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Excess demand or excess supply? A comparison of renewable energy certificate markets in the United Kingdom and Australia

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ABSTRACT

Comparing the United Kingdom's Renewables Obligation and Australia's Renewable Energy Target, this paper reconstructs the market for green certificates in which penalties are imposed on missed certificates. Our analysis shows that excess demand in the Renewables Obligation makes the penalty the *minimum* certificate price, but excess supply in the Renewable Energy Target makes the penalty the *maximum* certificate price. Further, excess supply also implies that the sales of certificates are not guaranteed in the Renewable Energy Target. Therefore, compared to the Renewables Obligation, generators face greater risk under the Renewable Energy Target as there is more uncertainty about the price of certificates and the possibility of sales.

1. Introduction

The aim of carbon neutrality by 2050 is being pursued globally, including within the EU and the United Kingdom (UK). The decarbonisation of the electricity sector is a central strategy (European Commission, 2018; BEIS, 2021), and tradeable green certificates (TGC) schemes have been used in many countries to support and encourage electricity generation from renewable sources. Originating from the United States under a state-level Renewable Portfolio Standard that established renewable energy targets, they address carbon emissions and climate change. Such *quota-based* schemes promote renewable electricity supply by requiring electricity retailers to purchase adequate certificates from the certificate market. Market competition is expected to establish the price of certificates, which determines the revenue generators receive from selling their certificates. TGC schemes aim to promote investment in renewable technology more competitively, and such market-oriented schemes are suggested to be more compatible with the liberalisation of the electricity market (Schallenberg-Rodriguez, 2017).

The first nationwide TGC scheme was introduced in Australia in 2001 and was known as the Mandatory Renewable Energy Target (RET). In the UK, a nationwide TGC system is adopted via its Renewables Obligation (RO) scheme, which was implemented in 2002. Over the previous two decades, there has been a marked difference in the accumulated installed capacity under these two long-standing TGC schemes, and this paper is the first to compare the design of the RO scheme in the UK and the RET scheme in Australia and identify reasons for this capacity differential. We suggest that the key difference between these two schemes is the condition of the certificate market: *excess demand* in the RO (i.e., the requirement is greater than availability) but *excess supply* in the RET (i.e., the requirement is less than availability). The feature of excess demand is a unique design in the RO, while other TGC schemes, including the RET, are featured with excess supply. Furthermore, expectations of future certificate prices also influence current prices in the RET.

As the standard model of the TGC market is limited in facilitating a comparison between the certificate markets under excess demand and excess supply, we reconstruct the model with revised demand and

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supply curves. The different designs between the RO and the RET brought two implications for investor confidence through different market conditions. First, the excess demand under the RO makes the penalty the *minimum* certificate price, but the excess supply under the RET makes the penalty the *maximum* certificate price. Also, scheme-specific mechanisms push certificate prices in opposing directions. In the RO, a recycling mechanism that redistributes the total penalty back to those retailers who purchase certificates further pushes the certificate price above the penalty. In contrast, a refunding mechanism in the RET allows retailers to temporarily remain inactive in the certificate market to avoid high certificate prices and further pushes down the price without a lower boundary. These features make generators (and thus investors) face a higher *price risk* and, thus, less confidence about the value of their certificates under the RET compared to the RO.

The second implication is for the number of certificates sold. While excess demand implies that generators have strong confidence that all certificates will be sold at or above the penalty, excess supply implies that generators face uncertainty about the sale of their certificates, as some of these will remain unsold; this is known as the *volume risk*. Therefore, generators face greater price and volume risks under the RET as there is more uncertainty about the price of certificates and the possibility of sales. Moreover, these risks were further amplified by regulatory risks and a changing government narrative in Australia, which imposed additional uncertainty over the *extent* of excess supply. These features may go some way to explaining the relatively lower growth rate of renewable generation in Australia.

The remainder of this paper is organised as follows. Section 2 provides a literature review, and Section 3 illustrates a standard model. Section 4 provides a background of the RO in the UK and the RET in Australia. Section 5 provides an economic analysis of the design of these two schemes and the impact that these have on the market for tradeable green certificates. Concluding comments are then provided in Section 6.

2. Literature review

The concept of tradable green certificates (TGC) comes from the Renewable Portfolio Standard, which is a state-mandated program in the United States that establishes the percentage of the state's overall electricity that must come from renewable energy, with Iowa as the earliest state to adopt in 1983 (Berry and Jaccard, 2001; Barbose et al., 2015; Upton and Snyder, 2017; Young and Bistline, 2018). Other than the UK and Australia, many countries also adopted the TGC scheme to encourage the installation of renewable technologies (Darmani et al., 2016). In 2002, Italy mandated that all retailers demonstrate that at least 2% of their sales originated from renewable electricity (Lorenzoni, 2003). Belgium also implemented TGC schemes to meet the EU's renewable energy requirements, aiming for 6% of total electricity consumption by 2010 (Verhaegen et al., 2009). The TGC system was introduced in Sweden in 2003 to encourage an additional 10 TWh of green electricity by 2010 (Nilsson and Sundqvist, 2007; Bergek and Jacobsson, 2010; Darmani, 2015). To strengthen their commitment to renewable energy further, Sweden and Norway collaborated to establish a common green certificate market in 2012 (Finjord et al., 2018). Among other European countries, Poland introduced the TGC scheme in 2005, aiming to ensure that 7.5% of the total electricity consumption would be powered by renewable sources by 2010 (Wedzik et al., 2017), and Romania implemented a TGC scheme in 2008 to make its commitment to green energy (Colesca and Ciocoiu, 2013). Japan launched its TGC scheme in Asia in 2003 (Dong and Shimada, 2017). In 2012, Korea implemented the TGC scheme, aiming to promote the deployment of renewable energy more cost-effectively (Kwon, 2015, 2020; Yoon and Sim, 2015). The two largest developing economies, India in 2011 (Shrimali and Tirumalachetty, 2013) and China in 2017 (Feng et al., 2018; Wang et al., 2019; Tu et al., 2020; Song et al., 2021) also launched their TGC schemes respectively, both aiming to achieve 15% of electricity from renewable sources in 2020.

One strand of the associated literature discusses the effectiveness of the RO scheme, which, in its early stages, was criticised for a lack of effectiveness as investors of renewable projects faced both price and volume risks. Regarding price risk, Mitchell et al. (2006) suggest that retailers only need to ensure they have adequate certificates to meet their obligations, and so the value of certificates declined if there were more certificates in the market. In addition, Woodman and Mitchell (2011) suggest a 'cliff-edge' effect, i.e., the price might fall rapidly to zero when obligation targets are met. Regarding the volume risk, Mitchell and Connor (2004) suggest that renewable generators were uncertain about the demand for their renewable electricity (and associated certificates) after meeting the 10% emissions reduction target by 2010. Although this target was extended to 20% by 2020 (DTI, 2006), Mitchell et al. (2006) further suggest that, as the amount of renewable energy generation increased, the number of certificates exceeded the retailers' obligation, making certificates challenging to sell.

In the same way, Woodman and Mitchell (2011) echo such sentiments that certificates would be unsold in the market once obligations on renewable energy output in a particular year were met. In such cases, there was no guarantee of contracted output from any retailer, and the price of certificates might drop to zero. Given these uncertainties, both Mitchell et al. (2006) and Woodman and Mitchell (2011) highlight the difficulties of predicting the return on investment of renewable energy projects. Consequently, guaranteed headroom was added in 2010-11 to increase the obligations imposed on retailers, and this revised way of calculating obligations ensured excess demand for certificates in the market, preventing a collapse of their price, but Wood and Dow (2011) suggest it was difficult to predict the impact of the reform on certificate prices from newly added headroom, which made the design more complicated and created barriers to investment, especially for small independent companies. Li et al. (2020) argue that the recycling mechanism caused strategic behaviour and lower revenue received by generators. Shao et al. (2021) indicate that independent retailers had difficulty purchasing certificates in the market with inadequate supply compared with retailers integrated with generators. Nonetheless, Bunn and Yusupov (2015) and Shao et al. (2022) confirm that the amendment helped improve the effectiveness of the RO scheme in promoting electricity generation from renewable sources, and Shao et al. (2023) suggest that the RO scheme helped reduce costs of importing coals and carbon emission certificates.

