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Carbon pricing in practice: a review of existing emissions trading systems

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ABSTRACT

This article analyses the implementation of emissions trading systems (ETSs) in eight jurisdictions: the EU, Switzerland, the Regional Greenhouse Gas Initiative (RGGI) and California in the US, Québec in Canada, New Zealand, the Republic of Korea and pilot schemes in China. The article clarifies what is working, what isn't and why, when it comes to the practice of implementing an ETS. The eight ETSs are evaluated against five main criteria: environmental effectiveness, economic efficiency, market management, revenue management and stakeholder engagement. Within each of these categories, ETS attributes – including abatement cost, stringency of the cap, improved allocation practices over time and the trajectory of price stability – are assessed for each system. Institutional learning, administrative prudence, appropriate carbon revenue management and stakeholder engagement are identified as key ingredients for successful ETS regimes. Recent implementation of ETSs in regions including California, Québec and South Korea indicates significant institutional learning from prior systems, especially the EU ETS, with these regions implementing more robust administrative and regulatory structures suitable for handling unique national and sub-national opportunities and constraints. The analysis also shows that there is potential for a 'double dividend' in emissions reductions even with a modest carbon price, provided the cap tightens over time and a portion of the auctioned revenues are reinvested in other emissions-reduction activities. Knowledge gaps exist in understanding the interaction of pricing instruments with other climate policy instruments and how governments manage these policies to achieve optimum emissions reductions with lower administrative costs.

Key policy insights

- Countries are learning from each other on ETS implementation.
- Administrative and regulatory structures of ETS jurisdictions appear to evolve and become more robust in every ETS analysed.
- A 'double dividend' for emissions reductions may also exist in cases where mitigation occurs as a result of the ETS policy and when auction revenues are reinvested in other emissions-reduction activities.

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1. Introduction

The 2015 Paris Agreement has prompted governments to consider stronger policies to achieve decarbonization. Arguably, the most economically efficient way to reduce GHG emissions is through the use of carbon pricing policy instruments (Aldy, 2015; Edenhofer et al., 2015; Metcalf & Weisbach, 2009; Schmalensee & Stavins,

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2015). Carbon pricing mechanisms fall into three main categories: cap-and-trade (i.e. emissions trading systems (ETS)), carbon taxation or hybrid mechanisms that combine elements of both.

This article focuses exclusively on ETSs and how they work in practice. An ETS establishes a cap either on total emissions or on emissions intensity, as measured by emissions per unit of gross domestic product (GDP). An ETS may include emissions from all GHGs or just some, such as CO_2. Governments then provide allowances in the primary market,[1] typically for free or through an auction, equal to the level of the cap (Aldy & Stavins, 2012). A hybrid approach of partial auctioning and free allocation of some emission allowances is common in ETS markets. Firms may then trade allowances during a specified compliance period, after which they are surrendered to the government. Firms with lower abatement costs are expected to sell their allowances to firms with higher abatement costs in the secondary market,[2] and overall, emissions reductions are theoretically achieved at least cost.

Each ETS evaluated here has strengths and weaknesses. This article evaluates the implementation of the ETSs of the EU, Switzerland, the Regional Greenhouse Gas Initiative (RGGI) and California in the US, Québec province in Canada, New Zealand, the Republic of Korea and China's seven city and provincial pilots – Beijing, Shanghai, Tianjin, Chongqing, Shenzhen, Guangdong and Hubei (see Appendix 2 for a brief summary of these eight ETSs). These cases were selected to cover ETSs at the supranational, national and sub-national levels. They represent diverse geographies and a range of inception dates, allowing us to identify best practices, linkage opportunities and learning within and across systems, and knowledge spillovers, if any, from older to newer systems.

The ETSs are evaluated against five main criteria: environmental effectiveness, economic efficiency, market management, revenue management and stakeholder engagement. Within each of these categories, ETS attributes including abatement cost, stringency of the cap, improved allocation practices over time and the trajectory of price stability are assessed for each system. Past scholarly literature on ETSs typically assessed the environmental and economic effectiveness of one particular jurisdiction or comparatively for sub-regions within a higher jurisdiction (Haites et al., 2018; see Appendix 1 of the supplementary section for a list of key existing studies). This article, however, evaluates ETS implementation across different levels of jurisdiction and geographies, and over time. Other performance attributes besides environmental and economic effectiveness are assessed as discussed in Section 2.

The article is organized as follows: Section 2 introduces the methodological framework employed to evaluate the performance of the eight ETSs. Section 3 compares the implementation of the ETSs using the methodological framework. Sections 4 and 5 provide key findings, identify knowledge gaps in existing literature and recommend key areas for future research.

2. Methods

Key design considerations for an ETS include determining which GHGs and which sectors will be regulated under the cap; at what point of regulation emissions will be regulated (upstream or downstream); the stringency of the cap (or the total allowable emissions); costs of abatement, compliance and ETS administration; method of allowance allocation and distribution; monitoring, reporting and verification (MRV) of emissions and allowances; and impacts on international competitiveness (PMR and ICAP, 2016; Schmalensee & Stavins, 2017). Additional considerations include policies that provide system flexibility such as banking credits for future compliance and borrowing credits from future compliance periods, creation of an allowance reserve to stabilize secondary market prices and ensure liquidity, creation of new trading registries to monitor and track carbon allowance markets, accounting for carbon offsets, international linkage, revenue management and stakeholder engagement (PMR and ICAP, 2016; Schmalensee & Stavins, 2017).

Based on these attributes, we created a qualitative evaluation framework to assess the relative performance of the eight ETSs against five main criteria: environmental effectiveness, economic efficiency, market management, revenue management and stakeholder engagement, and 18 sub-attributes (see Table 1). Based on a detailed review of the existing literature, we appraise the performance of the ETSs for each criterion and characterize each attribute as functioning at a low, medium or high level (Anger, Asane-Otoo, Böhringer, & Oberndorfer, 2016; Álvarez & André, 2015; Burtraw & McCormack, 2017; Haites, 2016; Holt & Shobe, 2015; Ji, Zhang, & Yang, 2017; Schmalensee & Stavins, 2015; and studies listed in Appendix 1 of the supplementary section).

Table 1. Assessment framework for comparing ETS regimes.

Overall assessment	ETS Attributes	Low	Medium	High
Environmental effectiveness	**Coverage of key emitting sectors**	ETS fits into overall climate policy with many sectors unregulated.	ETS fits into overall climate policy with some additional carbon mitigation policies; significant EITE exemptions.	ETS fits into overall climate policy covering all sectors with minimal EITE exemptions; or EITE coverage under an alternative policy.
	Emissions cap to covered emissions	Cap set equal or higher than the covered BAU emission levels at the beginning of a compliance period without further decrease over time.	Cap set less than the covered BAU emission levels at the beginning of a compliance period with some decrease over time.	Cap set less than the covered BAU emission levels at the beginning of the compliance period with definite decrease over time.
	Stringency of cap	No annual tightening of cap.	Ad-hoc decreases in emissions cap.	Pre-determined annual tightening of emissions cap.
Economic efficiency	**Abatement cost**	High permit price without EITE included.	Low/moderate permit prices without EITE included.	Low to moderate permit prices with EITE included.
	Cost of compliance (i.e. MRV costs)	High marginal. MRV costs per tonne of emissions, no assistance to firms from government.	Moderate. marginal MRV costs to the firms with government assistance.	Low marginal. MRV costs to the firms with government assistance.
	Cost of administration	Marginal cost to administer the ETS is relatively high compared to other ETSs.	Marginal cost to administer the ETS is moderate.	Marginal cost to administer the ETS is relatively low.
Market management	**Method of current allocations**	Free allocations, grandfathered, no clear baselines.	Free allocations, benchmarked with baseline year estimates.	Full auction or partial free allocations, benchmarked with emissions inventory data.
	Improved allocation practices over time	No change in initial allocation methodology.	Changes from initial methodology.	Increase in auctioning.
	Percentage auctioning	No or partial auctioning, no plans to increase in the future.	Partial auctioning with plans to increase in the future.	Full auctioning.
	Trajectory of price stability	High volatility throughout a period.	Stable, but volatile around period beginning/end.	Stable.
	Price signal commitment	Absence of emissions cap commitment for future periods; Uncertainty about ETS. No price stability measures.	Cap commitment for future periods; Price floor or ceiling, no collar; Presence of an allowance reserve with a quantity-based trigger or no clear criterion; Unclear banking/borrowing rules that allow for hoarding of allowances.	Cap commitment, higher price floor; price ceiling; An allowance reserve with price-based trigger and clear guidelines for intervention; banking/borrowing with well-defined limits to avoid hoarding of allowances by firms.
	System flexibility	No allowance reserve; no reserve auctions.	Presence of an allowance reserve with rigid intervention time frames or time delay. Absence of both price and emissions containment. Allowance reserve quantity triggered; removed allowances not retired.	Presence of price triggered allowance reserve with independence to intervene anytime, reduced time lag. Presence of both price and emissions containment measures. Removed allowances are retired.
	Current linkage	No link or unilateral link to offsets without limits.	Unilateral link with offset limits, bilateral link without common compliance.	Bilateral link with similar compliance rules.

