total ROCs presented across three obligations would receive 3% of the buy-out fund. In 2018-19, after withdrawing £5.6 million for administration costs, the buy-out fund for redistribution was £841.94 million. As suppliers presented 107.64 million of ROCs in total, the recycle value suppliers received back for each ROC they presented was £7.82.

While actual prices of ROCs were determined in bilateral trades and unknown to the public, the regulator suggested that the price of ROC should reflect both the buy-out price and the recycle value. The first term is the penalty saved from meeting the obligation and the second term is the gain received from redistribution. In 2018-19, as the buy-out price was £47.22 and the recycle value was £7.82, the suggested total worth of a ROC was £55.04 in this obligation period.

3. Compliance at the disaggregated level

In this section, we examine compliance by individual suppliers.[8] The data for individual suppliers are collected from Renewable Obligation annual reports from 2002-03 to 2018-19. During these periods, the number of suppliers who presented ROCs increased from 39 to 134. These suppliers were either independent or subsidiaries of the Big Six. For example, Bulb Energy is independent, while British Energy Direct is a subsidiary of EDF Energy.

3.1. Statistics of variables

There are 1,003 observations from 216 suppliers across 17 reporting years. As suppliers entered and left the market continuously, 216 suppliers were recorded but the maximum number of suppliers existed in the market was 134 in 2018-19. Table 3 summarises the statistics of variables. The variable directly related to compliance is the number of ROCs presented by suppliers, but it depends on the quantity of electricity sold, given the obligation level. Therefore, it is more informative to consider the percentage of obligation met, after taking suppliers' size into account. Specifically, this percentage is the ratio of the number of ROCs presented to the number of ROCs required from individual supplier, ranging from 0% to 100%, with a mean of 50.04%. The number of ROCs required ranges from 1 to 20.3 million, showing dramatic differences in the size of suppliers. Whether a supplier is a subsidiary of the Big Six is indicated by an ownership dummy variable with a value of one. The mean of this dummy variable is 0.246, suggesting that 24.6% of observations are from

[7] Specifically, the whole scheme is referred to as Renewable Obligation, but its components include Renewables Obligation England and Wales, Renewable Obligation Scotland (ROS) and Northern Ireland Renewables Obligation (NIRO).

[8] These retailing firms are referred to as licensees in Annual Reports, as a licence is needed to operate in the UK electricity markets, but for convenience we refer them to as suppliers.

subsidiaries of the Big Six.[9] The ratio of ROCs issued to ROCs required indicates the tightness of the ROC market, as a higher ratio indicates that more ROCs are available when the demand remains the same. The Herfindahl-Hirschman Index measures the competitiveness in the electricity retail market.[10] A lower index indicates a more competitive market and may suggest that more small suppliers are available. Over the 17 years, the number of suppliers increased from 34 to 134, while the index decreased from 1,203 to 692. Last, location dummy variables indicate where the supplier was operating. While 71% of observations supply electricity in more than one ROC regions, the rest serve in only one of the three ROC regions (England and Wales, Scotland, and Northern Ireland), with 17.7%, 0.8%, and 10.4% respectively.

Variables	Definition	Observations	Mean	Min	Max
$C_{i,t}$	The percentage of obligation met	1,003	50.04	0	100
$Q_{i,t}$	The number of ROCs required	1,003	846,178	1	20,273,284
$D_{i,t}$	Ownership dummy (a subsidiary of the Big Six if 1)	1,003	0.246	0	1
IRR_t	The ratio of ROCs issued to ROCs required (in percentage)	1,003	82.64	55.38	107.1
HHI_t	The Herfindahl-Hirschman Index (electricity retail market)	1,003	949.23	691.97	1202.83
$LD_{\mathbf{0},\boldsymbol{i},\boldsymbol{t}}$	Location dummy 0 (supply in more than one ROC regions if 1)	1,003	0.711	0	1
$LD_{1,i,t}$	Location dummy 1 (supply in England and Wales only if 1)	1,003	0.177	0	1
$LD_{\mathbf{2},\boldsymbol{i},\boldsymbol{t}}$	Location dummy 2 (supply in Scotland only if 1)	1,003	0.008	0	1
$LD_{3,i,t}$	Location dummy 3 (supply in Northern Ireland only if 1)	1,003	0.104	0	1

Table 3: Statistics of variables

3.2. Compliance by individual suppliers

The percentages of obligation met by individual suppliers from selective years are shown in Fig. 1, including 2002-03, 2010-11, 2015-16, and 2018-19.[11] On the X-axis, suppliers are ranked in the ascending order of the number of ROCs required. As the obligation level is the same for all suppliers in each year, a higher number of ROCs required indicates a higher sales of electricity by the supplier. The Y-axis indicates the percentage of obligation met. Two types of suppliers are shown in Fig. 1. A plus symbol indicates a subsidiary of the Big Six, and a circle symbol indicates an independent supplier. The horizontal solid line is the ratio of ROCs presented to ROCs required, showing the percentage of obligation met at the aggregate level in a given year.[12] The horizontal dashed line is the ratio of ROCs issued to ROCs required. From Fig. 1, the first observation is that nearly all ROCs issued were sold (and presented), suggest that suppliers were willing to purchase ROCs if they are available. Second, subsidiaries of the Big Six tend to have better compliance than independent suppliers. Third, compliance by independent suppliers tends to be better when there are sufficient ROCs available.

[9] In terms of suppliers, 32 out of 216 belonged to the Big Six.

[10] The formula used to calculate HHI is $HHI = \sum_{i=1}^{N} s_i^2$, where s_i is the market share of firm i in the market, and N is the number of firms. Given the fixed obligation level in a specific year, the number of ROCs required reflects the sales of electricity by an supplier, so market shares can be calculated as the percentage of ROC required from supplier i to total ROC required.

[11] Given limited spaces, we show compliance by individual suppliers from four years: the first year of introducing the RO scheme (2002-03), the year of introducing headroom (2010-11), the year with the best overall compliance at 99.9% (2015-16), and the most recent year in the dataset (2018-19).

[12] Note that the ratio at the aggregate level is different from the average ratio at the disaggregated level. For example, a ratio at the aggregate level is 0.6 (=600/1000) but the average of ratios can be 0.524 at the disaggregate level (=500/700+100/300).