A second strand of literature has developed to discuss the effectiveness of the RET scheme. In an early study, Kent and Mercer (2006) suggest that RET has encouraged renewable energy development but that problems such as a low target and a lack of legislative clarity exist. Several studies have also highlighted similarly detrimental aspects of the scheme. For example, Kann (2009) suggests that the regulatory risk surrounding the legislation of the RET was a primary barrier to project finance for investment in renewable generation. MacGill (2010) also echoes the sentiment that the high investment risk from volatile certificate prices hindered renewable projects.

Regarding targets, Valentine (2010) argues that the scheme stimulated technological change in the electricity sector only before 2020, as the target for renewable generation would remain fixed from 2021 to 2030. On the aspect of legislation, Nelson et al. (2013) suggest that the uncertainty surrounding the RET prevented the market for certificates from operating efficiently as buyers and sellers of these were concerned about possible further legislative changes. Indeed, Warren et al. (2016) suggest that Australia's climate and energy policies have been heavily influenced by the election cycle and different views across political parties, and Simpson and Clifton (2014) confirm that policy continuity and excessive reviewing procedures were the main concern by most respondents in submissions to a national consultative review. Further, Simshauser and Tiernan (2019) and Simshauser and Gilmore (2022) indicate that the uncertainty in policy continuity brought about cycles in renewable investment and, thus, higher volatility in electricity prices. Nonetheless, MacGill and Healy (2013) indicate that the RET created competitive pressures to reduce costs by providing technology-neutral support and effectively achieved its target. Byrnes et al. (2013) also confirm that RET significantly encouraged the deployment of renewable energy generations, although this effectiveness was reduced as the generations with the lowest cost were developed at the expense of emerging technologies.

The TGC system was compared with the price-based Feed-in Tariff (FIT) scheme to evaluate effectiveness. On the one hand, studies suggest that FIT outperforms TGC. Menanteau et al. (2003) argue that the fixed price set by FIT offers investors enhanced predictability, providing safer investments while reducing transaction expenses. Del Río and Gual (2007) suggest that the environmental benefits of FIT seem to outweigh their costs. Lipp (2007) argues that the costs associated with renewable electricity generation under TGC schemes exceed those of FIT. Butler and Neuhoff (2008) suggest that, compared with TGC, FIT reduces electricity prices and increases installation. Nicolini and Tavoni (2017) also confirm that FIT outperforms TGC in promoting renewable electricity deployment. Currier (2016) and Currier and Rassouli-Currier (2018) indicate that green producers may not be incentivised to exploit their technology's full cost-reduction potential under TGC. On the other hand, a balanced view is suggested by other studies. Ringel (2006) suggests that TGC ensures the fulfilment of the renewable energy target and ensures that this aim is precisely met, but also argues that, regardless of which scheme is chosen, whether installation targets are met will depend heavily on detailed regulations. Abdmouleh et al. (2015) suggest that FIT offers flexibility in promoting a diversity of renewable technologies and provides investors with guaranteed returns over extended periods, but the TGC encourage competition among renewable electricity generators, which can promote innovation and drive down costs. Sun and Nie (2015) argue that FIT is preferred if the objective is to build a less risky environment for investors, but TGC is more aligned with market dynamics and encourages competitive practices if aiming to implement market-oriented policies. Marques et al. (2019) indicate that FIT promotes the growth of less mature technology, but TGC becomes better integrated within the market framework and offers long-term benefits.[1]

3. The standard model

Early models used to analyse the performance of certificate markets originated from the seminal work of Morthorst (2000), which developed a graphical analysis of the certificate market in Denmark. This model and its variants have subsequently formed the basis for further analysis in the following studies on various issues, such as the international power spot market (Morthorst, 2003), the short and long-term financial risks (Lemming, 2003), the effects of technological advancements (Agnolucci, 2007), the negative impact of over-investment on certificate prices (Kildegaard, 2008), and the influence of tax-financed certificate support schemes (Helgesen and Tomasgard, 2018).

Fig. 1 illustrates the standard model of the TGC market with a penalty imposed on each certificate missed. On the demand side, retailers are willing to pay a price no more than the penalty. If the price is higher than the penalty, retailers are better off if they pay the penalty than buying the certificate. When retailers have met their obligations, the demand for certificates disappears as retailers are not incentivised to buy more. Therefore, such an approach postulates a flat demand curve at the penalty price and then drops to zero when the obligation is met.

Meanwhile, on the supply side, as generators receive revenue from selling electricity and green certificates, the marginal cost of a certificate can be defined as the difference between the marginal cost of generation and the electricity price. If the price of certificates falls below the marginal cost of certificates, generator becomes unprofitable and thus stops

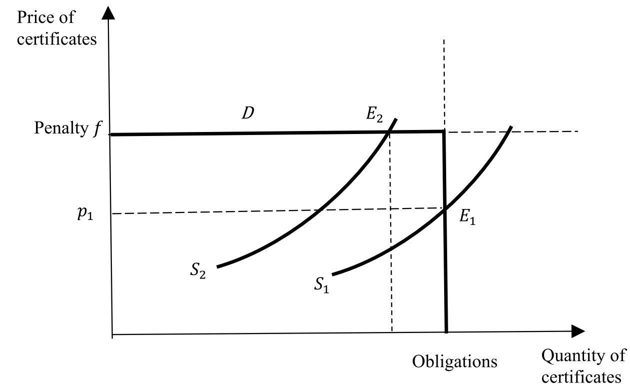

Fig. 1. The standard model for a tradable green certificate market.

operations and does not supply electricity to the market. Therefore, the supply curve is upward sloping, based on the ascending order of generators' marginal costs of certificates.

Two possible equilibria can be achieved depending on the supply curve's position. First, if the supply curve is S_1, when there are abundant generators with lower marginal costs of certificates, the equilibrium is at E_1. At this equilibrium, the price of certificates is lower than the penalty, retailers meet their obligations (full compliance), and there is no demand for certificates from generators with marginal costs of certificates higher than p_1.

Second, if the supply curve is S_2, when there are fewer generators with lower marginal costs of certificates, the equilibrium is at E_2. At this equilibrium, the price of certificates is equal to the penalty, retailers fail to meet their obligations (partial compliance), and there is no demand for certificates from generators with marginal costs of certificates higher than the penalty f.

However, this standard model and its variants are limited in comparing the certificate markets under excess demand (the RO) and excess supply (the RET). In the RO, this model is limited in capturing the situation of inadequate certificates and the price above the penalty. In the RET, this model is also limited in explaining the observation of partial compliance when the certificate price is much lower than the penalty and spare certificates are available in the market. Further, this standard model does not accommodate the impacts of expected future certificate prices.

4. Background: the RO and the RET

This section briefly explains the developments of electricity from renewable sources in the UK and Australia and elaborates on the characteristics of the RO and RET schemes.

4.1. Developments of electricity from renewable sources in the UK and Australia

Both countries achieved their targets for renewables by 2020, but with interesting differences. For the UK, renewables' share of electricity generation increased to 36.9% in 2019 (BEIS, 2022), well above its 2020 target level of 30% announced in 2010 (DECC, 2010). In contrast, for Australia, the Clean Energy Regulator (CER) confirmed that the target of 33,000 GWh of renewable electricity was met in 2020 (CER, 2022b), but this target was reduced from 41,000 GWh when the Australian government confirmed the continuation of the RET in 2015.[2]

Fig. 2 shows the development of electricity generated from four key

[1] A recent literature review on renewable energy subsidy policies, including TGC and FIT, is provided by Shen et al. (2020).

[2] The Clean Energy Regulator is the independent statutory authority responsible for administering the legislation to reduce carbon emissions and increase the use of clean energy in Australia.

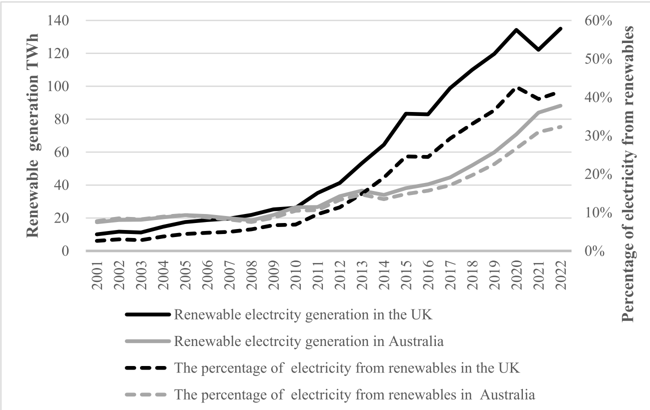

Fig. 2. Renewable generations and the percentage of electricity from renewables in the UK and Australia, 2001–2022 [4].
Source: Department for Business, Energy & Industrial Strategy (BEIS, UK) and Department of Industry, Science, Energy and Resources (DISER, Australia).

renewable sources (bioenergy, wind, solar, and hydro) in the UK and Australia from 2001 (the date RET started) to 2022.[3] In the UK, the electricity generated from renewable sources increased from 10.07 TWh in 2001 to 135.01 TWh in 2022 (BEIS, 2022). In contrast, the increase in Australia has been more modest, increasing from 17.43 TWh in 2001 to 88.21 TWh in 2022 (DISER, 2022).