(*Continued*)

Table 1. Continued.

Overall assessment	ETS Attributes	Low	Medium	High
Stakeholder engagement	**# of meetings per period or comments received** **Outcomes**	Stakeholder engagement with regulated firms only prior to the beginning of a period. No option for public to play a role in the rule making process. No correlation between rule modification/change outcomes and stakeholder recommendations. Evidence of Stakeholder fatigue.	Stakeholder engagement with regulated firms through the establishment of emissions accounting process; Use of consistent schedule post ETS establishment or whenever a change in rules is necessary. No option for public comments. Rule modification/change outcomes follow stakeholder recommendations. Evidence of disagreement among stakeholders on the outcome.	Stakeholder engagement with regulated firms through the establishment of emissions accounting process; Use of a consistent schedule post ETS establishment or whenever a change in rules is necessary. Option for public to voice their opinions at meetings or comments. Clear correlation between rule modification/ change outcomes and stakeholder recommendations. Overall agreement within stakeholders about the outcome.
Revenue management	**Revenue raised**	No revenue raised. Net expense for the government administering the ETS and firms to comply with ETS.	Some revenue raised through auctions. Covers administrative costs and MRV transaction costs.	Significant revenue generated to spend on additional environmental goals; Revenues to alleviate the social and economic burden of an ETS.
	EITE earmarking	No revenue raised; EITE sectors get allocations for free; EITE sectors also get assistance to comply with the ETS.	Revenue used to reduce the burden of EITE sectors in addition to free allowances granted.	Revenue used to reduce the burden of EITE sectors without free allowances.
	Green earmarking	No additional green spending.	Smaller share of revenue used for green spending.	Bigger share of revenue used for green spending.
	Earmarking for distributional equity	No money allocated to assist low income communities.	Smaller share of revenue used to assist low income communities.	Bigger share of revenue allocated to assist low income communities.

Sources: PMR and ICAP (2016); references listed in Appendix 1 of the supplement.

3. Comparative assessment of ETS regimes

3.1. Environmental effectiveness

The environmental effectiveness of each ETS is assessed based on the number of key emitting sectors covered in the jurisdiction's overall climate policy, the quantity of emissions included under a cap relative to the jurisdiction's ETS-covered emissions, the tightening of the cap over time and emissions reduction achieved (Haites et al., 2018). The coverage of key emitting sectors is assessed based on whether the ETS covers the major emitting sectors and a majority of the GHGs, or at least covers sectors that are not otherwise covered by alternative carbon mitigation policies. The proportion of total covered emissions capped under the ETS and the rate at which the cap is tightened over time is used to assess the stringency of the programme. A cap nearly equal to the covered sector's business as usual (BAU) emission levels without a tightening schedule for future years would mean that the system is not inducing emissions reductions beyond reductions in the emissions intensity of its economy. Table 2 provides a summary of the environmental benchmarks compared across the ETS cases.

3.1.1. Coverage of key emitting sectors

All the ETSs fall short of a 100% economy-wide cap either because the entire economy is not capped or only some GHGs are regulated. California and Québec, whose ETSs are bilaterally linked, regulate the most with their second compliance period covering 85% of GHG emissions (including the energy-intensive transport sector). The RGGI system regulates only CO_2 in the electricity sectors of the nine participating states, namely, Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont. Regulated CO_2 emissions total to 20% of its sub-jurisdiction's total GHG emissions (Ramseur, 2017), leaving emissions-intensive sectors such as transportation unregulated. New Zealand, Korea and China's pilot programmes fall short of achieving full coverage using their ETS or other climate policies. Although the New Zealand (NZ) ETS requires all sectors to report emissions, purchase and surrender New Zealand Units (NZU), it exempts biological emissions from agriculture (Ministry for the Environment, 2016a). The New Zealand economy is driven by primary production and biological gases (i.e. methane and nitrous oxide) account for 54% of New Zealand's GHG emissions (Parliamentary Commissioner for the Environment, 2016), effectively reducing the overall GHG coverage by half. The EU ETS covers about 45% of the jurisdiction's GHG emissions with some national-level carbon taxes such as in Norway, Sweden and Ireland, covering remaining GHG emissions in their respective jurisdictions.

3.1.2. Emissions cap and stringency

Emissions caps can be set as an absolute cap in tons of GHGs or as a cap on GHG intensity, denoted in terms of GHG per unit of GDP. The level of the cap can be decided using a 'top-down' approach of imposing estimated emission reductions or through a 'bottom-up' approach of participating entities or regions reporting projected emissions reductions for a compliance period (Ellerman, Buchner, & Carraro, 2007). In order to establish an appropriate top-down emissions cap, regulators need reliable estimates on current and likely future emissions (Munnings, Morgenstern, Wang, & Liu, 2016). Similarly, for a bottom-up cap to be effective, regulators must have reliable information regarding current firm-level emissions and the emissions-reduction potential of the participating firms or regions. Either way, an information asymmetry exists because firms hold the information needed by regulators. This challenge can be addressed by establishing an emissions inventory system with mandatory reporting prior to the initiation of the programme or by using the ETS market itself to discover the real price of abatement. The first report on verified emissions published by the European Commission at the aggregated EU-wide level had a dramatic impact on the carbon price, which fell by almost 50% in a few days as surrendered allowances in the first phase indicated that the nationally aggregated emissions cap had resulted in an overestimation of 125 million allowances (Chevallier, 2011). Since there was no provision to bank allowances between phase one and later phases, the prices collapsed further. Since phase two, the EU has allowed banking between phases. In phase three, the system has transitioned to a jurisdiction-wide cap that decreases 1.74% per year (Ellerman & Buchner, 2008; Meadows, 2017; Schmalensee & Stavins, 2015). The EU ETS also implemented an EU Transaction Log (EUTL) to track the trading of allowances within each member country (Frunza, 2013).

Table 2. Environmental effectiveness of ETS regimes.

	Coverage of key emitting sectors	Total emissions in $MMTCO_{2e}$	BAU emissions in the regulated sectors at the beginning of a compliance period (in $MMTCO_{2e}$) *Coverage*Total emissions*	Emissions cap at the beginning of a compliance period (in $MMTCO_{2e}$)	Stringency of cap (% cap reduction/ year)
European Union	45%; national carbon tax policies covering remaining emissions in some countries; ETS covers CO_2, N_2O, PFCs with individual states adding more GHGs	4598 (2013)	0.45*4598 = 2069	2084 (2013)	1.7% – phase 3 2.2% – phase 4
Switzerland	11% covering CO_2, N_2O, CH_4, HFCs, NF3, SF6, PFCs. Carbon tax covers CO_2 only.	52 (2013)	0.11*52 = 5.7	5.6 (2013)	1.7%
RGGI	20% with some additional mitigation policies, transportation sector not covered; only CO_2 covered	n/a	86	83 (2014)	2.5%
California	85% with additional mitigation policies; ETS covers CO_2, N_2O, CH_4, HFCs, NF3, SF6, PFCs	440 (2015)	0.85*440 = 374	394 (2015)	~3%
Quebec	85% with additional mitigation programmes; ETS covers CO_2, N_2O, CH_4, HFCs, NF3, SF6, PFCs	80 in 2015	0.85*80 = 68	65 in 2015	~3%
New Zealand	52% and few other mitigation policies; GHGs except biological gases (CH_4 and N_2O) covered. Effective coverage without biological gases is 25%	80 (2015)	0.25*80 = 20	13 (2015)	None
Korea	68%; few other mitigation policies. covers CO_2, CH_4, N_2O, PFCs, HFCs, SF6	690 (2014)	0.68*690 = 469	573 (2015)	~2% – phase 1
Chinese Pilots	All partial coverage with few other mitigation policies (Beijing: 50%, Tianjin: 45%, Shanghai: 60%, Chongqing: 40%, Shenzhen: 40%, Guangdong: 60%, Hubei: 33%); only CO_2 covered.	188 (2012) 250 (2014) 610 (2012) 463 (2012) 297 (2012) 153 (2012) 215 (2012)	n/a[a]	Beijing – 46 (2016); Chongqing – 100 (2016); Guangdong – 422 (2016); Hubei – 253 (2016); Shanghai – 155 (2016); Shenzhen – 31.45 (2015); Tianjin – 160	n/a

Source: As listed in Appendix 1 of the supplement.
[a] Emissions cap and total emissions data not available for the same years.

Switzerland calculated the emissions-abatement potential of each participating firm individually before allocating allowances and allowed firms to voluntarily opt in to the ETS programme (CDC et al., 2015b). To align with the EU ETS, Switzerland made its emissions cap mandatory for all of its participants in the second compliance period with a 1.74% decrease per year.