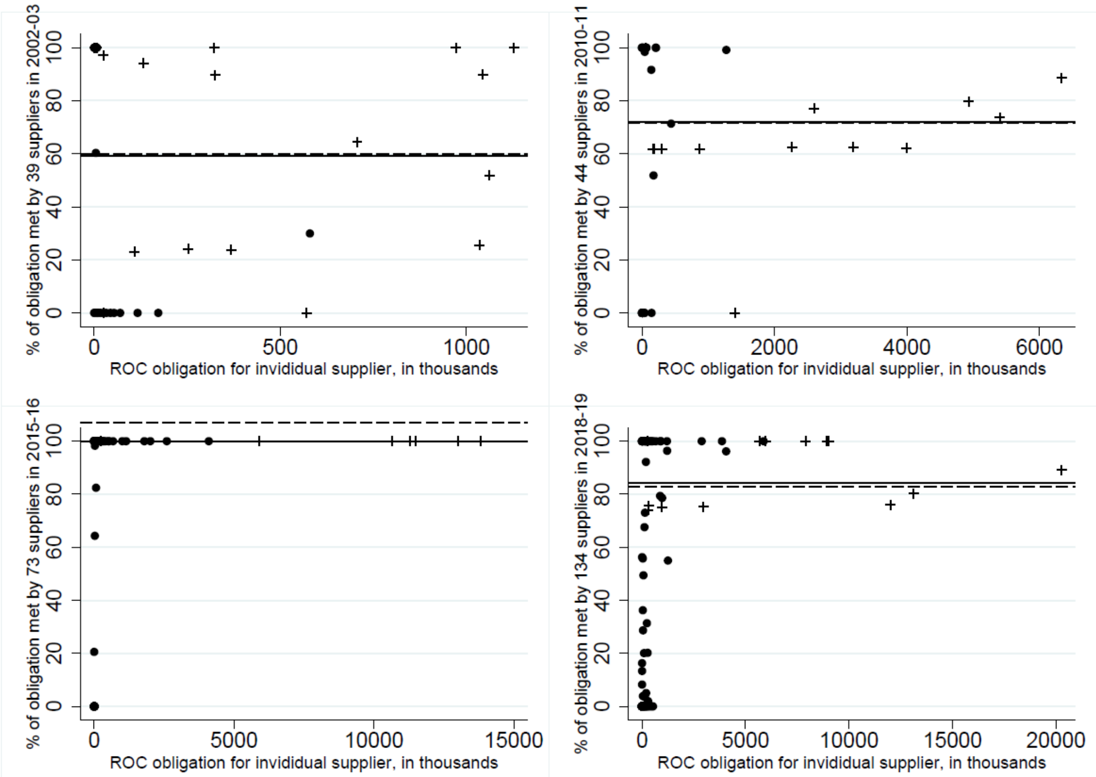

Fig. 1: Percentage of obligation met by suppliers in selective years, 2002-03, 2010-11, 2015-16, 2018-19. The solid line is the ratio of ROCs presented to ROCs required (i.e., compliance at the aggregate level). The dashed line is the ratio of ROCs issued to ROCs required. A plus symbol indicates a subsidiary of the Big Six, and a circle symbol indicates an independent supplier.

3.3. Regression analysis

3.3.1. Econometric model

In our model, the dependent variable, $C_{i,t}$, is the percentage of obligation met by an individual supplier i. The model is written as

$$C_{i,t} = \beta_0 + \beta_1 \cdot \ln(Q_{i,t}) + \beta_2 \cdot D_{i,t} + \beta_3 \cdot IRR_t + \beta_4 \cdot HHI_t + \delta_j \sum_{j=1}^{N=3} LD_{j,i,t} + \varepsilon_{i,t} \quad (1)$$

The following independent variables are considered. The first is the number of ROCs required from an individual supplier, $Q_{i,t}$, reflecting the quantity of electricity sold and the size of the supplier. This variable is in logarithmic form. The second is the ownership dummy variable, $D_{i,t}$, with a value of one if the supplier is a subsidiary of the Big Six and with a value of zero if it is independent. The third variable, IRR_t, is the ratio of the total number of ROCs issued to the total number of ROCs required, reflecting the tightness of the supply of ROCs. Next, HHI_t measures the competitiveness of the electricity retail market. $LD_{j,i,t}$ are location dummy variables indicating the location of suppliers. Suppliers operating in more than one ROC region is used as the base group, so the dummy variable $LD_{0,i,t}$ is not included in the model. The error term is $\varepsilon_{i,t}$ and the model is estimated using the pooled ordinary least squares method with robust standard errors.

3.3.2. Results

As shown in Column 1 in Table 4, our estimation explains 29.3% of the variation in the obligation met by individual suppliers using the full sample. Holding other factors fixed, a 1% increase in the number of ROCs required from the supplier (or the size of the supplier) increases its compliance by 0.047%, suggesting that large suppliers have better compliance than small suppliers.[13] Meanwhile, if a supplier is a subsidiary of the Big Six, its compliance is 15.46% higher than that of an independent supplier. This suggests that subsidiaries of the Big Six have an advantage in accessing ROCs when the supply is insufficient in the market. Besides, dynamically, when there is a 1% increase in the ratio of ROCs issued to ROCs required, suppliers' compliance is 0.69% higher on average. That means, if more ROCs are issued, suppliers are willing to buy and present additional ROCs to meet their obligations. Note that the increase in average compliance is less than 1%, but it does not necessarily indicate spare ROCs in the market. Instead, it may suggest that larger suppliers benefit more from the higher availability of ROCs.[14] Next, when the market is less competitive, average compliance is better. The results suggest that, if the HHI increases by 1%, average compliance increases by 0.38%. A possible explanation is that if we have fewer small suppliers with low compliance in the market, average compliance is better because large suppliers tend to have better compliance. Furthermore, compared with suppliers operating in more than one area, suppliers operating only in England and Wales or Scotland have lower compliance. A possible reason is that these suppliers have restricted access to ROCs geographically. Most of these results are statistically significant at the 1% significance level.