A series of renewable energy policies could stimulate the growth patterns of electricity generation. Therefore, to better understand the impact of the RO and the RET on renewable electricity, Fig. 3 shows the installed renewable capacity that received accreditation under these two schemes. The installed renewable capacity in the RO grew rapidly from 1.68 GW in 2002 to 35.40 GW in 2021 (Ofgem, 2022), while the in the RET was relatively slower, from 8.46 GW in 2001 to 29.40 GW in 2021 (CER, 2022a).

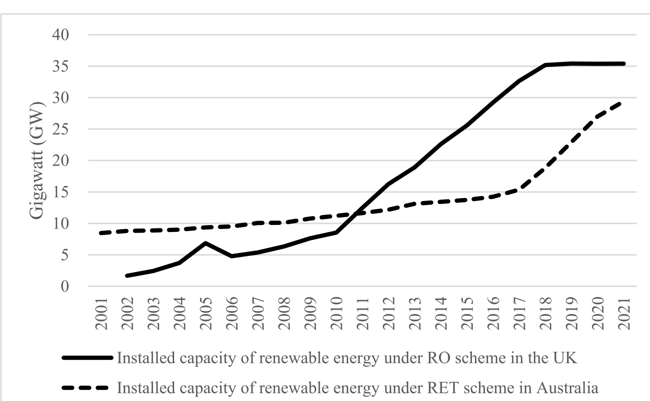

Fig. 3. Renewable capacity accredited under the RO and the RET, 2001–2021[5].
Source: Ofgem (UK) and Clean Energy Regulator (Australia).

4.2. Terminologies in the RO and the RET

The RO and the RET are TGC schemes to support renewable energy-sourced electricity under which regulators issue certificates to accredited generators and announce an obligation level to electricity retailers. Electricity retailers can calculate the required certificates by multiplying this level with their electricity sales. If they fail to submit the required number, they must pay a penalty for each missed certificate. Both schemes create a certificate market, providing additional revenue to renewable electricity generators through selling certificates and the revenue from selling electricity. Table 1 summarises the different terminologies used between them.

4.3. The RO scheme in the UK

The RO scheme was introduced in April 2002 to support investment in large-scale projects in renewable electricity, and it was closed to new entrants in March 2017.[6] As shown in Table 2, over the period 2002-03 to 2021-22, the obligation level increased from 0.030 certificates/MWh to 0.492 certificates/MWh, and the total number of certificates required increased from 9.26 million to 127.82 million (Ofgem, 2022).[7]

Before 2010-11, pre-specified obligation levels were announced for each reporting year, but a problem experienced in the early stages of the RO was that developers of any renewable project faced both a *price* risk and a *volume* risk. Therefore, a guaranteed buffer (*headroom)* was added in April 2010 to increase the obligation requirements imposed on retailers. In such calculations, a 10% headroom was added to the expected total issued certificates, detailed in Section 5.1.3.[8] This revised way of calculating obligation level ensures excess demand (i.e., insufficient supply) in the market, i.e., the number of certificates issued is less than the number of certificates required to prevent a crash in certificate prices and boost inventors' confidence about the value of certificates. Table 2 shows that the obligation level increased markedly from 2010-11 after the introduction of headroom.

As seen in Table 2, the certificates issued to renewable generators increased substantially from 5.56 million in 2002-03 to 109.31 million in 2021-22, with the required numbers showing a similar increase from

Table 1
Different terminologies used in the RO and the RET.

	UK	Australia
Names of TGC scheme	renewables obligation (RO)	renewable energy target (RET)
Retailers who submit certificates	suppliers	liable entities
Tradable green certificates	renewable obligation certificates (ROCs)	large-scale certificates (LGCs)
Certificates submitted to regulators	certificates presented	certificates surrendered
Obligation level (the number of certificates required for each MWh of electricity sold)	obligation level	renewable power percentage (RPP)
Penalty on each certificate missed	buy-out price	shortfall charge
Redistribution payment from the total penalty	recycle value	N/A

[3] Other minority renewable technologies, such as tidal and wave, are not included due limitations on data availability.

[4] The data for Australian is based on its financial year. For example, the electricity generation in 2002 is 18.84 TWh, which is for 2002.07-2003.06.

[5] The data for the UK is based on the financial year. For example, the installed capacity in 2002 is 1.68 GW, which is for 2002.04-2003.03.

[6] The obligation years of the RO scheme were from April to March in the next year, consistent with the financial year.

[7] In July 2011, the government announced it intended to close the RO to all new generating capacity on 31 March 2017. However, the RO was closed earlier for solar and onshore wind in 2015 and 2016. There were a number of grace periods, which allowed generators to gain accreditation under the RO in certain circumstances after 31 March 2017.

[8] A headroom of 8% was introduced in the first year of implementation, 2010-11, then was raised to 10% from 2011-12.

Table 2
Obligation level, certificates required and available, compliance rate, penalty, and recycle value. The ratios are presented as $n:1$ because excess demand is the feature of the RO.

Obligation year	Obligation level (certificates/ MWh)	Certificates required	Certificates available	The ratio of required to available	Compliance rate	Penalty (£)	Recycle value (£)
2002-03	0.030	9,261,568	5,562,669	1.665:1	58.86%	30.00	15.94
2003-04	0.043	13,627,412	7,658,007	1.779:1	55.84%	30.51	22.92
2004-05	0.049	15,761,067	10,872,929	1.450:1	68.88%	31.39	13.66
2005-06	0.055	18,032,904	13,784,456	1.308:1	75.97%	32.33	10.21
2006-07	0.067	21,629,676	15,032,228	1.439:1	67.56%	33.24	16.04
2007-08	0.079	25,551,357	16,151,978	1.582:1	64.45%	34.30	18.65
2008-09	0.091	28,975,678	18,996,453	1.525:1	65.40%	35.76	18.61
2009-10	0.097	30,101,092	21,275,284	1.415:1	70.89%	37.19	15.17
2010-11	0.111	34,749,418	24,884,608	1.396:1	71.86%	36.99	14.35
2011-12	0.124	37,675,829	34,753,771	1.084:1	91.32%	38.69	3.58
2012-13	0.158	48,915,432	44,647,787	1.096:1	91.53%	40.71	3.67
2013-14	0.206	61,858,174	62,819,706	0.985:1	98.22%	42.02	0.70
2014-15	0.244	71,922,000	73,373,129	0.980:1	99.10%	43.30	0.35
2015-16	0.290	84,439,465	90,465,238	0.933:1	99.94%	44.33	0.00
2016-17	0.348	100,748,885	92,216,714	1.093:1	89.54%	44.77	5.10
2017-18	0.409	117,842,123	100,581,303	1.172:1	87.59%	45.58	5.85
2018-19	0.468	127,623,995	105,948,003	1.205:1	84.34%	47.22	7.82
2019-20	0.484	130,183,968	114,706,958	1.135:1	89.06%	48.78	5.65
2020-21	0.471	119,090,744	105,263,447	1.003:1	88.40%	50.05	4.42
2021-22	0.492	127,815,053	109,312,159	1.170:1	85.50%	50.80	7.44

Source: Renewables Obligation Annual Reports, Ofgem, UK, and authors' calculation based on the data.

9.26 million to 127.82 million over the same period.[9] The ratios of these required-to-available figures are presented as $n:1$, showing how many certificates are required for each certificate issued. Noticeably, there was excess supply from 2013-14 to 2015-16 due to an inaccurate forecast in the calculation of the obligation level, but investor confidence was unlikely to be damaged as headroom was consistently used in the calculation, and excess demand returned from 2017-18, see further discussion in Section 5.1.4.

As there were insufficient certificates in the market, all retailers could not meet their obligations, leading to partial compliance. However, Shao et al. (2021) indicate that all issued certificates were sold, suggesting *retailers are willing to purchase certificates,* but there was no availability in the market. This partial compliance has been explained by other studies from different aspects, such as low penalty (Jacobsson et al., 2009; Darmani et al., 2016), the design of the recycling mechanism (Buckman, 2011), non-mature market environment (Haas et al., 2011).