RGGI, California and Québec set top-down emissions caps based on projected emission levels calculated using estimates of future economic growth. RGGI and California also factored in the effect of complementary policies on total emissions. In spite of careful projections, the emissions cap of 188 million tons that RGGI set in 2005 ended up being too high, as actual emissions were 124 million tons when the programme launched in 2009. This overallocation in the case of RGGI did not represent a substantial problem for the market due to the creation of a price floor which kept allowance prices from falling to near zero. Excess allowances, roughly 23%, were permanently removed from the market after the first compliance period (RGGI, 2017b, 2017e). Lower electricity demand resulting from energy-efficiency improvements, an economic downturn, fuel switching from coal to natural gas and additions of nuclear, wind and solar generation all contributed to the overallocation of allowances (Jones, Atten, & Bangston, 2017; RGGI, 2010). RGGI authorities corrected course and set a 44% lower cap in the next compliance period with an annual reduction of 2.5% until 2020 (Ramseur, 2017). While the EU ETS and RGGI initially suffered from miscalculated top-down emission caps, the credibility of Korea's ETS cap has also been questioned for its heavy reliance on a bottom-up approach using reporting from manufacturers to derive an abatement target, while discounting the concerns of environmental organizations and civil society (Kim, 2015).

The NZ ETS originally operated without a nationwide cap in order to accommodate carbon sequestration from its forestry sector and unlimited international offsets from the Kyoto Protocol's clean development mechanism (CDM). With the allowance supply restricted to domestic NZU units, the system is moving towards an effective fixed cap that equals the annual free allocations and forest carbon removal allowances issued (ICAP, 2017c). Finally, the Chinese ETS pilots vary significantly in the way they set their emissions targets with Guangdong choosing an absolute cap, Shanghai allocating allowances without announcing an emissions cap, and Shenzhen issuing both intensity and absolute caps for the 2013–2015 period. It is unclear whether Guangdong, Shanghai and Shenzhen did economic assessments to estimate their current and future CO_2 emissions (Munnings et al., 2016). Reflecting the variation in economic conditions between the Chinese cities, Guangdong increased its emissions cap to allow for increased industrial production, Hubei decreased its cap to reflect new economic growth patterns, Chongqing reduced its cap by 4.13% a year, and Beijing, Shanghai, Tianjin and Shenzhen kept their caps unchanged between 2013 and 2015 (Xiong, Shen, Qi, Price, & Ye, 2017).

3.1.3. Emissions reductions achieved

Emissions reductions achieved by an ETS can be measured by the change in actual emissions covered by the ETS (Haites et al., 2018), but it is difficult to directly attribute these results to the ETS in jurisdictions with other complementary emissions-reduction policies. The endogenous and simultaneous nature of interaction between complementary policies such as feed-in tariffs or energy efficiency performance standards, and the ETS, makes it difficult to estimate the net impact of an ETS on overall emissions reduction (Hood, 2013). With this caveat, we provide existing estimates of emissions reduced across the ETS programmes.

For the EU, studies estimate that a 2.5–5% total emissions reduction (about 150–300 $MMTCO_{2e}$) was achieved during phase one and a 6.3% reduction (i.e. 260 $MMTCO_{2e}$) between 2008 and 2009 in phase two of the EU ETS against baseline emissions (Brown, Hanafi, & Petsonk, 2012; Hu, Crijns-Graus, Lam, & Gilbert, 2015). Another study estimates that an average annual emissions reduction in the range of 40 to 80 $MMTCO_{2e}$ per year, (i.e. 2 to 4% of total capped emissions) is attributable to the EU ETS in phases one and two (Laing, Sato, Grubb, & Comberti, 2014). Bel and Joseph (2015), however, estimate that most emissions reductions are likely to be linked to the 2008 economic crisis so the impact of the EU ETS is just 11.5% to 13.8% of the total GHG emissions reduced during phases one and two (Bel & Joseph, 2015). In phase three, verified GHG emissions from fixed installations covered by the ETS decreased 2.9% from 2015 to 2016 while the EU's total GHG emissions fell by 0.7% in the same period (European Commission, 2017b). With new measures to reduce the allowance surplus in phase three, the EU ETS is anticipated to induce greater emission reductions after 2025 (Hu et al., 2015). For Switzerland, there is no literature analysing the impact of the Swiss ETS programme on the country's

overall emissions mitigation trajectory (FOEN, 2016a). Similar to Switzerland, there are no studies estimating the emissions reduced by the Chinese ETS pilots since their implementation in 2013.

In the RGGI jurisdiction, economy-wide CO_2 emissions dropped 35% between 2009 and 2014 compared with a 12% drop in non-RGGI states during the same period (CERES, 2015). CO_2 emissions in the electricity sector (the sector regulated by RGGI) dropped 52.3% between 2009 and 2012 (Murray & Maniloff, 2015). Although these emissions reductions cannot be solely attributed to RGGI due to the presence of other policies and factors such as the renewable portfolio standard (RPS), economic recession and lower natural gas prices, total emissions in the jurisdiction's electricity sector in this period could have been 24% higher in the absence of the programme (Murray & Maniloff, 2015).

The California Air Resources Board (CARB) estimates that California is on track to reduce its emissions to 1990 levels by 2020. Emissions of regulated entities were estimated to be 9% below the 2014 annual cap of 160 $MMTCO_{2e}$ at the end of the first compliance period (Camuzeaux, 2015). It is too early to know how much the Québec system has reduced its emissions, but in 2013, a 7.5% reduction from 2005 levels was calculated for the province, although not directly attributable to the ETS (Government of Canada, 2016).

In New Zealand, Bertram and Terry (2010) conclude that domestic emissions were reduced by only 23 $MMTCO_{2e}$ in 2008 and 19 $MMTCO_{2e}$ in 2009. Free allowances to emissions intensive and trade exposed (EITE) firms, the absence of a nationwide emissions cap and an international offset cap until 2015 allowed many ETS participants to meet their obligations without real reductions in firm-level emissions (Bullock, 2012). Similarly, in Korea, a lack of liquidity and the political nature of allowance allocations reduced confidence in the system (Kim, 2015; PMR & ICAP, 2016). Market liquidity has remained stagnant, resulting in negligible amount of emissions being traded in the early phase (Suk, Lee, & Jeong, 2017).

3.2. Economic efficiency

The economic efficiency of an ETS is assessed based on the marginal cost of abatement and cost of compliance (i.e. MRV costs) for firms regulated under an ETS, and the government's cost of administering the ETS (PMR & ICAP, 2016). In general, it was difficult to find compliance and administrative costs in the literature, and this is one knowledge gap that should be addressed through future research.

The marginal costs of abatement provided in Table 3 do not always help us assess the cost effectiveness of a system because sectors that are difficult to regulate are often exempted from the ETS. For instance, the RGGI has one of the lowest marginal abatement costs ($4.50 in 2016) but the system does not regulate the jurisdiction's energy intensive transport sector. California has a higher marginal abatement cost ($12.83 in 2016) but covers more than three fourths of the economy's emissions including electricity, transport and industrial sectors.

The methodological framework assesses an ETS with low permit prices, a low cost of compliance and low administration costs as the best performing system (see Table 1). However, the framework is limited in its

Table 3. Economic efficiency of ETS regimes.

	Economic efficiency		
	Abatement cost (price per allowance unit; average of 2016)	Cost of compliance (i.e. MRV costs)	Cost of administration
European Union	$6.50	$72,440 per installation ($0.2 per tonne of CO_{2e}) with two thirds spent on monitoring	$2750 per member state per installation
Switzerland	$8.30	n/a	n/a
RGGI	$4.50 Secondary market consistent with auction price	n/a	n/a
California	$12.83 secondary mkt. allowance futures price	n/a	n/a
Quebec	$12.83 secondary mkt. allowance futures price	n/a	n/a
New Zealand	$12.5 (June 2016)	n/a	n/a
Korea	$14.3 (June 2016)	n/a	n/a
Chinese Pilots	**Beijing:** $8.14; **Tianjin**: $2.88; **Shanghai:** $1.08; **Chongqing:** $1.52; **Shenzhen:** $5.46; **Guangdong:** $2.00; **Hubei:** $2.49 (all data for June 2016)	n/a	n/a

Sources: As listed in Appendix 1 of the supplement; European Commission, 2016b.

assessment of efficiency when considering the alternative non-market-based policies that currently or in the future may cover the emissions not covered by an ETS. Covering economy-wide emissions under a market-based policy like ETS is likely to be more cost effective than non-ETS sectors regulated by non-market based environmental policies (Schmalensee & Stavins, 2017).