To avoid the problem of multicollinearity, in particular, that a large supplier tends to be a subsidiary of the Big Six, we consider variance inflation factor (VIF) which measures the multicollinearity among the independent variables. For the model with the full sample, VIF ranges from 1.03 to 1.80, suggesting a moderated level of correlation and limited impacts on our estimates.[15] This may be explained by the fact that the Big Six own suppliers with varying sizes in the retail market, i.e., 7.2% of observations less than the median size (501 observations), and 42.1% of observations higher than the median size (501 observations).[16]

Independent variable: Percentage of obligation met by ROCs				
	Full sample 2002-03 - 2018-19	Subsample 2002-03 - 2010-11	Subsample 2011-12 - 2018-19	Subsample 2011-12 - 2018-19
Variables	Coefficients			
Number of ROCs required (in logarithmic form)	4.718*** (0.508)	1.282 (0.897)	6.461*** (0.585)	6.480*** (0.586)
Ownership Dummy (A subsidiary if 1)	15.46*** (2.986)	17.17*** (5.063)	13.82*** (3.300)	128.4*** (23.37)
Ratio of ROCs issued to ROCs required	0.691*** (0.0946)	0.412 (0.363)	1.258*** (0.325)	1.444*** (0.343)
HHI (in logarithmic form)	38.06*** (7.243)	2.292 (19.24)	23.82 (16.41)	21.97 (16.43)

[13] First, as this independent variable is measured in logarithmic form, its coefficient needs to be divided by 100 in interpretation. Second, this small coefficient is resulted from the large variation in the number of ROCs required or the size of suppliers.
[14] Details see Appendix.
[15] A value greater than 2.5 indicates potentially considerable correlations between independent variables in the model.
[16] In terms of the average size, the proportions of observations from subsidiaries of the Big Six are the following: 13.9% of observations less than the average size (820 observations), and 72.7% of observations higher than the average size (183 observations).

Interaction term: Ratio of issued to required * ownership				-1.213**
				(0.610)
Location dummy 1 (supply in England & Wales only if 1)	-8.720**	-24.56***	-0.959	-0.930
	(4.229)	(6.803)	(5.426)	(5.437)
Location dummy 2 (supply in Scotland only if 1)	-22.11***	-39.93***	-8.638	-7.604
	(4.788)	(5.510)	(6.512)	(6.524)
Location dummy 3 (supply in Northern Ireland only if 1)	2.421	-3.960	5.432	5.252
	(4.271)	(7.886)	(4.899)	(4.908)
Constant	-319.5***	-12.16	-294.8***	-299.4***
	(50.29)	(129.9)	(87.77)	(87.61)
Observations	1,003	355	648	648
R-squared	0.293	0.195	0.370	0.375
Robust	Yes	Yes	Yes	Yes
Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1				

Table 4: Results from pooled OLS estimation.

Next, it is important to understand the behaviours of suppliers under different circumstances, so we estimate our model using two subsamples. The first subsample is from 2002-03 to 2010-11, with 355 observations.[17] In this subsample, the ratio of ROCs issued to ROCs required ranged from 55.4% to 76.3%, suggesting relatively large excess demand in the ROC market. In this case, subsidiaries of the Big Six might not have met their obligations yet, so we predict that it was harder for independent suppliers to access ROCs. As shown in Column 2 in Table 4, the regression results for this subsample suggests that compliance of subsidiaries of the Big Six was 17.17% better than that of independent suppliers. Besides, dynamically, when there was a 1% increase in the ratio of ROCs issued to ROCs required, the suppliers' compliance was 0.41% higher on average. This result is not statistically significant, possibly due to diversified changes in compliance by subsidiaries and independent suppliers. As suggested by the Appendix, if the average increase is less than the overall increase, large suppliers may benefit more from the additional supply of ROCs.

The second subsample is from 2011-12 to 2018-19, with 648 observations.[18] In this subsample, the ratio of ROCs issued to ROCs required ranged from 83% to 107.1%, showing relatively smaller excess demand in the ROC market. Therefore, subsidiaries of the Big Six might have met their obligations already, so it was easier for independent suppliers to access ROCs. As shown in Column 3 in Table 4, compliance of subsidiaries of the Big Six was 13.82% higher than that of independent suppliers. Compared with the previous subsample, the gap was smaller, showing that independent suppliers were in a better position to access ROCs in the second subsample. Dynamically, when there was a 1% increase in the ratio of ROCs issued to ROCs required, suppliers' compliance was 1.26% higher on average. As suggested by the Appendix, if the average increase is higher than the overall increase, small suppliers may benefit more from the additional supply of ROCs.

Furthermore, to understand the impact of higher availability of ROCs on both subsidiaries and independent suppliers, we include an interaction term between the ownership dummy and the ratio of ROCs issued to ROCs required in the model, as shown in Column 4 in Table 4. From the second subsample, the coefficient shows that, when the ratio of ROCs issued to ROCs required increased by 1%, average compliance was 1.44% higher for independent suppliers and only 0.23% (= 1.44% - 1.21%) higher for the subsidiaries of the

[17] In the first subsample from 2002-03 to 2010-11, 42.5% of observations were subsidiaries of the Big Six.
[18] In the second subsample from 2011-12 to 2018-19, 14.8% of observations were subsidiaries of the Big Six.

Big Six. This result suggests that independent suppliers benefited more from higher availability of ROCs in the second subsample.

Therefore, our estimation results show a positive gap between compliance from subsidiaries and independent suppliers, and this gap was larger when fewer ROCs were available in the market. This suggests that subsidiaries of the Big Six had an advantage in accessing ROCs when the excess demand for ROCs was large. We also find that, in the situation with relatively small excess demand for ROCs, compliance of independent suppliers increased more than that of subsidiaries of the Big Six when more ROCs are available. However, it does not necessarily suggest that independent suppliers became more competitive in accessing ROCs, but may reflect the situation that subsidiaries had met their obligations already.

4. Discussion

4.1. The movement of ROCs from owners to holders

The empirical analysis in Section 3.3.2 shows that subsidiaries of the Big Six had better compliance than independent suppliers. To understand this result, we trace the movement of ROCs from owners (i.e., generators) who received them to holders (i.e., suppliers) who presented them to the regulator.

We collect two sets of information from the Ofgem Renewables and CHP Register. The first set of information contains the accredited generation unit and the holder for each ROC from April 2006 to March 2019. The holder of the ROC was the supplier who acquired and presented it to the regulator. The second set of information is the list of owners of accredited generation units. From these two datasets, through generation units, we can identify the link between the owner and the holder of each ROC.