Moreover, if retailers fail to meet their obligations, they need to pay a penalty for each certificate missed, and this penalty increased steadily from £30.00 in 2002-03 to £50.80 in 2021-22 (adjusted with the Retail Prices Index annually). However, due to insufficient supply in the market, penalties for partial compliance may not be justified. Therefore, a recycling mechanism was implemented to redistribute the total penalty back to the retailers who present the certificates. The recycle value is the redistribution payment received by each certificate presented, and it is calculated by dividing the total penalty by the total certificates presented.[10] The recycle value is inversely related to the extent of excess demand because a larger excess demand, represented by a higher ratio of required to available, implies a larger total penalty as more retailers fail to meet their obligations and thus a higher recycle value.

4.4. *The RET scheme in Australia*

The RET scheme introduced in 2001 was designed to encourage investment in renewable capacity to achieve 9500 GWh of additional renewable electricity generation by 2010. In 2011, the scheme was announced to achieve a target of 41,000 GWh from utility-scale renewable generators by 2020.[11] However, in 2013, based on the argument that the scheme was costly and increased electricity prices, the Coalition government opposed it, and the Warburton Review was launched to investigate its economic impact (CER, 2014). As a result, investments in renewable projects were paused due to concerns about the possibility that the RET scheme might be abolished. Later, in 2015, it was confirmed that RET would continue but with its target reduced (for utility-scale generators) from 41,000 GWh to 33,000 GWh.

Under the RET scheme, as Table 3 shows, the obligation level increased from 0.0024 certificates/MWh in 2001 to 0.1864 certificates/MWh in 2022, and the required number increased from 0.3 million in 2001 to 33 million in 2022, which makes up the demand side of the certificate market. On the supply side, certificates are available for sale in the market after being allocated to renewable generators. In addition, surplus certificates from previous years are added to provide an accurate measure of market supply.[12,13] The ratios of these required-to-available figures are presented as $1:n$, showing how many certificates are available for the demand of one certificate. Table 3 shows that this ratio declined from 2011, suggesting a tightening in the market.

The penalty was set at A$40 per certificate missed and then raised to

[9] An amendment of the RO scheme introduced in April 2009 was banding, which provides different levels of support depending on technologies, breaking the one-to-one relationship between renewable generation and the number of certificates (Wang et al., 2023). For example, the banding level increased from one to 1.5 for offshore wind in 2009-10. However, this feature is not discussed in this study as it does not affect the process of calculating the obligation level and thus excess demand.

[10] For example, in 2019-20, with a total penalty for redistribution of £654.60 million and a total of 115.94 million certificates presented, retailers received a recycle value of £5.65 for each certificate presented.

[11] Another component of the RET is the small-scale renewable energy scheme supported small-scale installations like household solar panels. These two components have similar sizes. However, the current analysis will focus upon only the large-scale aspect of the scheme to provide comparability with the counterpart UK scheme which was used to support investment in large-scale renewable projects.

[12] Unsold (surplus) certificates can be banked by generators and become available in the future years, so the total availability of certificates in each year is the sum of those newly issued and previously unsold.

[13] Other than those surrendered for compliance, there is also voluntary surrender by retailers who wish to support additional generation of electricity from renewable energy sources or to meet GreenPower obligations. This allows retailers to offer a 'green' tariff option to consumers (CER, 2022a). This amount is considered when we calculate the surplus figures for each year.

Table 3
Obligation level, certificates available, compliance rate, and penalty. The ratios are presented as **1** : ***n*** because excess supply is the feature of the RET.

Obligation year	Obligation level (certificates/MWh)	Certificates required	Certificates available	The ratio of required to available	Compliance rate	Penalty (A$)
2001	0.0024	300,000	598,327	1:1.994	92.30%	57.14
2002	0.0062	1,100,000	2,479,954	1:2.255	99.00%	57.14
2003	0.0088	1,800,000	4,836,226	1:2.687	99.90%	57.14
2004	0.0125	2,600,000	6,541,554	1:2.516	99.80%	57.14
2005	0.0164	3,400,000	8,495,344	1:2.499	99.70%	57.14
2006	0.0217	4,500,000	10,630,351	1:2.362	99.70%	57.14
2007	0.0270	5,600,000	13,010,905	1:2.323	99.45%	57.14
2008	0.0314	6,800,000	15,999,054	1:2.353	99.81%	57.14
2009	0.0364	8,100,000	22,495,008	1:2.777	99.96%	57.14
2010	0.0598	12,500,000	48,142,006	1:3.851	99.21%	92.86
2011	0.0562	10,400,000	48,823,465	1:4.695	99.97%	92.86
2012	0.0915	16,763,000	47,344,571	1:2.824	99.98%	92.86
2013	0.1065	19,088,000	42,415,389	1:2.222	99.98%	92.86
2014	0.0987	16,950,000	37,365,870	1:2.204	99.97%	92.86
2015	0.1111	18,850,000	41,963,463	1:2.226	99.40%	92.86
2016	0.1275	21,431,000	35,320,821	1:1.648	89.30%	92.86
2017	0.1422	26,031,000	32,475,335	1:1.248	93.30%	92.86
2018	0.1606	28,637,000	32,391,450	1:1.131	86.10%	92.86
2019	0.1860	31,244,000	36,716,131	1:1.175	76.60%	92.86
2020	0.1931	33,850,000	40,552,980	1:1.198	79.70%	92.86
2021	0.1854	33,000,000	45,032,133	1:1.365	86.30%	92.86
2022	0.1864	33,000,000	49,890,639	1:1.512	86.00%	92.86

Source: Renewable Electricity Generation Annual Reports, Clean Energy Regulator, Australia, and authors' calculation based on the data.

A$65 in 2010. As the penalty is not tax-deductible, the post-tax equivalent value was A$57.14 before 2010 and A$92.86 after that.[14] The penalty referred to in this study as the post-tax equivalent value is directly related to the upper limit of the certificate price.

Regarding compliance, this has been above 99% before most years up until 2015, showing that almost all retailers surrender enough certificates to meet their obligations. In contrast, compliance fell below 90% in 2016, even though certificates were still available in the market, indicating *retailers were unwilling to purchase certificates*. This fact may be explained by the refunding mechanism, which allows for the payment of the penalty on certificates missed to be refunded in future years by the presentation of adequate certificates, and its impact will be elaborated in Section 5.2.

4.5. The role of the penalty

In principle, the penalty should play a pivotal role in determining the price of certificates in the market, as retailers should be willing to pay a price up to the penalty for each certificate. A scheme with a higher penalty (and thus a higher price of certificates) should be more effective in promoting investment in renewable energy. Fig. 4 shows the penalties in the RO and the RET in nominal values. While the penalty in the RO increased gradually, adjusted with the Retail Prices Index annually, the penalty in the RET remained flat except for a jump in 2010. For comparison from the point of view of international investors, the penalty in the RET is converted from Australian dollars to British pounds using the average exchange rate of each year from 2002-21. The comparison in Fig. 4 shows that the penalties in the RET are higher than those in the RO from 2009 to 2019 before converging in 2020 and 2021.

Although the change in the penalty in the RET may result from exchange rate fluctuation and the decision-making on renewable projects depends on other factors such as natural resources and consumer preferences, the penalty should still be a signal of determination of supporting policies. Therefore, from the perspective of global investors, a higher value of penalty in the RET should provide a higher incentive to develop renewable energy in Australia, but, as noted previously in Fig. 3, the development of renewable electricity capacities has been much faster under the RO than under the RET. To address this puzzling issue, we will explore the design of these two schemes.

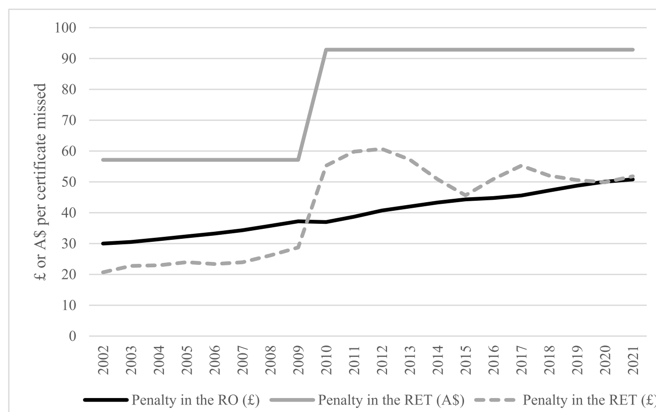

Fig. 4. The penalties in the RO and the RET, 2002–21, nominal values.
Source: Ofgem (UK), Clean Energy Regulator (Australia), DataStream.
Note: the penalty in the RO is based on the financial year, with the penalty for 2021, for example, being for 2021-22 (April 2021–March 2022).