3.3. Market management

In the primary market, the performance of allowance allocation can be assessed by examining the current method of allocations, the change in allocation methodology over time and the percentage of allowances auctioned (see Table 4). When compared to auctioning, free allocations affect the efficiency of allowance trading with poor price discovery in the market, and lack of transparency in transferring allowance value to firms can affect the fairness of the ETS (Burtraw & McCormack, 2017) to both ETS and non-ETS participants (Anger et al., 2016). Grandfathering (i.e. allocating permits based on historical emissions), fixed-sector benchmarking (i.e. based on a product or sector's historical or current emissions) and output-based allocation (i.e. based on a firm's current output) are the most common approaches for free allocation (PMR & ICAP, 2016). Within free allocations, fixed-sector benchmarking and output-based allocation can be relatively more effective in inducing low carbon production compared to grandfathering (Cong & Wei, 2010; Zhang, Wang, & Tan, 2015; Zetterberg, 2014), particularly in emissions-intensive firms (Ji et al., 2017). Hence, a system with 100% free allocations based on grandfathering of historical emissions is classified as low-performing, while a system with complete auctioning or partial free allocations benchmarked on a firm's emissions inventory is classified as high performing (see Table 1).

Similarly, indicators such as price stability, existence of an allowance reserve, price ceiling or price floor, banking and borrowing, percentage of offset credits allowed and the volume of trading in the market (i.e. liquidity) illuminate the tension between achieving long-term policy certainty while maintaining system flexibility to adjust to unforeseen circumstances. In this study, a system is assessed as low performing if there is no pre-determined annual emissions cap for future years and no price containment measures, but the system would qualify as high performing if there is a set annual cap that decreases at a pre-determined rate every year, along with both price containment and emissions containment features, with a price collar rather than a quantity collar (Holt & Shobe, 2015). Banking of allowances to future periods is often used as a tool that provides temporal flexibility and results in cost efficiency over time (PMR & ICAP, 2016). Hence, we use banking of allowances as a criterion to assess a system as better performing. Borrowing of allowances can happen either within years in a multi-year compliance period or between different compliance periods. Finally, linkage with other external markets could be compared across ETSs based on whether the market is unilaterally linked to international offsets (with or without limits on the amount of offset credits that may be purchased by a firm) or bilaterally linked with another jurisdiction, with or without mutual recognition of a compliance mechanism (Haites, 2016).

3.3.1. Allowance allocation and distribution

Once an emissions cap is defined, policy makers must choose whether to auction or freely allocate allowances. The basis for free allowance calculations includes the use of historical emissions, historical emissions intensity, industrial benchmarks that differentiate allocations based on the nature of a product or the production process, early-action incentives that reward new entrants with credits for emissions-reducing activities prior to enrolment and rolling baseline years that allow firms to be benchmarked on their latest emissions data if their emissions increased significantly from the original benchmark (European Commission, 2011; Pang & Duan, 2016; PMR & ICAP, 2016; Xiong et al., 2017; Ye, Jiang, Miao, Li, & Peng, 2016). Each ETS scheme uses a combination of these features when calculating their free allowance allocations to individual firms.

The EU ETS was initiated with a politically palatable, free, grandfathered allowance-allocation method, based on bottom-up reporting of historical emissions by firms in each member state in its first compliance period. In phase 2, the EU ETS mostly distributed free allowances based on a product's benchmarked emissions and historical production levels along with 3% auctioning (European Commission, 2011; ICAP, 2017f). Since phase 3, the EU ETS has auctioned 40% of its allowances with 100% in electricity and 15% in the aviation sector, while allocating freely to the manufacturing sector. California initially calculated its allocations based on a benchmarked,

Table 4. Market management in ETS regimes.

	Market management						
	Allowance allocation and distribution			Secondary market			International Linkage
	Method of current allocations	Improved allocation practices over time	Percentage auctioning	Trajectory of price stability	Price signal commitment	System flexibility	Linkage
European Union	Phase 1: 100% free (grandfathered) Phase 2: 97% free (partial benchmarking); 3% auctioning Phase 3: 40% auctioning (Elec – 100%; EITE manufacturing – free; non EITE manufacturing – free with a move to auction over time; aviation – 15% auctioning and remaining free.	Significant change in allocations between phases.	increased from 0% in phase 1 to 40% in phase 3.	Phase 1: Highly volatile, over allocation, price collapse to zero Phase 2: Highly volatile ($25 to $7.5) Phase 3: Less volatile ($6.1 to $8.6).	Phase 1 and 2: Individual nation caps, less decrease of cap per year compared to phase 3, default is free allowance. No MSR. Phase 3: Emissions cap with decrease per year. Default is auctioning. Single EU wide cap. MSR.	MSR in 2019, limited banking.	Unilateral link to CDM; bilateral link to Switzerland.
Switzerland	Phase 1: 100% free (grandfathered based on entity emissions) Phase 2: 100% free (industry benchmarks); phase out of free allocations for non EITE to 30% by 2020.	Significant changes in allocations between phase 1 and 2. Alignment with EU ETS allocation rules; Voluntary to mandatory with opt-in.	increase from 0% to 20% in 2013 to 70% in 2020.	Phase 2 auction clearing price: $8.3 avg. $7.5 to $9.3. less volatility.	Phase 2: emissions cap with clear decrease per year, CO_2 levy as a price signal, no MSR, linking with EU ETS.	Phase 2: Unlimited banking, carry over of CER, ERUs from previous phase, limited CDM offsets.	Bilateral link to EU; Unilateral link to CER, ERUs.
RGGI	Full auction, quarterly	Significant reduction in cap in 2014 to solve over allocation.	100% auctioning	Relatively consistent auction prices ($1.8 to $5), highly volatility in the number of allowances in circulation in the secondary market around the deadline for compliance in 2012. High volatility in the percentage of unsold auction allowances between years, leading to an interim downward adjustment of the cap.	Phase 1: No MSR, hoarding of private bank of surplus allowances by complying and non-complying entities Phase 2 and 3: MSR – injected additional allowances in auctions when necessary. Tighter cap from 2014, decreasing annually. No sunset date for the ETS but states could withdraw from the alliance.	Cost containment reserve from 2014 at $13, unlimited banking, and limited offsets. Emissions containment reserve for $6 from 2021.	Unilateral link to international offsets from states having an MOU with RGGI, no bilateral link
California	Mix of free allowances and auctioning. Allowances used only for ratepayer benefit and emissions reduction. Natural	No big change in allocations between compliance periods but transport added.	Partial auctioning	Period 1: high volatility in allowance futures market Period 2: relatively	Program expires in 2020. Auction reserve price with a defined increase every year.	Banking allowed with limits. No borrowing. Cost containment reserve with defined	Unilateral link to offsets from US, Canada, Indonesia,

	gas suppliers – increased auctioning over time. Industrial facilities – free allowances and transition to auctioning based on leakage risk. Auctioning for transport, natural gas extraction and other fuels.			stable in allowance futures market.	Cost containment reserve with defined increase in reserve every period.	increase in reserve every period. 8% offsets.	Mexico, and Brazil. Bilateral link to Quebec. Mutual recognition of compliance mechanism.
Quebec	Phase 1: Free allocation for EITE sectors based on historical levels, auction for electricity and fuel distributors. Phase 2: EITE free allocations based on real output, diminishes by 1–2% a year	Reduction in free allocations and change from grandfathering to output based allocation.	Partial auctioning to increase significantly.	Period 1: high volatility in allowance futures market Period 2: relatively stable in allowance futures market.	Auction reserve price with a defined increase every year. Cost containment reserve with defined increase in reserve every period.	Banking allowed with limits. No borrowing. Cost containment reserve with defined increase in reserve every period. 8% offsets.	Indirect link to international offsets through California link, Bilateral link to Quebec. Common compliance mechanism.
New Zealand	90% free allocation for high EITE; 60% free allocation for moderate EITE, future auctioning for non-forestry sectors. 100% free allowances for forestry sector.	Removal of unlimited offsets from period 1 to 2.	Less current or future auctioning.	Volatile.	No emissions cap yet. No emissions cap reduction schedule. Uncertainty on phasing out free allocations.	No price containment reserve. Banking allowed with limits. Price ceiling of $18. International offsets not eligible after 2015.	No linkage since 2016.
Korea	Phase 1: 100% free based on average GHG of base year 2011–13. Some sectors on benchmarks. Phase 2: 97% free allowances based on same formula Phase 3: less than 90% free allowances EITE will always receive free allowances.	No change in allocations except increase in auctioning.	Less current or future auctioning.	Phase 1: Less volatility, less trading activity in the market.	Uncertainty over emissions caps for phases 2 and 3. Price certainty for EITE sectors through phase three (i.e. until 2025).	Existence of MSR, unlimited banking and limited borrowing within a phase, limited offsets.	No linkage.
Chinese Pilots	Mostly free allocations with either grandfathering based on historic emissions, base year emissions etc. Some pilots with free allocations benchmarked sectorally.	n/a	Shenzhen – up to 10%; Guangdong – 3%; Hubei – 2.4%; Some auctioning in Tianjin and Shanghai – data n/a.	n/a	n/a	No borrowing, Banking is allowed during pilot phase.	No linkage.