There are 1,910 owners in the Register, and here we show the movement of ROCs from six owners. These examples do not give a full picture of the ROC market, but they suggest that owners who were subsidiaries prefer to sell ROCs to suppliers who shared the same parent company. For convenience, we refer them to as integrated generators and integrated suppliers, in the context of vertically integrated company.

Table 5A shows three owners who were fully owned by one of the Big Six. Nearly most of their ROCs were sold or transferred within the vertical integration. First, SSE Generation is a subsidiary of SSE. From 2006-07 to 2018-19, a total of 27.6 million ROCs were awarded, and 94.14% of these were presented by suppliers who were subsidiaries of SSE. Second, Scottish Power Renewables is owned by Scottish Power, and 94.91% of its awarded ROCs were transferred to subsidiaries of Scottish Power. Third, RWE Generation UK is a subsidiary of RWE Npower, and 98.36% of its awarded ROCs were presented by subsidiaries of its parent company.

A: Three examples of owner which is fully owned by one of the Big Six				
Owner	Parent company	Number of ROCs awarded (2006.04-2019.03)	ROCs presented by holders from the same parent company	Measured in percentage
SSE Generation	SSE	27,630,214	26,011,407	94.14%
Scottish Power Renewables	Scottish Power	24,750,608	23,489,702	94.91%
RWE Generation UK	RWE Npower	8,217,400	8,082,966	98.36%
B: Three examples of owner which is partially owned by one of the Big Six				
Owner	Parent company (% owned in 2019)	Number of ROCs awarded (2006.04-2019.03)	ROCs presented by holders from the same parent company	Measured in percentage

London Array	E.ON (30%)	21,197,914	10,686,709	50.41%
Gwynt y Mor Wind Farm	RWE Npower (50%)	9,804,147	5,401,358	55.09%
Lincs Wind Farm	Centrica (50%)	8,362,737	4,005,769	47.90%

Table 5: The movements of ROCs in six examples of owners.

Table 5B shows another three owners who are partially owned by the Big Six, but suppliers from the same parent company were still the main recipients of ROCs. First, London Array was partially owned by E.ON (30% in 2019), and around 50.4% of ROCs awarded were presented by subsidiaries of E.ON. Second, Gwynt y Mor Wind Farm was partially owned by RWE Npower (50% in 2019), and 55.1% of its ROCs were transferred to subsidiaries of its parent company. Third, Lincs Wind Farm was partially owned by Centrica (50% in 2019), and 47.9% of its ROCs were presented by British Gas, a subsidiary of Centrica.

Therefore, these examples suggest that integrated generators prefer to sell ROCs to integrated suppliers from the same parent company. This may explain the result in Section 3.3.2 that subsidiaries of vertically integrated companies had better compliance than independent suppliers.

4.2. The motivation for the internal transaction

In this section, we suggest that the recycling mechanism incorporated in the RO scheme incentivises integrated generators to sell ROCs to integrated suppliers, rather than independent suppliers. Here we use simple scenarios to illustrate this argument. Assume there are an independent supplier (S2) and a vertically integrated company, having an integrated generator (G1) and an integrated supplier (S1). Both S1 and S2 are required to present 10 ROCs. G1 is awarded 16 ROCs, less than the total number of ROCs required. The penalty is £30 for each ROC missed.

We first consider the situation without the recycling mechanism. In this situation, S2 faces a simple choice: buy and present ROCs or pay a penalty of £30 for each ROC missed. Therefore S2 is only willing to pay £30 to G1 for each ROC. In Scenario One, as Fig. 2A shows, G1 meets the demand from S2 first by selling 10 ROCs and then sell the rest to S1. S2 pays £300 for ROCs. S1 pays a penalty of £120 as it misses 4 ROCs, but the net gain of the integrated company is £180.

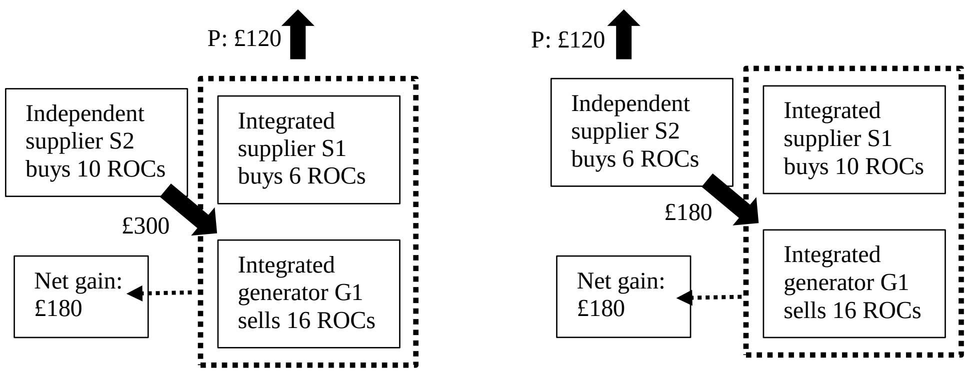

Fig. 2A (Left): Scenario One: G1 meets the demand for ROCs from S2 first, without the recycling mechanism. Fig. 2B (Right): Scenario Two: G1 meets the demand for ROCs from S1 first, without the recycling mechanism. *P* denotes penalty.

Alternatively, in Scenario Two shown in Fig. 2B, consider that G1 meets the demand from S1 first and then sell the rest to S2. S2 pays £180 for ROCs and a penalty of £120 as it misses 4 ROCs. S1 does not pay any penalty as its obligation is fully met. Therefore, the net gain of the integrated company is £180. Comparing these two scenarios, without the recycling mechanism, the net gain of the integrated company is the same and it is independent of the allocation of ROCs decided by G1.[19]

Now we turn to the scenarios with the recycling mechanism, which redistributes penalties back to suppliers, in proportion to the amount of ROCs each supplier presented. In theory, a supplier should be willing to pay a ROC price that reflects the penalty avoided and the recycle value to be received.[20] However, the recycle value is calculated at the end of the reporting period and a value of zero is possible, so S2 may not be willing to pay a price higher than the penalty.

In Scenario Three, consider that G1 meets the demand from S2 first and then sell the rest to S1, shown in Fig. 3A. S2 still pays £30 for each ROC so in total it pays £300 to G1. S1 pays a penalty of £120 as it misses 4 ROCs. The redistribution payment is £75 for S2 and £45 for S1.[21] Therefore, for the integrated company, as it receives £300 from S2, pays a penalty of £120, and receives a redistribution payment of £45, its net gain is £225.