5. The analysis of the RO scheme and the RET scheme

5.1. The certificate market in the RO

For the RO scheme, the two key features are excess demand and the recycling mechanism, which redistributes penalties back to retailers. This subsection illustrates a model with excess demand to suggest that the penalty sets a price floor for the certificate price, and the recycling mechanism pushes the certificate price higher.

5.1.1. Retailer in the RO

Retailers purchase electricity from generators and sell it to consumers in the electricity market. They are obliged to purchase certificates from generators. For individual retailer *i*, its profit function can be

[14] The penalty of A$65 per certificate not surrendered is non-tax deductible, which equates to a post-tax equivalent penalty A$92.86 given the 30% business tax rate. For illustration, LHS is the after-tax profit after purchasing the certificate, RHS is after-tax profit then deducted the penalty, making both sides equal gives the post-tax equivalent penalty, $0.7 \bullet (\Pi - p^c) = 0.7 \bullet \Pi - \text{A\$65} \Rightarrow p^c = \text{A\$92.86}$.

written as

$$\pi_i^s = (p^e - p^w)q_i^s - p^c R_i - (\alpha q_i^s - R_i)f + E_i(r)R_i \text{ if } \alpha q_i^s \geq R_i \quad (1)$$

On the RHS, the first term, $(p^e - p^w)q_i^s$, is the profit from selling electricity to end-users, where p^e is the retail electricity price, p^w is the wholesale electricity price, and q_i^s is the quantity of electricity sold. The second term, $p^c R_i$, is the payments from retailer i to generators for certificates, where p^c is the price of certificates that retailers pay to generators, and R_i is the number of certificates purchased. The third term, $(\alpha q_i^s - R_i)f$, is the penalty payment paid into the buy-out fund, where α is the obligation level, αq_i^s is the required number of certificates, and f is the penalty for each certificate missed.

According to the recycling mechanism, retailers receive a recycle value r for each certificate presented, which is equal to the total penalty divided by the total number of certificates presented,

$$r = \frac{\sum_{i=1}^{n}\left[(\alpha q_i^s - R_i)f\right]}{\sum_{i=1}^{n} R_i} = \frac{(\alpha Q^s - R)f}{R} \geq 0 \quad (2)$$

where n is the number of retailers, $Q^s = \sum_{i=1}^{n} q_i^s$ is the total electricity sold by all retailers, αQ is the number of certificates required, and R is the total number of certificates purchased and presented. As the total penalty is non-negative, the recycle value is no less than zero, $r \geq 0$.

In addition, Eq. (2) indicates that the recycle value is reversely related to the extent of excess demand in the market, holding the penalty fixed. When the extent of excess demand is larger, i.e., the value of $(\alpha Q^s - R)$ is larger, represented by a higher ratio of required to available in Table 2, more retailers will fail to meet their obligations, so the total penalty and, thus, the recycle value will be larger.

However, retailers should form their idiosyncratic expectations about the recycle value $E_i(r)$ based on the expected total electricity sold and the expected number of certificates presented because the recycle value is calculated at the end of the reporting year after all retailers present their certificates,

$$E_i(r) = \frac{[\alpha E_i(Q^s) - E_i(R)]f}{E_i(R)} \geq 0 \quad (3)$$

By presenting one certificate, the retailer avoids the penalty f and receives the expected recycle value $E_i(r)$, so the price of certificates can be described as

$$p_i^c = f + E_i(r) \quad (4)$$

which shows that the retailer is willing to pay a higher price for certificates if it has higher expectations of the recycle value. As the recycle value is greater than or equal to zero, the penalty is the minimum price that retailers are willing to pay. Meanwhile, when the obligation is fully met, there is no further demand for certificates. As shown in Fig. 5, the demand curve for certificates (D_{RO}) is downward sloping and then drops to zero at the level of obligations.[15]

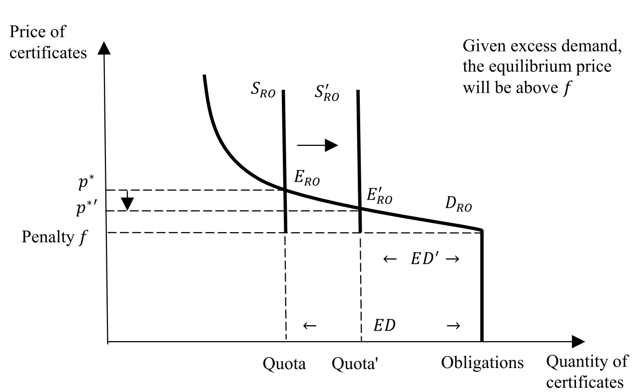

Fig. 5. The certificate market with excess demand and the recycling mechanism. The penalty is denoted as f.

5.1.2. Generators in the RO

Generators sell both the electricity generated and certificates to retailers in the electricity market. For individual generator j, the number of certificates awarded $\overline{R}_j^s$ depends on renewable generation,

$$\overline{R}_j^s = q_j^g \quad (5)$$

where q_j^g is the electricity generated from renewable sources, and generators receive one certificate per MWh.[16]

As there is excess demand for certificates, some retailers fail to meet their obligations and pay the penalty, so the recycle value is positive. Therefore, retailers buy the certificate if generators sell it at the penalty level. Given this market condition, generators are unwilling to accept any price lower than the penalty. Therefore, as shown in Fig. 5, the supply curve (S_{RO}) is drawn as a vertical line above the penalty.

5.1.3. The certificate market in the RO

Here, we turn to the certificate market. On the supply side, the total number of certificates issued (supply of certificates) depends on the total electricity generated by various renewable sources,

$$\overline{R}^s = \sum \overline{R}_j^s = \sum q_j^g \quad (6)$$

On the demand side, the total number of certificates required is shown as the product of the obligation level and total electricity sold, αQ^s, where $Q^s = \sum q_i^s$. Regarding the obligation level α, the regulator first estimates the number of certificates to be issued as $E(\overline{R}^s)$, and then raises it by a headroom $\gamma > 0$ to ensure excess demand, giving

$$(1+\gamma)E(\overline{R}^s) \quad (7)$$

The obligation level, α, is calculated by dividing this term by the expected total electricity to be generated, $E(Q^s)$, including both renewable and non-renewable sources,

$$\alpha \equiv \frac{(1+\gamma)E(\overline{R}^s)}{E(Q^s)} \quad (8)$$

After the obligation level is announced, together with the total electricity sold, the total required certificates (i.e., their demand) is

$$R^d \equiv \alpha Q^s = (1+\gamma)\frac{Q^s}{E(Q^s)} E(\overline{R}^s) > \overline{R}^s \quad (9)$$

Eq. (9) shows that, when the actual number of certificates issued and the total electricity supplied are not far from their expected values, the headroom γ creates a margin to help hold this equation and ensures that the certificate demand is greater than the certificate supply.

The equilibrium of the market featuring excess demand can be reached at E_{RO}, as shown in Fig. 5, with the interaction point between the demand curve (D_{RO}) and the supply curve (S_{RO}), establishing the equilibrium price is p^*, above the penalty (f). Retailers with expectations higher than that will buy certificates, and retailers with expectations lower than that will miss their obligation and pay the penalty. The horizontal difference between obligations and quota is the size of excess demand (ED).

[15] The demand curve approaches to infinity when the number of presented certificates approaches to zero.

[16] Banding imposes an additional parameter on the quantity of electricity generation in Eq. (5) for individual renewable generator depending on the type of technology. In general, the weighted-average banding level builds up the aggregate relationship between the quantity of renewable generation under the RO scheme and the number of certificates issued. For example, the weighted-average banding level was 1.04 in 2009-2010 (Ofgem, 2010).

Proposition 1. *In the certificate market with excess demand and the recycling mechanism, in equilibrium, the price of certificates is higher than the penalty, a fraction of retailers do not meet their obligations, and there are no spare certificates in the market.*

An increase in the supply of certificates shifts the supply curve rightwards, reduces the extent of excess demand, and lowers the equilibrium price (also shown in Fig. 5). However, if the quota is less than the obligation (i.e., excess demand), the price will remain above the penalty. Therefore, the penalty is considered the minimum price of certificates under this scheme.