Sources: As listed in Appendix 1 of the supplement.

three-year moving-average output for each industry. Electric utilities were given free allowances and required to consign the allowances to a state-run auction. The utilities were mandated to use the proceeds from the auction on investments in energy efficiency and renewable energy for the benefit of the rate payers. Electricity generating units had to purchase allowances from the state-run auctions. In the second trading period (2013–2020), California uses a mix of free allocations, auctioning and fixed price allowance sales for different sectors (see Table 4) (ICAP, 2017h). Québec allocated allowances freely based on an entity's historical emissions intensity from 2007–2010. However, during the second trading period, Québec harmonized its ETS with California, in preparation for linkage with the Californian system. The Swiss ETS has gone one step further in protecting its EITE sectors, by not only allocating most allowances for free, but also offering early-action credits and redistribution benefits from its CO_2 levy revenue for ETS-participating firms that are exempt from the CO_2 levy (FOEN, 2016a).

Along similar lines, the NZ ETS gave preferential treatment to its EITE sectors (i.e. agriculture and land use sectors) by assigning free allowances based on grandfathered historical emissions, fixed until 2018, with a linear phase-out of free allowances starting in 2019 and moving to full auctioning by 2030 (Bullock, 2012). With a change in government, New Zealand also introduced a 'transition period' where non-forestry sector participants were required to meet only half of their emission obligations (i.e. by surrendering one allowance for two units of emissions) with the price of NZUs capped at 25 NZ dollars (i.e. NZ $12.5 effective price per allowance) and the convertibility of NZUs to international offset units limited to prevent arbitrage when allowance prices are capped (Bertram & Terry, 2008; Bullock, 2012; ICAP, 2017c). This essentially protected emitters from carrying the full cost of compliance. Eventually, the New Zealand government decided to phase out its one-for-two transitional measure by 2019 in order to meet its climate change targets and incentivize firm-level emissions reductions (Ministry for the Environment, 2016b).

Korea's ETS established its emissions target through consultation with its EITE industries. In 2015, at the beginning of the Korean ETS (KETS) programme, it allocated allowances freely and provided early action credits for new entrants (Song, Lim, & Yoo, 2015). KETS allocated allowances at the firm level and calculated those allowances based on historical emissions at the sector/product level (Park & Hong, 2014). In the electricity sector, KETS created a mandatory upstream and downstream allowance obligation for power plants and electricity-consuming customers such as large commercial buildings (PMR & ICAP, 2016). Downstream obligations effectively create a price signal for indirect emitters because regulated electric utilities have limited ability to pass through compliance costs to consumers. KETS accounts for indirect downstream emissions by reflecting those allowances in a higher emissions cap (above the assigned cap of 1687 $MMTCO_{2e}$ in phase one), thereby preventing entities from being regulated twice for the same emissions (ICAP, 2016).

Finally, the Chinese ETS pilots experimented the most when it comes to allowance allocation and distribution methods. The pilots chose to allocate based on the method that best suited the region's economic structure. The Beijing and Tianjin pilots used a combination of historical emissions, historical carbon intensity and industrial benchmarks to allocate based on the region's historical average carbon intensity multiplied by an intensity decline coefficient (Xiong et al., 2017). Shanghai uses early action incentives to encourage early movers and employs a rolling baseline year so that enterprises can use the latest year's emissions data as a benchmark to receive allowances if their emissions increased over 50% from 2009 to 2011 (Xiong et al., 2017). The Guangdong and Hubei pilots follow the Shanghai formula without issuing early-action incentives, whereas Chongqing relies on self-declaration of emission reductions by entities. Shenzhen allocates 90% of allowances for free based on industrial benchmarks. For the manufacturing sector, Shenzhen follows a novel approach of post-allocation adjustment based on the difference between expected and actual firm-level emissions. Manufacturing firms are required to follow a strict MRV process and report their emissions output every year for adjustment (Ye et al., 2016). Out of the seven pilots, Beijing, Shenzhen and Hubei follow California's hybrid approach of distributing allowances freely, through auction and through fixed price sale. The Shanghai, Tianjin and Chongqing pilots distribute entirely for free, whereas Guangdong uses a combination of free distribution and auction (Xiong et al., 2017).

3.3.2. Liquidity, price stability commitment and system flexibility

Liquidity and price volatility are two aspects of the secondary market that ETSs try to manage in order to ensure a stable long-term signal to complying firms. The Chinese pilots and Korea ETS suffer from a lack of trading in the

market. Korea traded only 0.05% of freely allocated allowances in its first compliance period. The Korean government intervened by increasing borrowing from 10% to 20%, relaxing rules for entities to earn early action credits and auctioning 0.9 $MMCO_{2e}$ from its allowance reserve in June 2016 (World Bank, Ecofys, & Vivid Economics, 2016). Yet there has been little to no activity in the marketplace since 2016 (ICAP, 2017b), perhaps because of overallocation, imperfect information for emitters or the presence of complementary policies (Munnings et al., 2016; Zhang, Zhang, Liu, & Bi, 2013). Surveying the firms participating in Korea ETS, Suk et al. (2017) conclude that supply–demand imbalance, policy uncertainty and lack of preparedness of firms over carbon pricing as the key barriers to active trading in the secondary market (Suk et al., 2017).

The EU ETS in phases one and two, RGGI, California in phase one and New Zealand experienced excess allowances in the secondary markets from overallocation. In phase three, the EU ETS has responded by creating a Market Stability Reserve (MSR) to begin operating in 2019, with the aim of aligning the demand and supply of allowances by placing up to 900 million surplus 'backloaded' allowances into the MSR to be released in the event of an allowance shortage (European Commission, 2017a; Hu et al., 2015). The EU MSR acts like a quantity collar rather than a price collar. The EU also intends to double the MSR's capacity to absorb excess allowances in the market (Meadows, 2017). RGGI and California experienced excess market liquidity and price volatility in their initial compliance periods primarily due to miscalculation of future growth projections. Both established a reserve auction where allowances were sold at a reserve minimum price. RGGI cancelled about 23% of the allowances that went unsold (RGGI, 2017b, 2017e) while California allowed the retired allowances to re-enter the market if auctions cleared above the reserve price for two consecutive schedules (ICAP, 2017h). Korea appears to have learned from RGGI because it implemented a reserve auction. Korea allocated 9 million allowances for reserve auctions with about one third of those sold and the remaining retired (ICAP, 2017b). Unlike a quantity-based reserve, RGGI and California created a price containment reserve that will trigger additional auctions when permit prices hit a set price ceiling (see Table 4). The key difference, however, is that the RGGI price containment reserve has allowances outside the emissions cap while California's reserve allowances come under the total emissions cap. In addition to a price containment reserve, RGGI will also have an emissions containment reserve starting in 2021 that will allow states to withhold allowances from the market when permit prices hit a price floor of $6 in 2021 with a 7% annual escalator (Resources for the future, 2017).

New Zealand also experienced excess liquidity resulting from a glut of international offset credits in the trading market, which led to a collapse in the allowance price from $20 in May 2011 to $2 in May 2013 (Richter & Chambers, 2014). Unlike the other ETSs, until 2015, the NZ ETS did not have a limit on the number of international offset credits that could be purchased. In its second compliance period, NZ ETS brought the programme under a nationwide emissions cap and closed access to international offset credits (Diaz-Rainey & Tulloch, 2015).

Finally, the Québec and Swiss ETS programmes suffered from a lack of liquidity, primarily due to the small size of their markets. Thanks to electricity sectors dominated by renewables, both programmes had fewer low cost opportunities to reduce emissions, leading to a high marginal abatement cost. Prior to linking the Québec system to California, allowance prices were between $37–43 per ton in 2013, three times the current price under a linked market (Purdon, Houle, & Lachapelle, 2014). In the linked market, Québec currently maintains an allowance price containment reserve that aligns with California's (Government of Québec, 2015).

3.3.3. International linkage

Linkage between ETSs can be of three types: (1) a unilateral link where one ETS accepts the compliance instruments of another but not vice versa; (2) a bilateral link where each ETS accepts the compliance instruments of the other or have common compliance rules; (3) an indirect link where an ETS has a link to another ETS through a third market (Haites, 2016). Linked ETSs may benefit from improved cost effectiveness, better liquidity and price stability, lower emissions leakage and lower transaction costs (Haites, 2016; Metcalf & Weisbach, 2012). Linkages are likely when jurisdictions have similar environmental goals, economic conditions, a history of productive engagement on other issues and familiarity with each other's regulatory and political systems (Ranson & Stavins, 2016).

California is notable for its international linkage with the Québec cap-and-trade programme beginning in 2014. The two systems were fairly easy to link owing to extensive and transparent communications between

Table 5. Revenue management in ETS regimes.