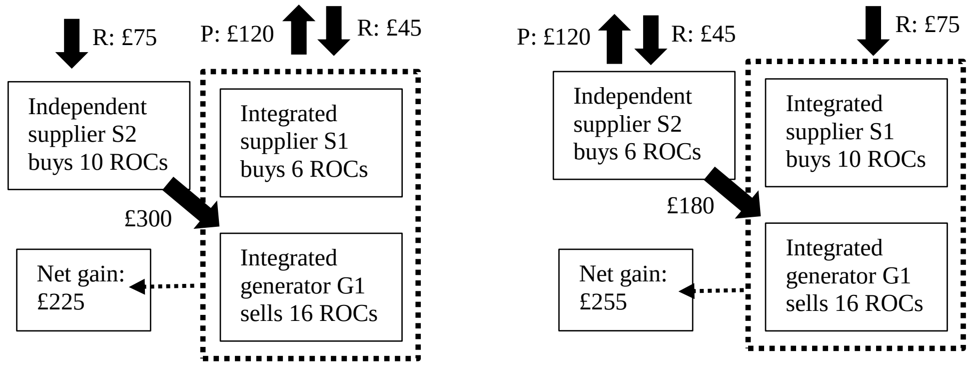

Fig. 3A (Left): Scenario Three: G1 meets the demand for ROCs from S2 first, with the recycling mechanism. Fig. 3B (Right): Scenario Four: G1 meets the demand for ROCs from S1 first, with the recycling mechanism. P denotes penalty and R denotes redistribution payment.

Alternatively, in Scenario Four, consider that G1 meets the demand from S1 first and then sell the rest to S2, shown in Fig. 3B. S2 pays £180 for 6 ROCs and a penalty of £120 as it misses 4 ROCs. In this case, the redistribution payment is £45 for S2 and £75 for S1.[22] Therefore, for the integrated company, as it receives £180 from S2 and a redistribution payment of £75, its net gain is £255. The difference between these two scenarios suggests that, with the recycling mechanism, the integrated company receives a higher net gain by meeting the demand from S1 first.

If S2 correctly predicts that the recycle value is £7.5 and pay £37.5 for each ROC, net gains of the integrated company raise to £300 in Scenario Three and Scenario Four. However, the recycle value is unknown until all suppliers submit their information to the regulator at the end of the reporting year. Given this uncertainty, S2 may not be willing to take the risk but only pay a price lower than £37.5 for each ROC. For any price lower than £37.5, the

[19] Internal transactions may still be preferred due to lower negotiation costs.
[20] As suggested in Annual Reports, the approximate price of ROC equals to the sum of the penalty and the recycle value, $price\ of\ ROC\ =\ penalty + recycle\ value$, but the recycle value is unknown during the transaction.
[21] Dividing the total penalty of £120 by the total of 16 ROCs presented, gives a recycle value of £7.5 for each ROC presented. S2 receives a redistribution payment of £75 as it presents 10 ROCs. S1 receives a redistribution payment of £45 as it presents 6 ROCs.
[22] The recycle value is still £7.5 for each ROC presented. S2 receives a redistribution payment of £45 as it presents 6 ROCs. S1 receives a redistribution payment of £75 as it presents 10 ROCs.

integrated company receives a higher net gain by meeting the demand from the integrated supplier first.

These scenarios show that, in a simplified market structure with the recycling mechanism, the integrated generator prefers to sell ROCs to the integrated supplier, leaving the independent supplier disadvantaged. Interestingly, given this market structure, the integrated company can reach a net gain of £300 if G1 does not sell any ROCs to S2. That is, the penalty of £300 paid by S2 will be fully redistributed to S1. This scenario (Scenario Five) may not be realistic but it confirms that independent supplier is disadvantaged in accessing ROCs when both vertical integration and the recycling mechanism are in place. In reality, as nearly all issued ROCs were sold and presented, holding spare ROCs were not preferred by integrated generators.

4.3. The behaviour of the vertically integrated company in a theoretical model

Scenario Five in Section 4.2 shows that the integrated company can receive a higher net gain by holding spare ROCs, but this is not observed in reality. In this section, we discuss the decision marking of the vertically integrated company in a more realistic setting to show that holding spare ROCs is the least favourite option, while meeting the demand from the integrated suppliers is the most favourite choice.

We consider G1's choices in two situations: (i) when both S1 and S2 need more ROCs to meet their obligations, and (ii) after S1 has met its obligation.

Assume there are n suppliers in the market, and the recycle value, r, is determined as

$$r = \frac{f\sum_{i=1}^{n}(Q_i - R_i)}{\sum_{i=1}^{n} R_i} = \frac{f(Q-R)}{R} = \frac{fQ}{R} - f \quad (2)$$

For supplier i, Q_i is the number of ROCs required, R_i is the number of ROCs it presented, $(Q_i - R_i)$ is the number of ROCs it missed. The penalty for each ROC missed is f, the total number of ROCs required is Q, and the total number of ROCs presented is R. As the first derivative of Eq. (2) with respect to R is less than zero, $dr/dR = -fQR^{-2} < 0$, the recycle value is negatively affected by the number of ROCs presented. That is, an additional ROC presented reduces the recycle value.

If an additional ROC is presented, the recycle value will become

$$r' = \frac{f[\sum_{i=1}^{n}(Q_i - R_i) - 1]}{\sum_{i=1}^{n} R_i + 1} = \frac{f(Q-R-1)}{R+1} = \frac{fQ}{R+1} - f \quad (3)$$

as the total number of ROCs missed is reduced by one and the total number of ROCs presented is added by one. So the decrease in the recycle value is

$$r' - r = \frac{f(Q-R-1)}{R+1} - \frac{f(Q-R)}{R} = -\frac{fQ}{R(R+1)} = -f\frac{Q}{R}\frac{1}{(R+1)} < 0 \quad (4)$$

where Q/R is the inverse of compliance at the aggregate level, f is the penalty (i.e., the buy-out price), and R is the total number of ROCs presented. Eq. (4) suggests that the change in the recycle value by this additional ROC is smaller when more ROCs are presented (i.e., R is larger). For example, in 2018-19, the penalty was £47.22, compliance was 84.3%, and the number of ROCs presented was 107.6 million, so an additional ROC presented reduces the recycle value by a very small amount, $£5 \cdot 10^{-7}$.[23]