Proposition 2. *In the certificate market with excess demand and the recycling mechanism, an increase in supply leads to a new equilibrium. Compared with the previous equilibrium, the price is lower, more retailers meet their obligations, and no spare certificates are left in the market.*

5.1.4. The price of certificates in the RO

In the RO scheme, most certificates are traded bilaterally, and their prices are unknown to the public. However, from annual RO reports, the sum of the penalty and the recycle value is used as an approximation, as in Eq. (4). Fig. 6 shows this approximated price from 2002-03 to 2019-20. The penalty is used as the minimum of the certificate price. Besides, when excess demand is greater, more retailers will miss their obligations, leading to a higher total penalty and a higher recycle value.

The one proviso to this is in 2015-16, as even though headroom had been implemented, there was excess supply in the market. Eq. (9) does not hold when there is a large deviation between the actual and expected values. In this obligation year, the actual certificates issued ($\overline{R}^s$, 90.4 million) exceeded the expected value ($E(\overline{R}^s)$, 86.6 million), and the expected electricity supplied ($E(Q^s)$, 303.8 TWh) is greater than the actual electricity supplied (Q^s, 295.8 TWh), giving an inequality as

$$R^d < \overline{R}^s \leftrightarrow \frac{\overline{R}^s}{E(\overline{R}^s)} \frac{E(Q^s)}{Q^s} > 1 + \gamma \tag{10}$$

Nonetheless, as the headroom continues to be used for future calculations, these unsold certificates will be demanded in future periods, so temporary excess supply has a limited impact on the market confidence, and the estimated price remains at the level of penalty.

5.2. The certificate market in the RET

For the RET scheme, the two key features are excess supply and the refunding mechanism, which allows retailers to remain inactive temporarily in the certificate market by paying the penalty and seeking a refund after presenting previously missed certificates in the future. This subsection illustrates a model with excess supply to suggest that the penalty can be considered the maximum for the certificate price. Also, the refunding mechanism pushes the certificate price downward when the current certificate price is high, and the expected future price is low. For simplicity, we assume that the discount factor is one, so future values are not discounted.

Fig. 6. Estimated certificate price and penalty from 2002-03 to 2021-22. The gap between them is the recycle value.
Source: Renewables Obligation Annual Report, Ofgem, UK.

5.2.1. Retailers in the RET

For individual retailer i, its profit function is

$$\pi_i^s = (p^e - p^w)q_i^s - p^c R_i - (\alpha q_i^s - R_i) f \ \text{if} \ \alpha q_i^s \geq R_i \tag{11}$$

where α is the obligation level, and f is the penalty but captures the same principles as discussed for Eq. (1) in the RO setting, except there is no recycle payment. We rearrange the second and the third terms that relate to the certificates,

$$R_i(f - p^c) - \alpha q_i^s f \tag{12}$$

which shows that if the price of certificates is less than the penalty, $f - p^c > 0$, retailers will buy all certificates required to meet their obligations.[17] Otherwise, if the certificate price is higher than the penalty, retailers will not buy any certificate but instead pay the penalty, so the penalty is the maximum price retailers are willing to pay. Besides, once obligations are met, the value of certificates drops to zero. Therefore, the demand curve is flat at the penalty and then drops to zero after the obligation is met, similar to that suggested by Morthorst (2000). This situation is depicted by the initial horizontal portion of the demand curve (D_{RET}) in Fig. 7.

However, the demand curve is modified by the refunding mechanism. On the one hand, if the retailer purchases the certificates and meets all its obligations, no penalty is paid, and the profit function is

$$\pi_i^s = (p^e - p^w)q_i^s - p^c R_i \tag{13}$$

On the other hand, assume the retailer pays the penalty for this obligation year and then seeks a refund in the future. We use $E_i(p^c)$ to denote retailer i's idiosyncratic expected future price of certificates. The expected future price will not be higher than the penalty as it is the maximum price of certificates, $E_i(p^c) \leq f$. Therefore, the retailer' profit function is

$$\widetilde{\pi}_i^s = (p^e - p^w)q_i^s - \alpha q_i^s f - E_i(p^c)R_i + \alpha q_i^s f \tag{14}$$

where the first $\alpha q_i^s f$ is the penalty paid, $E_i(p^c)R_i$ is the expected costs of purchasing certificates in the future, and the second $\alpha q_i^s f$ is the refund to be received after presenting the missed certificates. Comparing these

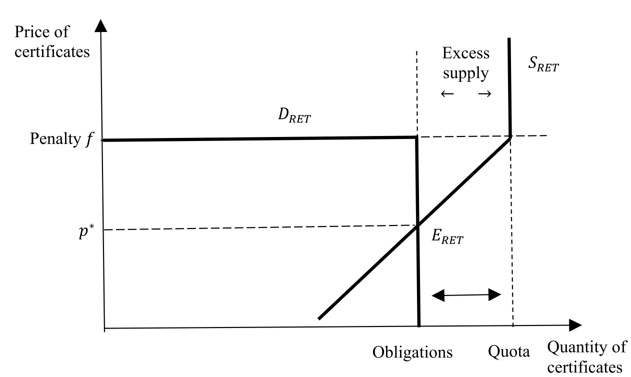

Fig. 7. The certificate market with excess supply and without the refunding mechanism. The penalty is denoted as f.

[17] If the price is equal to the penalty, the first term disappears, and the retailer is indifferent to buying any quantity of certificates.

two profit functions in Eq. (13) and Eq. (14), the retailer is better off remaining inactive in the certificate market by paying the penalty and seeking a refund in the future if

$$\widetilde{\pi}_i^s > \pi_i^s \Longrightarrow -\alpha q_i^s f - E_i(p^c)R_i + \alpha q_i^s f > -p^c R_i \Longrightarrow E_i(p^c) < p^c \tag{15}$$

That is, the expected future price is lower than the current price.

Given the idiosyncratic expected future prices of certificates across retailers, the current price determines the proportion of participating retailers. When the current price is high, expected future prices are more likely to be lower, so fewer retailers participate in the market and purchase certificates. In contrast, when the current price is low, expected future prices are less likely to be lower, so more retailers participate in the market. This situation gives a downward-sloping portion of the demand curve, D''_{RET}, as shown in Fig. 7B. Further, when the current price is at the level of penalty, retailers who predict the same maximum value for the next period still participate in the current market, giving the horizontal part of the demand curve.[18] When the current price reaches zero as the minimum, all retailers will participate in the current market, as the expected price cannot be lower than zero.

5.2.2. Generators in the RET

For individual generator j, the number of certificates issued depends on the actual electricity generated by renewable generators,

$$\overline{R}_j^s = q_j^g \tag{16}$$

Generators receive one certificate per MWh of electricity generated.

In the certificate market with excess supply, generators face a situation where their certificates may not be sold to retailers. Generators have their business network, so there is a variation in the difficulty of selling certificates. Assume generator i attaches an idiosyncratic perceived probability ρ_j to sell its certificates at the price of f and a probability of $1-\rho_j$ to holding certificates as unsold (gives a value of zero).[19] After taking this probability into account, the generator is willing to sell when the price, p_j^c, is

$$p_j^c = p_j f + (1-\rho_j)0 = \rho_j f \tag{17}$$

which is less than the penalty.

As generators have idiosyncratic perceived probabilities of selling their certificates, the prices they are willing to sell are idiosyncratic. If we rank these generators in ascending order of the price they are willing to sell, it gives an upward-sloping supply curve for certificates, S_{RET}, as shown in Fig. 7. That is, when the market price for certificates is higher (lower), more (less) generators are willing to sell their certificates. As all generators are willing to sell their certificates at a price equal to or above the penalty, the supply curve becomes vertical above the penalty. A remark here is that if every generator revises up (down) the probability of selling, the upward-sloping part will rotate clockwise (counter-clockwise) around the connection point with the vertical part when the market price remains the same.