Revenue management				
	Revenue raised	EITE earmarking	Green earmarking	Earmarking for distributional equity
European Union	$14.4 billion (2013–2015)	Manufacturing sub-sectors deemed at high risk for carbon leakage receive 100% free allocation. Sectors not deemed to be at risk of leakage will draw down free allowance allocation from 80% in 2013 to 30% by 2020.	82% ($11.8 billion) At least 50% of auction revenues must be distributed for climate and energy related purposes.	No explicit low-income provisions.
Switzerland	n/a	n/a	n/a	n/a
RGGI	$2.84 billion (2008–2017)	n/a	81% of revenue has been allocated to energy efficiency, clean & renewable energy and greenhouse gas abatement efforts.	At least 25% of revenue must be allocated for 'consumer benefit'– no explicit low-income provisions.
California	$3.385 billion (2014–2017)	Receive free allowances for transition assistance and to prevent leakage. Starting in 2018, transition assistance declines. The amount of free allocation is determined by leakage risk (measured through emissions intensity and trade exposure) and sector-specific benchmarks.	25% revenue is required by law to be used for green spending.	$1.2 billion in cumulative investments benefiting disadvantaged communities (A minimum of 25% of the proceeds be invested in projects that are located within and benefiting individuals living in disadvantaged communities).
Quebec	$2.05 billion (2013–2017)	n/a	100% of revenue allocated to climate change mitigation and adaptation.	No explicit low-income provisions.
New Zealand	No revenue	90% free allocation for high EITE entities, 60% free allocation for moderately EITE.	n/a	n/a
Korea	No revenue	Sectors whose production costs are 30% or more, sectors whose trade intensity level is 5% or more, or sectors whose production cost rate is 5% or more and their trade intensity level of 10% or more, are eligible to receive free allowances.	n/a	n/a
Chinese Pilots	n/a	n/a	n/a	n/a

Sources: As listed in Appendix 1 of the supplement.

the two governments going as far back as 2008 (Benoit & Côté, 2015). California and Québec created a common, electronic allowance registry to avoid gaming and potential double-counting. Strong verification and data accuracy safeguards were put in place to ensure the integrity of allowance credits, in addition to that of the offsets. To maintain price stability, the price floor was set at the highest minimum price of either region in US dollars. Linking with the California system allowed Québec's cap-and-trade market to increase its liquidity through increased access to allowances. Ontario, which recently inaugurated its cap-and-trade programme, announced plans to link up with Québec and California in 2018, which will further increase the total number of tradable allowances and offsets (ICAP, 2017d).

On January 2016, the Swiss government agreed to link its ETS with the EU ETS market (The Federal Council, 2016). The Swiss ETS aligned its compliance instruments during its second trading period with the EU ETS. As a small ETS market with only 5.3 $MMTCO_{2e}$ emissions cap, the Swiss ETS could potentially gain from linking with the EU ETS. Through linkage, the existing lack of market liquidity will ease. Further, carbon leakage and competitiveness concerns for Swiss companies can be reduced because 60% of its exports and 78% of imports occur within the EU region (Hawkins & Jegou, 2014).

The KETS could potentially link to its regional neighbour, the Tokyo-Saitama ETS in Japan (Wakabayashi & Kimura, 2018), or with the EU ETS. However, there is little indication of learning on the part of KETS from the Québec-California linkage when it comes to solving its liquidity issues.

Cutting off links to other markets can also be an option. Diaz-Rainey & Tulloch (2015) argues that the case of the NZ ETS shows both the power and dangers of tacit linking to international carbon markets. As discussed in the previous section on carbon leakage, excess liquidity from international offsets forced the NZ ETS to delink itself from the CDM and international offset markets in 2015 and move towards a domestic market (Bullock, 2012). The EU ETS also delinked from the international CDM market in 2012. In May 2011, New Jersey announced that it would leave RGGI, but is now expected to re-join along with Virginia in the coming year (Profeta, 2017).

3.4. Revenue management

Tracking revenue generation and use in an ETS helps further corroborate the extent to which a system strives to balance the social, economic, environmental and political needs that arise out of implementing a carbon pricing policy. Table 5 shows the key metrics used to compare revenue management practices across the ETS cases. By rating ETSs across these revenue metrics, we intend to simply assess their performance individually for each revenue use category rather than making a collective judgment as to whether directing revenues towards one purpose is better or worse than the other.

In 2015 alone, carbon pricing policies generated $26 billion in revenues worldwide (World Bank, 2016). Revenues generated from auctioning allowances could be used in additional climate change mitigation, reducing ETS administrative costs, alleviating compliance cost burden for EITE firms, addressing distributional inequity by augmenting expenditure on public goods, reducing distortionary taxes, reducing budget deficits or to increase the flow of climate finance from developed to developing countries (Bowen, 2015; World Bank, 2016).

The EU ETS generated about $17 billion in auctions between 2012 and 2016, with at least 50% of the revenue distributed for climate- and energy-related purposes and for retrofitting existing infrastructure (European Commission, 2017). Using revenue from allowance auctions, the EU plans to establish two new funds: an 'Innovation' fund to extend existing support for demonstration of innovative technologies, and a 'Modernization' fund to facilitate investments in modernizing the power sector and fostering energy efficiency (Meadows, 2017). Similarly, RGGI has generated about $2.7 billion in revenue, of which at least 25% must be used for 'consumer benefit or strategic energy purpose' by participating states (RGGI Inc., 2010). In practice, RGGI states allocated 42% for energy efficiency programmes, 11% for bill assistance to low-income residents, 9% for GHG abatement, 8% for renewable energy development, 8% for state budget reductions, 4% for programme administration and 1% for RGGI management between 2009 and 2014 (Ramseur, 2017). Allowance revenue has generated employment in the RGGI region, with estimates showing a net effect of 30,200 job-years between 2009 and 2025 (Hibbard, Okie, Tierney, & Darling, 2015). Similar to the EU and RGGI, California raised $3.385 billion in revenue through 2017 and has invested revenue into high speed rail, low carbon transit, weatherproofing of low income homes and environmental conservation efforts (CCI, 2017). Québec expects to raise $3.3 billion by 2020 towards the

Table 6. Overall assessment of ETS regimes based on Table 1.

Overall assessment	Attributes	European Union	Switzerland	RGGI	California	Quebec	New Zealand	Korea	Chinese Pilots
Environmental relevance	**Coverage of key emitting sectors**	Medium	High	Low	High	High	Low	Medium	Low
	Emissions cap to total emissions ratio	Medium	High	High	Medium	Medium	Low	Low/Medium	Low
	Stringency of cap	Medium	Medium	Medium	High	High	Low	Medium	Low
Economic efficiency	**Abatement cost**	Medium	Medium	High	Low	Low	n/a	n/a	n/a
Market management	**Method of current allocations**	High	Medium	High	High	High	Low	Low/Medium	Low
	Improved allocation practices over time	High	High	High	High	High	Low	Low	n/a
	Percentage auctioning	Medium	Medium	High	Medium	Medium	Low	Low	n/a
	Trajectory of price stability	Low (Phase 1&2) Medium (Phase 3)	High	Medium	Medium (Phase 1) High (Phase 2)	High	Low	High	n/a
	Price signal commitment	Medium	Medium	Medium/ High	Medium	Medium	Low	Low	n/a
	System flexibility	Medium	Medium	High	High	High	Low	High	n/a
	Current linkage	High	High	Low	High	High	Low	Low	n/a
Revenue management	**Revenue raised**	High	Medium	High	High	High	Low	Low	n/a
	EITE earmarking	Medium	n/a	n/a	Medium/High	Medium/High	Low	Low	n/a
	Green earmarking	High	High	High	Medium	High	n/a	n/a	n/a
	Earmarking for distributional equity	Low	Low	High	High	Low	n/a	n/a	n/a

Source: Self-generated.

Québec Green Fund, a dedicated fund used to enhance the region's emissions reductions (CDC et al., 2015a). Overall, ETSs with a revenue generation instrument seem to redouble efforts on environmental effectiveness than directing revenues towards non-environmental purposes. As of 2014, about 70% of cap-and-trade revenues around the world earmarked revenues towards environmental purposes (Carl & Fedor, 2016).

3.5. Stakeholder engagement

The level of stakeholder engagement can be assessed to some extent by tracking the number of meetings held per year or per period with stakeholders and the extent to which the general public is allowed to participate in the rule making or rule modification process. The frequency of stakeholder meetings may be judged as low to high based on whether these meetings were convened on demand from the stakeholders or pre-determined by the ETS-enforcing agency of the government. Similarly, the involvement of the public may be rated from low to high based on the existence of public participation either through public town hall meetings or opportunities for the public to submit comments on ETS rule modifications. In addition to the metrics proposed, it is important to track the outcome of engaging stakeholders during any rule modification process so as to fairly assess its effectiveness in achieving consensus.

With the exception of RGGI and California, stakeholder engagement is not explicitly emphasized in other ETS programmes. California schedules stakeholder meetings and public town halls when a rule change is proposed and receives public comments on the rule changes. California's ETS has received significant public support, with 54% of the state's residents favouring the programme even if it raised consumer prices (Baldassare, Bonner, Kordus, & Lopes, 2016). RGGI conducts regular quarterly stakeholder meetings and receives public comments on major rule changes. There is some evidence that the RGGI may have fared better in building constituency support for the full auctioning of allowances when compared to California (Rabe, 2016). RGGI and its state constituents regularly framed the auction process as delivering significant benefits to both the environment and the economy while there are claims that California equivocated over its plans for using auction revenues and alienated stakeholders in the process (Rabe, 2016).