Now consider that G1 has a spare ROC, and the number of ROCs presented by S1 and S2 are R_1 and R_2 respectively. In the first case, assume both S1 and S2 have not met their obligations yet. If G1 transfers this ROC to S1, the number of ROCs presented by S1 increases from R_1 to $R_1 + 1$, and the payoff of the vertically integrated company (VI) is

$$PO_{VI,1} = f + r'(R_1 + 1) - rR_1 \tag{5}$$

where $PO_{VI,1}$ is the payoff of VI in the first case, f is the penalty saved and $r'(R_1 + 1) - rR_1$ is the change in the redistribution payment. Meanwhile, because the recycle price falls, the payoff of S2 is the decrease in the redistribution payment,

$$PO_{S2,1} = r'R_2 - rR_2 < 0 \tag{6}$$

In contrast, if G1 sells this ROC to S2 at a price of p, the payoff of VI is

$$PO'_{VI,1} = p + r'R_1 - rR_1 \tag{7}$$

where $r'R_1 - rR_1$ is the decrease in the redistribution payment. Meanwhile, the number of ROCs presented by S2 increases from R_2 to $R_2 + 1$, and its payoff is

$$PO'_{S2,1} = -p + f + r'(R_2 + 1) - rR_2 \tag{8}$$

where p is the price paid for this ROC, f is the penalty saved and $r'(R_2 + 1) - rR_2$ is the change in the redistribution payment.

From VI's perspective, G1 is willing to sell this ROC to S1, instead of S2, when the payoff is higher from this choice. The condition for this choice is

$$PO_{VI,1} > PO'_{VI,1} \Leftrightarrow f + r'(R_1 + 1) - rR_1 > p + r'R_1 - rR_1 \Leftrightarrow f + r' > p \tag{9}$$

This suggests that, if the price of this ROC is less than the sum of the penalty and the revised recycle value, VI will receive a higher payoff from transferring this ROC to S1 than selling it to S2.

Then from S2's perspective, it is willing to buy and present this ROC, if a higher payoff is received from this choice. The condition for this choice is

$$PO_{S2,1} < PO'_{S2,1} \Leftrightarrow r'R_2 - rR_2 < -p + f + r'(R_2 + 1) - rR_2 \Leftrightarrow f + r' > p \tag{10}$$

That is, if the price is less than the sum of the penalty and the revised recycle value, S2 will receive a higher payoff from purchasing this ROC from G1.

These two conditions give an interesting conclusion. S2 is happy to purchase this ROC if the price is less than the penalty saved and the revised recycle value to be received, but this is also the condition that G1 prefers to sell this ROC to S1. So S2 is not able to buy this ROC given the price it is willing to offer. In contrast, G1 is happy to sell this ROC to S2 at a higher price, but S2 is not willing to offer that as it will receive a lower payoff from

[23] $r' - r = -f \frac{Q}{R} \frac{1}{(R+1)} = -£47.22 \cdot \frac{100}{84.3} \cdot \frac{1}{(107{,}600{,}000+1)} = -£5 \cdot 10^{-7}$.

buying this ROC. Therefore, G1's preference for selling this ROC to S1 will not be undermined as S2 is not willing to offer a price higher than $f + r'$. [24]

In the second case, assume S1 has met its obligation, but S2 has not. If G1 transfers this ROC to S1, this ROC will be held as a spare one. In this case, payoffs for VI and S2 are zeros, $PO_{VI,2} = PO_{S2,2} = 0$, as there is no change in the total penalty, the total number of ROCs presented, and the recycle value.

In contrast, if G1 sells this ROC to S2, the payoff of VI is

$$PO'_{VI,2} = p + r'R_1 - rR_1 \tag{11}$$

where p is the price of ROC in this transaction and $r'R_1 - rR_1$ is the decrease in the redistribution payment. Meanwhile, the number of ROCs presented by S2 increases from R_2 to $R_2 + 1$, and its payoff is

$$PO'_{S2,2} = -p + f + r'(R_2 + 1) - rR_2 \tag{12}$$

where p is the price paid for this ROC, f is the penalty saved and $r'(R_2 + 1) - rR_2$ is the change in the redistribution payment.

From VI's perspective, the condition that G1 prefers selling this ROC to S2, instead of holding it as spare, is

$$PO'_{VI,2} > PO_{VI,2} = 0 \Leftrightarrow p + r'R_1 - rR_1 > 0 \Leftrightarrow p > -(r' - r)R_1 \tag{13}$$

where $r' - r$ is the decrease in the recycle value and $-(r' - r)R_1$ is the decrease in the redistribution payment in positive value. This suggests that when the price of this ROC is greater than the decrease in the redistribution payment, VI is willing to sell the ROC to S2. Eq. (13) shows the minimum price that VI is willing to accept. For example, in 2018-19, given the decrease in the recycle value by an additional ROC was £$5 \cdot 10^{-7}$ from the discussion on Eq. (4), if the number of ROCs presented by S1, R_1, was 20 million (around 1/5 of total ROCs presented), the lowest price that VI was willing to accept for this additional ROC is £10.[25] A higher market share of S1 leads to a higher minimum price that VI is willing to accept because the decrease in the redistribution payment is larger when S1 presents more ROCs.

Then from S2's perspective, it is willing to buy this additional ROC when the following condition is met,

$$PO'_{S2,2} > PO_{S2,2} = 0 \Leftrightarrow -p + f + r'(R_2 + 1) - rR_2 > 0 \Leftrightarrow f + r' + (r' - r)R_2 > p \tag{14}$$

where f is the penalty saved, r' is the revised recycle value, and $(r' - r)R_2$ is the decrease in the redistribution payment. That is, if the price of this ROC is less than the sum of the penalty, the revised recycle value, and the decrease in the redistribution payment, S2 is willing to purchase and present this additional ROC. Eq. (14) shows the maximum price that S2 is willing to offer. For example, in 2018-19, given the penalty was £47.22 and the decline in the recycle value by an additional ROC was £$5 \cdot 10^{-7}$ from the discussion on Eq. (4), if the number of ROCs presented by S2, R_2, was 1 million (around 1/100 of total ROCs presented), the highest price that S2 was willing to pay for this additional ROC was £$46.72 + r'$, where

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[24] Strictly speaking, the revised recycle value is unknown during the transaction. Our conclusion may not hold if S2 is willing to offer a high price based on a high expectation of the revised recycle value. However, this is unlikely to be the case, we assume rational expectations for simplicity, $E(r') = r'$.