5.2.3. The certificate market in the RET

Here, we turn to the market for certificates in the RET. As the supply curve is first proposed in this study, the market for the RET is elaborated with details. On the supply side, the total number of certificates issued (i.e., the supply of certificates) is

$$\overline{R}^s = \sum \overline{R}_j^s \tag{18}$$

On the demand side, the government sets an annual target Ω as a fixed amount of electricity that should come from renewable sources. Meanwhile, given the estimated electricity generation, the obligation level, α, is calculated as

$$\alpha \equiv \frac{\Omega}{\sum E(q_i^s)} = \frac{\Omega}{E(Q^s)} \tag{19}$$

where $E(Q^s)$ is the estimated total electricity generated, including renewable and non-renewable sources. Given the obligation level α and the actual volume of electricity sold Q^s, the required number of certificates (i.e. demand for certificates) is then equal to

$$R^d = \alpha Q^s = \frac{\Omega}{E(Q^s)} Q^s \tag{20}$$

The excess supply in the RET is illustrated as

$$\frac{\Omega}{E(Q^s)} Q^s = R^d < \overline{R}^s \tag{21}$$

Although a refunding mechanism is available, the regulator held a negative view of it before 2018, so we first demonstrate the equilibrium *without* the refunding mechanism. This scenario is identified in Fig. 7. In the case of excess supply, generators attach a probability to selling certificates and are willing to accept a price lower than the penalty. The intersection between the demand curve D_{RET} and the supply curve S_{RET} establishes the equilibrium price for certificates. At the equilibrium E_{RET}, all retailers have met their obligations, and the price is lower than the penalty f. The horizontal difference between the quota and obligations is the excess supply.

Proposition 3. *In the certificate market with excess supply, in equilibrium, the price is below the penalty, all retailers have met their obligations, and spare certificates are available in the market.*

When the market is tightening, i.e., the excess supply is declining, the supply curve S_{RET} shifts to the left. Meanwhile, the upward-sloping part of the supply curve rotates clockwise as generators assign a higher probability of selling their certificates and increase the price they are willing to sell.[20] As shown in Fig. 7A, the new equilibrium E'_{RET} gives a higher certificate price and full compliance. In contrast, if the excess supply increases, the price of certificates will drop without any lower

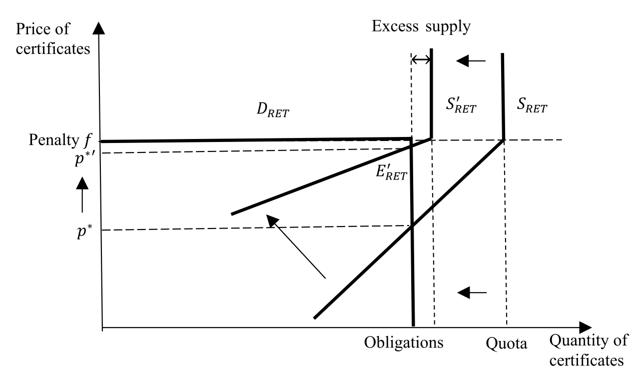

Fig. 7A. The impact of a decrease in the excess supply in the market of certificates with excess supply and without the refunding mechanism. The penalty is denoted as f.

[18] If we assume that all retailers remain inactive when the price is at the level of penalty, the demand curve will be downward sloping from the point on the y-axis.

[19] As the certificate market always has excess supply, if a certificate is unsold in this period, it is likely it will be unsold in future periods. Therefore, we attached a value of zero to unsold certificates.

[20] If excess supply diminishes and becomes excess demand, the supply curve will become a vertical line above the penalty, as shown in Fig. 5.

boundary. This result implies that any regulatory risks bringing uncertainty over the extent of excess supply will damage investor confidence as there is no benchmark for the price of certificates.

Proposition 4. *In the certificate market with excess supply, a decrease in the excess supply leads to a new equilibrium. Compared to the previous equilibrium, the price is higher, all retailers meet their obligations, and fewer spare certificates are left in the market.*

A refunding mechanism complicates the analysis, as depicted in Fig. 7B. When a reduced excess supply pushes the certificate price up, a fraction of retailers respond to the higher prices by remaining inactive in the market and paying the penalty. As discussed in Section 5.2.1, a downward-sloping part appears in the demand curve D''_{RET}. Meanwhile, as a fraction of retailers become inactive, generators lower the probability of sales and are willing to sell their certificates at a lower price, so the upward-sloping part of the supply curve will rotate anti-clockwise to S''_{RET}.

The new equilibrium is achieved at the intersection point between the new demand curve D''_{RET} and the new supply curve S''_{RET}. At the new equilibrium E''_{RET}, the market price is lower than the penalty, compliance is partial, and spare certificates are available in the market.[21] Previous studies did not capture this situation.

Proposition 5. *In the certificate market with excess supply and the refunding mechanism, in equilibrium, the price is lower than the penalty, some retailers do not meet their obligations, and spare certificates are available in the market.*

Another relevant condition for considering the refunding mechanism is the expected future prices. If the expected future price is as high as the current price, retailers would not be motivated to use the refunding mechanism, as it is equivalent to purchasing the certificate now or in the future. However, if the expected future price is relatively lower, retailers will benefit from using the refunding mechanism to avoid the current high price, so more retailers will remain inactive in the current market, bringing downward pressure on the current price. As depicted in Fig. 7C, the demand curve changes to D'''_{RET}. Meanwhile, as more retailers do not purchase certificates, generators assign a lower probability of selling their certificates, leading to a further rotation of the supply curve to S'''_{RET}.

Proposition 6. *A lower expected future certificate price leads to a new equilibrium with excess supply and a refunding strategy in the certificate*

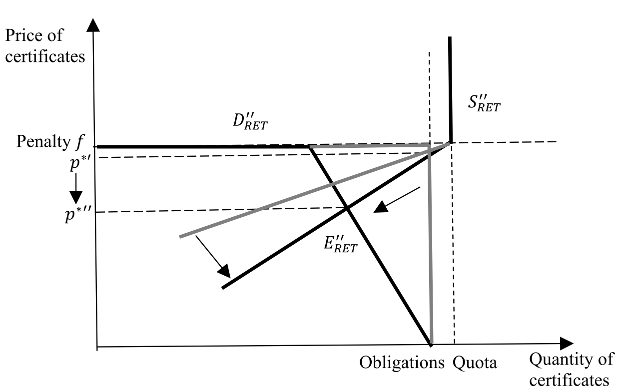

Fig. 7B. The impact of the refunding strategy on the market of certificates with excess supply. The penalty is denoted as f.

[21] A further implication of the refunding mechanism is that temporary excess demand will not push the price to the level of the penalty as retailer can use refunding if excess supply is the norm in the future.

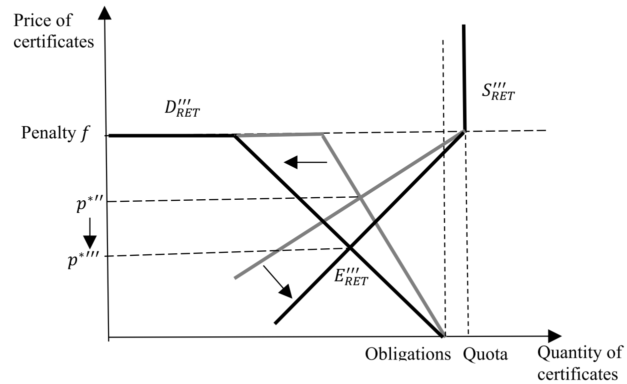

Fig. 7C. The impact of a lower expected future price on the market of certificates with excess supply and the refunding mechanism. The penalty is denoted as f.

market. Compared with the previous equilibrium, the price is lower, more retailers do not meet their obligations, and spare certificates are still left in the market.

5.2.4. The price of certificates in the RET

In the RET, certificates were traded bilaterally or on the secondary markets. Based on Skinner (2019) and (CER, 2022b), we reproduce the certificate price from January 2010 to June 2023 in Fig. 8.

From 2010 to 2015, the price fluctuated between A$30 and A$40 due to abundant excess supply. As the price was relatively low, the compliance rate was high and close to 100 per cent, with limited use of the refunding mechanism. This situation is shown in Fig. 7 and Proposition 3.

With the launch of a government review to investigate the RET scheme between 2013 and 2015, investment in renewable capacity paused as investors were concerned that the scheme might be closed. The price began to rise after the government's commitment to the continuation of the scheme in 2015 because the slow growth in renewable capacities in previous years indicated a tightening of supply in the certificate market (CER, 2022a). In October 2016, the highest price reached A$89.5, closing to its upper limit of A$92.86, and remained above A$80 for the following year. The situation with reduced excess supply and high certificate price is shown in Fig. 7A and Proposition 4.