The KETS is a good example of learning from the successes and failures of prior implementation when it comes to planning and engaging stakeholders early. Prior to introducing KETS, the Korean government launched a GHG and Energy Target Management System (TMS), a mandatory negotiated agreement aimed at curtailing energy use and GHG emissions, thereby easing firms into the process of monitoring and verifying emissions data (Oh, Hyon, & Kim, 2016). The Chinese ETS pilots, in turn, represent experimentation in the marketplace, engaging and familiarizing stakeholders with new forms of regulations and testing compliance enforcement prior to the launch of its nationwide ETS (Duan, Pang, & Zhang, 2014).

4. Overall assessment

Table 6 provides an overall assessment of the eight ETSs as defined in the assessment framework (see Table 1). Relative to other systems, the California–Québec linked system performs the best in terms of environmental effectiveness with near full coverage of key emitting sectors, including transportation and a tightening of the cap by 3% every year. The New Zealand and Chinese pilots perform relatively poorly with significant exemptions of coverage to EITE sectors and no policies aimed at tightening the emissions cap over time. As best practice, an ETS covering a substantial portion of a jurisdiction's point-source emissions with scheduled timetables for tightening of emissions caps over time is ideal (Haites et al., 2018).

In terms of economic efficiency, the lack of data regarding the cost of compliance and cost of ETS administration hamper us from making an assessment. In terms of marginal abatement cost, RGGI performs the best with a low marginal cost of abatement that encompasses the entire electricity sector through full auctioning of allowances. A low marginal abatement cost, however, may not be the best indicator of a system's performance because ETSs that cover only the entities that are easiest to mitigate may push more costly sectors out of the system to be regulated through alternative means. Low permit prices may also arise owing to overallocation of allowances or hoarding of allowances by firms from a previous compliance period.

In the primary market, RGGI, California and Québec perform the best with full auctioning or majority auctioning with free allocations benchmarked by sector emissions. The EU and Switzerland perform relatively well with improved allocation methodologies and an increasing auctioning schedule in their later compliance periods. This indicates significant institutional learning about effective allocation from prior compliance periods within the ETSs. New Zealand and Korea are assessed as low-performing systems due to 100% free allocations and indefinite extension of free allocations to EITE-exposed industries with minimal or no increase in auctioning. As best practice, an ETS with near full coverage and free allowances is more politically palatable in many jurisdictions. Transitioning to full auctioning over time, however, ensures revenue generation, helps with price discovery and assigns allowances to highest valued use (Burtraw & McCormack, 2017).

In the secondary market, the RGGI demonstrates a stronger price signal commitment and system flexibility with clearly defined auction schedules, tightening of the emissions cap every year, a price ceiling that triggers the price containment reserve (i.e. economic effectiveness) and an upcoming price floor of $6 per tonne which triggers the emissions containment reserve (i.e. environmental effectiveness). The EU–Switzerland linked system is assessed as medium performing because the market stability reserve (MSR) set to become active in 2019 is triggered based on a quantity collar rather than a price floor/ceiling and cannot be adjusted dynamically (Acworth, 2014; Holt & Shobe, 2015). Unlike RGGI, California and Québec, the allowances pulled out of the EU market are proposed to remain for future use in the reserve without any expiration date. California–Québec's linked system is assessed as medium because of the uncertainty in the direction of the ETS beyond 2020. As best practice, a well-defined emissions cap schedule with price collar and a price-triggered allowance reserve that automatically cancels upon being retired from the market ensures a credible price signal to firms regulated by the system (Holt & Shobe, 2015).

Owing to lack of data, we are unable to assess the ETSs for their stakeholder engagement practices. However, there is evidence that the RGGI and California systems conduct scheduled quarterly meetings with stakeholders and receive public comments on rule modifications (CARB, 2017b; RGGI Inc., 2017d). There is also evidence of Korea's active engagement with stakeholders throughout the process of initiating its ETS starting with the emissions inventory system two years prior to the start of the ETS.

Finally, in terms of revenue generation and use, the EU, RGGI, California and Québec raise significant revenue through auctioning. RGGI devotes a larger percentage of its revenue to address social, environmental and economic needs such as supporting EITE industries, energy efficiency programmes and low-income communities (Ramseur, 2017**)** than other ETSs. Québec earmarks all of its revenues to additional climate change mitigation. Overall, many ETSs seem to strive for a 'double dividend' in emissions reductions by reinvesting a good portion of their revenues into additional emissions-reduction activities.

5. Other findings and knowledge gaps

Each national context creates unique opportunities and constraints resulting in no ETS policy being alike. Certain attributes such as free allowance allocations or auctioning lend themselves better to particular national circumstances, while others, such as price collars and price/emissions containment reserves, can help achieve market efficiency irrespective of where the ETS is implemented. RGGI, California-Québec, the EU ETS (in phases three and four) and Korea all have shown good administrative prudence by implementing these market management features.

We find patterns of learning from a system's own prior experience and from other ETSs. Korea officially cooperated with the EU for assistance in managing its ETS and help regulated firms learn from the EU on compliance and allowance trading (European External Action Service, 2016). Similarly, the Chinese ETS pilots signed agreements with California, the UK, France, Norway, Finland, Germany, Québec and the European Commission to get technical assistance on ETS implementation (Swartz, 2016). Within an ETS, the EU evolved in its allocation methodology and price stability measures. California appears to have learned significantly from exchanges of knowledge with the EU ETS and RGGI in shaping allocation of permits and offset rules to avoid mistakes like overallocation, double counting and windfall profits to permit holders (Bang, Victor, & Andresen, 2017).

Knowledge gaps on the administrative cost of running an effective ETS, the cost of compliance to the firms and the extent of stakeholder engagement currently make comparisons on economic efficiency and stakeholder

engagement across the eight ETSs impossible. Finally, this article assesses ETS regimes in isolation from other policies, but research is needed to assess the impact of complementary policies on the overall emissions coverage and the efficacy of ETSs themselves. The presence of complementary policies can achieve significant emission reductions but contribute to an overabundance of supply in the ETS market, which places downward pressure on permit prices (Schmalensee & Stavins, 2015). These knowledge gaps need to be addressed in order to guide future market-based climate policy design and implementation.

Notes

1. Primary market refers to the allowance allocation and distribution stage of an ETS, in which governments distribute emission allowances for free based on assessed firm-level quotas, through auctioning, or a combination of both.
2. The secondary market is the ETS jurisdiction's trading market where participating firms are allowed to buy and sell the allowances they received initially in the primary market.

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Appendices

Appendix 1. Studies assessing the performance of ETS regimes

ETS jurisdiction	Key studies	Data sources for Tables 1–5
EU	Ellerman and Buchner (2008); Ellerman et al. (2007); Brown et al. (2012); Martin, Muûls, and Wagner (2015); Liang, Sato, Grubb, and Comberti (2014); Ellerman, Marcantonini, and Zaklan (2016); and European Commission (2016a, 2017a, 2017b)	European Commission (2017a); ICAP (2017e); European Energy Exchange (2017); and Intercontinental Exchange (2017)
Switzerland	FOEN (2016a); Rutherford (2014)	CDC, EDF, and IETA (2015b); and ICAP (2017f)
RGGI	Hibbard and Tierney (2011); and Hibbard et al. (2015)	RGGI Inc. (2010); ICAP (2017g); CDC, EDF, and IETA (2015c); and RGGI (2017a, 2017b, 2017c).
California	Bang et al. (2017)	CARB (2010, 2012, 2017a); CCI (2017); ICAP (2017h); and Climate Policy Initiative (2017)
Quebec	Purdon et al. (2014); Benoit and Côté (2015); and Government of Québec (2015)	Government of Québec (2015); CDC, EDF, and IETA (2015a); and ICAP (2017a)
New Zealand	Ministry for the Environment (2016a); Leining and Kerr (2016); Richter and Chambers (2014); and Diaz-Rainey and Tulloch (2015)	Ministry for the Environment (2016a); ICAP (2017b); and EDF, MOTU, & IETA (2014)
South Korea	Oh et al. (2016); PMR & ICAP (2016); Kim (2015); and Song et al. (2015)	Park and Hong (2014); ICAP (2017c); and EDF, CRIK, and IETA (2016)
Chinese pilots	Duan et al. (2014); Pang and Duan (2016); Zhang, Wang, and Du (2017); Dong et al. (2016); Yang et al. (2016); Yu and Lo (2015); Deng, Li, Pang, and Duan (2018); and Zhang et al. (2014)	Zhang (2015); Xiong et al. (2017); Swartz (2016); and Munnings et al. (2016)
Comparative studies	Schmalensee and Stavins (2017); Borghesi, Montini, and Barreca (2016); Villoria-Saez, Tam, del Río Merino, Arrebola, and Wang (2016); and Dong et al. (2016)	

Appendix 2. Brief description of ETS systems

EU ETS

Begun in 2005, the EU ETS was one of the main policy tools used by the EU to implement the 1997 Kyoto Protocol to the UN Framework Convention on Climate Change (UNFCCC). The programme now operates in 28 EU member states plus Iceland, Liechtenstein and Norway. The ETS covers about 11,000 entities accounting for 45% of EU-wide GHG emissions from multiple sectors. The EU ETS has proceeded through three distinct trading periods, with phase three (2013–2020) employing an allowance cap reduction of 1.74% per year, a market stability reserve (MSR) to begin in 2019, banking and borrowing restricted to a year, offsets capped at 50% of total emissions reductions, a noncompliance penalty of 100 EUR per ton of regulated emissions, and 50% of auction

revenue directed towards climate and energy related investments (European Commission, 2016a; European Commission, 2017a; Frunza, 2013; Meadows, 2017).