[25] $p > -(r' - r)R_1 \Rightarrow p > -(-£5 \cdot 10^{-7}) \cdot 20{,}000{,}000 \Rightarrow p > £10$.

$r' \geq 0$ was the non-negative revised recycle value.[26] A higher market share of S2 leads to a lower maximum price that S2 is willing to offer, as S2 needs to take a larger decrease in the redistribution payment into account.

Therefore, combining the minimum price that VI is willing to accept from Eq. (13) and the maximum price that S2 is willing to offer from Eq. (14), we suggest that this transaction of ROC occurs when the price is in the following region,

$$f + r' + (r' - r)R_2 > p > -(r' - r)R_1 \tag{15}$$

Eq. (15) gives a comfortable range to the price that G1 sells this ROC to S2. In our example, it is between £10 and $£46.72 + r'$. This range varies upon market shares of S1 and S2, but it is highly likely to hold if S1 is one of the big suppliers and S2 is a small independent supplier. Therefore, after S1 has met its obligation, it is highly likely to see that G1 sell this additional ROC to S2, instead of holding it as a spare one.

Payoffs received by VI and S2 from the above analysis are summarised in Table 6. To summarise, when both S1 and S2 have not met their obligations, G1 prefers to sell the ROC to S1; after S1 has met its obligation, it is highly likely that G1 will sell the ROC to S2, instead of holding it as a spare one. In this more realistic setting, these results are consistent with what we observed in reality: integrated suppliers have better compliance than independent suppliers, and nearly all issued ROCs were sold and presented.

Payoff matrix		S2 (independent supplier)	
		Case 1: S1 and S2 does not meet full obligation	Case 2: S1 meets full obligation, but S2 does not
Vertical integration (generator G1 and integrated supplier S1)	G1 sells the ROC to S1	$PO_{VI,1} = f + r'(R_1 + 1) - rR_1$; $PO_{S2,1} = r'R_2 - rR_2$	$PO_{VI,2} = 0$; $PO_{S2,2} = 0$
	G1 sells the ROC to S2	$PO'_{VI,1} = p + r'R_1 - rR_1$; $PO'_{S2,1} = -p + f + r'(R_2 + 1) - rR_2$	$PO'_{VI,2} = p + r'R_1 - rR_1$; $PO'_{S2,2} = -p + f + r'(R_2 + 1) - rR_2$

Table 6: The payoff matrix for the vertical integration and the independent supplier.

4.4. The recycling mechanism as a way of refunding

As discussed in Section 2.4, when the number of ROCs issued is less than the number of ROCs required, it is impossible for all suppliers to meet their obligations fully. Therefore, penalties are not justified when suppliers are willing to meet their obligations but there are no sufficient ROCs available.

A simple refund mechanism can be designed in the following way. Assume there are two suppliers and 10 ROCs are required from each, but there are only 16 ROCs were issued. The penalty is £30 for each ROC missed. As shown in Table 7A, assume two suppliers present 7 and 9 ROCs respectively, their penalty will be £90 and £30. In a simple refund mechanism, as only 16 ROCs were issued, expected ROCs presented should be 8 from each supplier. Then penalties on 2 missing ROCs are unjustified, so each supplier should receive a refund of £60. In this case, the net penalties are £30 and -£30 respectively for these two suppliers.

A: 16 ROCs are issued, all of them are presented.

[26] $f + r' + (r' - r)R_2 > p \Rightarrow £47.22 + r' + (-£5 \cdot 10^{-7}) \cdot 1{,}000{,}000 > p \Rightarrow £46.72 + r' > p$.

Supplier	ROCs required	ROCs presented	Penalty (£30)	Refund (£)	Net Penalty
A	10	7	£90	-£60	£30
B	10	9	£30	-£60	-£30
Total	20	16	£120	-£120	£0
B: 16 ROCs are issued, 15 of them are presented.					
Supplier	ROCs required	ROCs presented	Penalty (£30)	Refund (£)	Net Penalty
A	10	6	£120	-£60	£60
B	10	9	£30	-£60	-£30
Total	20	15	£150	-£120	£30

Table 7: The simple refunding mechanism

The drawback of this approach is that the regulator receives a positive net penalty when some issued ROCs are not presented. Table 7B shows that the regulator has a total net penalty of £30 when supplier A presents 6 ROCs and supplier B presents 9 ROCs, leaving 1 ROC in the market. In this case, additional legislation may be required for the regulator to handle this positive gain. One possible option is that this £30 can be directly given to the generator which holds the spare ROC, but this approach may discourage generators from actively participating the ROC market as they receive transfer payments regardless whether their ROCs were sold.

In contrast, the recycling mechanism implemented in the RO scheme provides an alternative way of refunding unjustified penalties. There are two main differences. First, the supplier who presents more ROCs receives a higher refund. Given the same compliance with Table 7A, supplier A now receives a lower refund of £52.5 but supplier B receives a higher refund of £67.5, as shown in Table 8A.[27] So this design may drive up competition for ROCs, leading to higher ROC prices and then higher revenues received by generators. This feature may be desirable as the RO scheme was introduced to promote investment in renewable generation projects. Second, when some issued ROCs are not presented, all penalties are redistributed back to suppliers. Given the same compliance with Table 7B, the total penalty of £150 is redistributed back to supplier A and B, as shown in Table 8B.[28] The zero total net penalties require no further action from the regulator, making it attractive if a hands-off approach is preferred. Also, this design encourages generators to participate in the market because they will not receive any transfer payment if they hold any spare ROCs.

A: 16 ROCs are issued, all of them are presented.					
Supplier	ROCs required	ROCs presented	Penalty (£30)	Refund (£)	Net Penalty
A	10	7	£90	-£52.5	£37.5
B	10	9	£30	-£67.5	-£37.5
Total	20	16	£120	-£120	£0
B: 16 ROCs are issued, 15 of them are presented.					
Supplier	ROCs required	ROCs presented	Penalty (£30)	Refund (£)	Net Penalty

[27] Dividing the total penalty of £120 by the total of 16 ROCs presented, gives a recycle value of £7.5 for each ROC presented. Supplier A receives a redistribution payment of £52.5 as it presents 7 ROCs. Supplier B receives a redistribution payment of £67.5 as it presents 9 ROCs.