The refunding mechanism allows retailers to remain temporarily inactive to avoid the high price. However, the government regulator

Fig. 8. Certificate prices and penalty between January 2010 and December 2022 (reproduced).
Source: Skinner (2019) and CER (Australia)

indicated in 2016 that such a trading strategy was against the RET's intent, and it would name retailers who took this strategy, which would adversely affect their brands (CER, 2022a). Therefore, during 2016 and 2017, although prices remained high, retailers were reluctant to use the refunding mechanism. However, as allowed, retailers carried 10 per cent of their obligation forward without penalty, so the compliance rate was reduced to around 90% in these two years.[22]

Interestingly, the government regulator reversed their position in October 2018 and stated that it would no longer object to using the refunding mechanism as a commercial response to the status of the market (CER, 2022a). This policy shift led to a major realignment of prices as retailers realised they could delay the purchase of certificates without fear of negative brand implications. Thus, retailers delayed the purchase of certificates, so the weakened demand pushed the certificate price down sharply. This negative impact of the funding mechanism on the certificate price is shown in Fig. 7B and Proposition 5.

Another crucial condition for considering the refunding mechanism is that the expected price is low in the future so that retailers can buy back at such a low price. As the target for 2030 is maintained at the 2020 level and is achieved, the demand for certificates will remain at the same level until 2030. At the same time, as the renewable capacity and, thus, the supply of certificates continue to grow, the excess supply of certificates will push the price down. The government regulator suggested that the future certificate prices would be around A$20 in 2022 and A$15 in 2023 (CER, 2022b), and this lower expected future prices encouraged retailers to use the refunding mechanism. Therefore, due to lower expected future prices and the refunding mechanism, the certificate price halved within a few months from October 2018 to between A$30 and A$50 until 2020, and compliance declined to around 80% (CER, 2022a). Thus, the RET moved to a situation of low certificate price and partial compliance with spare certificates in the market. This situation is shown in Fig. 7C and Proposition 6.

However, retailers gradually recognised that the market would remain tight, so they began to expect higher future certificate prices and have less incentive to delay their purchases. Therefore, in 2021 and 2022, retailers increased their purchase of certificates and pushed the prices to A$70, with an increase in the compliance rate to 86% (CER, 2022a).

The certificate price was below the penalty level in the RET from 2010 to 2022. The certificate price was pushed up when the market was tighter, i.e., the extent of excess supply decreased, such as in 2015-18. However, as the refunding mechanism allows retailers to delay the purchase of certificates, the expectation of future certificate prices alleviated the impact of tight market conditions on the price of certificates, as in 2018-20. Therefore, although the certificate price was below the penalty level as predicted, the link between the current market conditions (i.e., measured by the ratio of required to available) and the certificate price in the RET tends to be weaker than that in the RO.

6. Conclusion

Tradable Green Certificate schemes have been implemented in many countries to encourage decarbonisation in the electricity sector, and this helps achieve carbon reduction (and subsequent neutrality) goals. We constructed models with revised demand and supply curves to compare the designs of two long-standing TGC schemes, the RO scheme in the UK and the RET scheme in Australia. Our analysis showed that the RO was uniquely featured with excess demand (i.e., requirement is greater than availability) in the certificate market, while the RET featured excess supply (i.e., requirement is less than availability).

The first implication of this is upon the price of certificates. The excess demand in the RO makes the penalty the minimum for the certificate price, but the excess supply in the RET makes the penalty the maximum. Moreover, scheme-specific mechanisms have additional impacts on the price of certificates. The recycling mechanism in the RO pushes the price above the penalty, but the refunding mechanism in the RET brings downward pressure on the price. Therefore, in the RO, there is a guarantee on the price, but in the RET, there is no mechanism to prevent the price from falling below any particular level, leading to the price risk. Nonetheless, one pitfall of excess demand was low compliance, as insufficient certificates were in the market (Shao et al., 2021).

The second implication is on the number of certificates sold. Excess demand in the RO implies that generators are confident their certificates can be sold at or above the level of penalty. In contrast, excess supply in the RET implies that some certificates may not be sold, and indeed, there will be no demand for certificates in the market when obligations are fully met, leading to the volume risk.

Moreover, these two schemes have inherently different stability in terms of regulatory risk. In the RO, the major reforms were the introduction of headroom, which ensures excess demand and raises investor confidence about the value of certificates and banding, which provides varying levels of support to different technologies. The RET was more frequently intervened by the regulator, such as the proposed early closure and the changed opinion regarding the refunding mechanism, bringing additional uncertainty to the extent of excess supply and then amplifying the price risk and the volume risk faced by investors. Therefore, these uncertainties in the RET made it less effective at encouraging investment in renewable energy, and the growth in renewable generation and the installed capacity under the TGC scheme has undoubtedly been slower in Australia compared with the RO in the UK.

On the theoretical aspect, by moving away from the conventional setup, our revised model captured the observation of partial compliance when the certificate price was lower than the penalty, and there were spare certificates available in the market in the RET, which was the result of expected lower future certificate prices and the design of the refunding mechanism. This observation is at variance with models used in the existing literature, which suggested that retailers who had not met their obligations would purchase certificates if prices were below the penalty and certificates were available in the market.

Focusing on key components of TGC schemes in both countries, our analysis offers insights into the growth in renewable generation and provides suggestions for the effectiveness of TGC schemes and implications for their design in the context of a growing global policy.[23] TGC schemes with excess supply by policy design have been widely implemented in countries such as the United States, India, and China, and our findings suggest that the effectiveness of these schemes can be improved when excess demand is accounted for in their design. This approach would remove both the price risk and the volume risk faced by investors, thus stimulating the adoption of renewable energy.

Our study has focussed on the designs of the quota schemes by keeping the key elements, which means that other bespoke scheme features were not discussed. For example, the other element of the RET, the small-scale renewable energy scheme, was not included to provide comparability with the RO scheme, which supported only large-scale investment in renewable projects. In addition, other than the price risk and the volume risk in the certificate market, the incentive for investing in renewable generation is also affected by the wholesale electricity price and its volatility. For example, investors are not interested if the revenue (i.e., certificate price plus electricity price) is

[22] In practice, retailers are allowed to carry less than 10% of their obligation forward without occurring a penalty, but ultimately they need to buy certificates to cover this shortfall or pay the penalty in the future (CER, 2022a). This option can be referred to as a soft form of refunding mechanism as it follows the same logic except penalty is not required immediately.

[23] The TGC system can also be implemented in other sectors. For example, the Renewable Transport Fuel Obligation has been implemented in the transportation sector in the UK.

insufficient to cover the long-run costs of the targeted renewable technology. Moreover, our analysis shows the first step to compare certificate markets between two TGC systems, and further research from the inclusion of more realistic features such as market power and long-term contracts may bring more fruitful findings.

Further, renewable energy development is affected by factors other than supporting schemes alone. For example, Australia has abundant coal reserves, which account for nearly one-tenth of total world reserves, and the low-cost coal-fired generation, together with the established coal industry, make the transition towards renewables (politically and economically) more difficult. Regarding methodology, we have relied on the market dynamics based on revised demand and supply curves. Future research considering other methods, such as simulation and experiment, should provide further contributions to discussing the effectiveness of TGC schemes.

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CRediT authorship contribution statement

Yunfei Wang: Writing - original draft, Investigation, Formal analysis, Data curation. **Jinke Li:** Writing - review & editing, Writing - original draft, Methodology, Conceptualization. **Nigel O'Leary:** Writing - review & editing, Supervision. **Jing Shao:** Writing - review & editing, Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. A list of variables

Common variables in the RO and RET	
π_i^s	Retailer i's profit
p^e	Retail electricity price
p^w	Wholesale electricity price
p^c	Price of certificates
q_i^s	Quantity of electricity sold by retailer i
R_i	Number of certificates purchased and submitted by retailer i
α	Obligation level
f	Penalty
q_j^g	Electricity generated from renewable generator j
$\overline{R}_j^s$	Number of certificates awarded to renewable generator j
Q^s	Total electricity sold
R^d	Total certificates required
$\overline{R}^s$	Total certificates available
$E(Q^s)$	Expected total electricity to be supplied
Specific variables in the RO	
$E(\overline{R}^s)$	Estimated the number of certificates to be issued
$E_i(r)$	Retailer i's idiosyncratic expected recycle value
γ	Headroom
Specific variables in the RET	
$\widetilde{\pi}_i^s$	Retailer i's profit if using the refund mechanism
$E_i(p^c)$	Retailer i's idiosyncratic expected future price of certificates
ρ_j	Generator j's idiosyncratic probability of selling its certificates
p_j^c	Generator j's idiosyncratic price of willingness to sell
Ω	Annual target

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