Switzerland ETS

Switzerland follows a hybrid approach to reducing its GHG emissions with a carbon tax (i.e. the CO_2 levy covering 51% CO_2 emissions) and ETS (covering 33% CO_2 emissions) operating simultaneously. The first phase of the ETS, from 2008–2012, was voluntary for firms wanting to be exempt from the CO_2 levy. Energy-intensive industries could voluntarily participate and receive free allowances based on a company's potential to reduce emissions (CDC, EDF & IETA, 2015b). Non-complying firms simply faced a price cap imposed by the CO_2 levy. In the latest phase, 2013–2020, the Swiss ETS imposes an economy-wide emissions cap, mandatory enrolment for large entities, a combination of free and auctioned allowances with auctioning set to increase to 70% by 2020, creation of an allowance reserve for new entrants, non-compliance penalties equal to the EU ETS, an offset mechanism aligned with the EU ETS rules, and inclusion of the aviation sector under a linked system with the EU ETS (FOEN, 2016b; Hawkins & Jegou, 2014; Rutherford, 2014).

Regional Greenhouse Gas Initiative (*RGGI*)

The RGGI covers 23% of GHG emissions in nine north-eastern states in the United States (i.e. 2% of US emissions) by capping CO_2 emissions from 165 regulated electricity generating units in total (EIA, 2016; Ramseur, 2017). RGGI is a transparent system with full auctioning of allowances, an allowance cap that reduces at 2.5% per year until 2020 and at 3% thereafter, an allowance reserve to manage permit prices, a price floor of $2.15, unlimited banking without borrowing from future compliance periods, offsets up to 3.3% of emissions obligation, and periodic adjustments of the programme through consultative review meetings (EIA, 2016; ICAP, 2017e). A recent programme innovation is the emissions containment reserve (ECR); set to be implemented in 2021, which will allow states to withhold allowances from the total pool of allowances if prices fall below $6 in 2012, with a 7% annual escalator. Participation is voluntary among RGGI states, with New Hampshire and Maine opting not to participate (RGGI, 2017). An emissions containment reserve is essential the opposite of a cost containment reserve. A CCR releases allowances when prices are high, while a ECR absorbs allowances when prices are low (RFF, 2017).

California Cap-and-Trade (*CAT*)

The California cap-and-trade programme began in 2013 after it was granted legal authority through the Global Warming Solutions Act of 2006 (AB 32), requiring the state to reduce emissions to 1990 levels by 2020. During the first compliance phase (2013–2014), the programme covered 35% of the state's emissions and all six major GHGs. In the second compliance period (2015–2017), the programme regulates 85% of California's emissions (the three-year average cap being 382.4 $MMTCO_2e$). Electric utilities are allotted allowances on behalf of their ratepayers with investor-owned utilities obligated to consign allowances to state auctions, while publicly-owned utilities may either consign to state auctions or bank in an allowance account. Industrial facilities receive a declining amount of free allowances in order to avoid leakage and to promote a smooth transition. The remaining allowances, roughly 6% of current year vintage in the first compliance period, are auctioned. The total number of auctioned allowances is expected to increase in each subsequent compliance period (ICAP, 2017h). An additional feature of the programme is the allowance price-containment reserve (APCR), which gives regulators the power to remove or add allowances into the market, up to 4% of the annual allowances budgets through 2020, in the event of a drastic allowance price increase. The APCR allowances are priced at three tiers with various escalation mechanisms and can only be used by the regulated entities and cannot be resold. The APCR will be replaced in 2021 with two price containment points below a hard price ceiling (State of California, 2017), a $10 price floor with 5% escalator per year, offsets up to 8% of a firm's emissions, linkage to the Québec cap-and-trade programme, free allowances to energy-intensive and trade-exposed (EITE) industries to reduce leakage, and rigorous monitoring of allowances, offsets and emissions reductions (ICAP, 2017).

Québec Cap-and-Trade

In 2009, Québec adopted a GHG emissions reduction goal of 20% below 1990-levels by 2020. In 2011, Québec initiated its emissions trading scheme with its first compliance period beginning in 2013. Subsequently in 2014, the programme formally linked with the California cap-and-trade system, creating the largest carbon market in North America and the first sub-national programme to link internationally (CDC, EDF, & IETA, 2015a). The 2018 cap for the third compliance period is 58.96 million allowances with a 3.5% yearly cap reduction, covering 132 entities, roughly 85% of the province's GHG emissions. (ICAP, 2017) The ETS allocates allowances freely but decreases free allowances by 1 to 2% per year, directs auctioned revenues to the Québec Green Fund, sets a price floor averaging the highest minimum price between California and Québec markets, maintains an allowance price containment reserve, and utilizes stringent and transparent monitoring, reporting and verification (MRV) processes (Government of Québec, 2015; ICAP, 2017a).

New Zealand ETS

In 2008, the New Zealand ETS (i.e. NZ ETS) was introduced by legislation in order to meet the country's international obligations under the Kyoto Protocol, with the objective of delivering emissions reduction in a cost-effective manner while increasing the long-term resilience of New Zealand's economy (Richter & Chambers, 2014). Until 2015, the ETS covered all sectors under a Kyoto-based target without a nationwide emissions cap. From 2016, the ETS imposes a nationwide emissions-intensity-based cap, upstream regulation in the energy sectors, voluntary opt-in for downstream users, output-based grandparenting of allowances to eligible EITE sectors such as agriculture with a linear phase-out of free allowances by 2030, unlimited Kyoto offsets until 2015, and strict MRV process with audits of self-assessment and penalties for non-compliance (ICAP, 2017c; Leining & Kerr, 2016).

Republic of Korea ETS

In 2012, the Act on 'Allocation and Trading of Greenhouse Gas Emissions' established an ETS, beginning in January 2015. The Korean government followed a careful approach of defining timelines, establishing strategic governance architecture and an independent allowance committee, creating market stabilizing measures, and providing support for losses incurred by entities participating in the ETS. The Korean ETS (KETS) allocates allowances freely based on historical GHG emissions, both upstream at the point of electricity generation and downstream at consumption, and it benchmarked allowances for other sectors (EDF, CRIK, & IETA, 2016; PMR & ICAP, 2016). In addition, KETS has an allowance price containment reserve, a reserve auction price of €12, credits for emissions reductions achieved prior to joining KETS, unlimited banking with borrowing up to 20% within phases, offsets up to 10% of a firm's obligation, and a non-compliance penalty up to $70 per ton of regulated emissions (Oh et al., 2016; PMR & ICAP, 2016).

China: Provincial ETS Pilots

In 2011, the Chinese government initiated seven pilot ETS programmes for CO_2 emissions (Beijing, Tianjin, Shanghai, Chongqing, Shenzhen, Guangdong, and Hubei) requiring the regions to launch by 2013 and fully initiate by 2015 (Zhang, Karplus, Cassisa, & Zhang, 2014). Chinese ETS pilots covered indirect electricity emissions within the pilot regions and emissions from imported electricity outside of the pilot regions (Zhang, 2015). Nearly all of them allocated allowances for free, except for a small percentage of auctioning in Guangdong, Shenzhen, and Hubei, but the systems differed in their method of allocation (Dong, Ma, & Sun, 2016; Duan et al., 2014). All of them accepted offsets through CERs generated outside the pilot regions, established market stabilizing mechanisms using auctions triggered by price ceilings, allowance reserves, buy-back of surplus allowances in the market, or a combination of these features (Pang & Duan, 2016).

Incomplete reporting practices, a lack of a legal framework to enforce compliance, and weak penalties are identified as some of the key challenges that emerged in the seven pilots (Yu & Lo, 2015). A survey of Chinese firms conducted in 2015 revealed that the carbon price failed to 'stimulate companies to upgrade mitigation technologies' and that the majority of firms considered participation in the ETS pilots only a means of improving ties with governments and earning a good social reputation (Yang, Li, & Zhang, 2016).