[28] The recycle value is £10 in this case, as the total penalty is £150 and the number of ROCs presented is 15. Supplier A receives a redistribution payment of £60 as it presents 6 ROCs. Supplier B receives a redistribution payment of £90 as it presents 9 ROCs.

A	10	6	£120	-£60	£60
B	10	9	£30	-£90	-£60
Total	20	15	£150	-£150	£0
C: 16 ROCs are issued, 2 of them are presented.					
Supplier	ROCs required	ROCs presented	Penalty (£30)	Refund (£)	Net Penalty
A	10	1	£270	-£270	£0
B	10	1	£270	-£270	£0
Total	20	2	£540	-£540	£0

Table 8: The recycling mechanism

However, as all penalties are redistributed back to suppliers, they may collude with each other to abuse the mechanism. As Table 8C shows, suppliers can both present one ROC and get back all penalties, dramatically reducing revenues from selling ROCs received by generators. This problem should be easily identified if the regulator closely monitors the market. Besides, Li et al. (2020) suggest that this problem can also be mitigated by (i) increased competition in the retail sector makes collusion more difficult, and (ii) the existence of vertically integrated companies as integrated suppliers and independent suppliers may have different interests.

5. Conclusion and Policy Implications

In the UK, the proportion of electricity generated from renewable sources increased dramatically after the RO scheme was introduced. While the literature was focused on the impact on renewable capacity deployment, our paper explains the large variation in compliance by suppliers. We find that subsidiaries of the Big Six had better compliance than independent suppliers, and then we trace the movement of ROCs and use six examples to show that integrated generators are more likely to sell ROCs to integrated suppliers within the vertical integration. Next, we use simple scenarios to show that, given the existence of the recycling mechanism, this preference helps maximise the net gain of the vertically integrated company. We further develop a model under a more realistic setting to confirm this preference and also show that holding spare ROCs is unlikely to happen. Indeed, these findings are consistent with our observations: integrated suppliers have better compliance than independent suppliers, and nearly all issued ROCs were presented. Last, we discuss that the recycling mechanism helps refund unjustified penalties when there is no sufficient ROCs in the market. We explain that the recycling mechanism can increase competition for ROCs and allow a hand-off approach for the regulator, but there is a possibility that suppliers can jointly abuse the mechanism.

The RO scheme was introduced to encourage investment in renewable generation by allowing renewable generators to receive additional revenue from selling ROCs. The amendment of guaranteed headroom allows for excess demand (or insufficient supply) that helps boost investors' confidence about the value of ROCs. Therefore, penalties on ROCs missed may not be justified as suppliers may be willing to purchase and present ROCs but there is insufficient supply. So a recycling mechanism was incorporated to refund these unjustified penalties. Compared with a simple refunding mechanism, it helps promote competition for ROCs. While the quota system is also employed in other countries to promote renewable energy, such as the United States and Australia, the recycling mechanism is a unique design in the UK. This is because in other countries there is excess supply of ROCs, so penalties are justified as suppliers can always find ROCs in the market. But, as the arguments for guaranteed headroom suggested, investors have less confidence about the value of ROCs. Indeed, prices of certificates were quite volatile in both the United States and Australia, and the development of renewable capacity was slower, compared with the UK. Although insufficient supply helps promote renewable generation development, our paper suggests two problems should be addressed. First, independent suppliers were disadvantaged when both vertical integration and the recycling mechanism are in place. This problem can be mitigated by using a trading platform with anonymous buyers and sellers. Second, suppliers may collude with each other to abuse the recycling mechanism. This issue can be mitigated through close monitoring by the regulator, increased competition in the retail sector, and the existence of vertically integrated companies.

There are several limitations in the paper. First, only six examples were discussed when we trace the movements of ROCs from generators to suppliers. There are 1,910 owners on the Register, and it would be ideal to fully identify whether they are subsidiaries of the Big Six or independent. This will give accurate information about the movement of ROCs allocated to the Big Six. Second, we develop an economic model to illustrate that vertically integrated companies benefit from the internal transaction of ROCs, but a full-fledged model with independent generators should give a better understanding of the dynamics of the ROC market.

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Appendix

This Appendix discusses the relationship between the increase at the aggregate level and the average increase at the disaggregated level. By comparing these two changes, we can suggest how the increase is shared at the disaggregated level. Consider two values, A and B, with $A > B$. Assume there is a 1% increase in the sum, then the amount of increase is

$$0.01(A + B)$$

If this increase is allocated proportionally to their size, the average increase is also 0.01,

$$\left(\frac{0.01A}{A} + \frac{0.01B}{B}\right)/2 = 0.01$$

If the increase is allocated disproportionally, the increase in the sum is not equal to the average increase. First, if the allocation is in favour of the large value, by a marginal c, the average increase is less than the aggregate increase,

$$\left(\frac{0.01A + c}{A} + \frac{0.01B - c}{B}\right)/2 = 0.01 + \left(\frac{c}{A} - \frac{c}{B}\right)/2 < 0.01 \ \ as \ \ \left(\frac{c}{A} - \frac{c}{B}\right) < 0$$

Second, if the allocation is in favour of the small value, by a marginal c, the average increase is greater than the aggregate increase,

$$\left(\frac{0.01A - c}{A} + \frac{0.01B + c}{B}\right)/2 = 0.01 + \left(-\frac{c}{A} + \frac{c}{B}\right)/2 > 0.01 \ \ as \ \ \left(-\frac{c}{A} + \frac{c}{B}\right) > 0$$

The above arguments can be illustrated by a numerical example. Assume the number of ROCs available is 1,000. A large supplier A has 800 and a small supplier B has 200. Now assume the availability increases by 1% to 1,010.

- First, if these additional ROCs are distributed according to their relative sizes, A will have 808 and B will have 202. Both increase by 1%, so the average increase is 1%.
- Second, if this additional ROC is allocated in favour of A, say A has 809 and B has 201. The increases for A is 1.13% and for B is 0.5%. The average increase is 0.82%.
- Third, if this additional ROC is allocated in favour of B, say A has 807 and B has 203. The increases for A is 0.88% and for B is 1.5%. The average increase is 1.19%.

Therefore, by comparing the percentage increase at the aggregate level with the average percentage increases at the disaggregated level, we can understand how the increase is shared by players with different sizes.

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