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Regulating greenhouse gas emissions by an inter-temporal policy mix: an experimental investigation*

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Emissions taxes impose a fixed price on emissions, whereas under tradable permit schemes prices emerge in the secondary permit market. The delayed price discovery under tradable permits creates uncertainty about the future cost of compliance that liable emitters face. To mitigate this uncertainty, some jurisdictions have designed policies to regulate GHG with an emissions tax that is in force for several years, subsequently transforming into a tradable permit scheme. This paper examines the effects that this staged transition – from no regulation to a regulation by a tax, to a regulation by tradable permits – has on abatement investment, quantity of emissions, permit prices and overall regulation efficiency. The effects of the inter-temporal mix of policy instruments are compared to the effects of single policy instrument: a tax-only, and a tradable permit-only regulation. Our investigation relied on laboratory economics methods to test economic behaviour under these three policy regimes. We find that a staged transition from a tax to a tradable permit scheme results in more socially desirable outcomes on a range of criteria when compared to a regulation based solely on tradable permits, and specifically, it improves ability to make better abatement investment decisions.

Key words: abatement investment, cap and trade, emission markets, emission taxes, environmental policy, permit trading.

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1. Introduction

Incentive-based policies, such as emissions taxes and emissions permit trading schemes, are increasingly used to regulate greenhouse gas (GHG) emissions in many jurisdictions around the world (de Vries and Hanley 2016). Emissions trading schemes have been implemented in the European Union in 2005 (Betz and Sato 2006), in New Zealand in 2008 (Bullock 2012), in Northeast and Mid-Atlantic US states (Ruth *et al.* 2008), and in California in 2013 (Schobe *et al.* 2014). Emissions taxes are in place in Norway (Bruvoll and Larsen 2004), in several Canadian provinces (Sawyer and Gass 2014), and in Ireland since 2010 (Conefrey *et al.* 2013). A contemporaneous policy mix (a hybrid of tax and a tradable scheme existing at the same time) operates in Switzerland since 2008 (IETA 2013), and an inter-temporal policy mix with a staged transition from an emissions tax to an emissions trading scheme was initiated in Quebec in 2011 (Sawyer and Gass 2014) and in Australia in 2012 (Rootes 2014).

Although the desirability of incentive-based policy instruments is widely documented (Downing and White 1986; Aldy and Stavins 2012; Keohane and Olmstead 2016), the choice of which specific incentive-based policy instrument to implement still generates significant debate (Goulder and Schein 2013). Recent literature shows that taxes perform better under a given set of assumptions, while tradable permits might be preferred under an alternative set of assumptions (Garcia *et al.* 2018). Tradable permit schemes are seen as more popular and politically more palatable compared to a tax, largely due to the business sector's perception that the direct market-based nature of the tradable permits imposes lower compliance costs on emitters compared to a tax (Svendsen 1999). However, the literature does not provide unequivocal evidence that this is so. In particular, the argument that tradable permit schemes are cost-effective relative to taxes relies critically on the assumption of the absence of transaction costs and market power, risk-neutrality among market participants and availability of full information. It has been shown that these assumptions are untenable, particularly because of the effects that market uncertainty has on abatement investment decisions (Betz and Gunnthorsdottir 2009; Hahn and Stavins 2011). Uncertainty about future emissions permit prices can lead firms to invest more or less than the optimal levels of abatement (Malueg 1989) thereby raising the total social cost of regulation (Hahn and Stavins 2011; Aldy and Stavins 2012).

On the other hand, a tax presents itself as a simpler regulation for emissions reduction. An emissions tax could be set at a rate that impels polluters to curb emissions to the target level (Milliman and Prince 1989). The steady price signal provided by a tax lends emitters greater certainty about future compliance costs and the benefit of undertaking investment in abatement. Under certain conditions, an appropriately set tax could result in the lowest cost of compliance (Requate 2005). However, emission taxes on GHG are sometimes extraordinarily unpopular, as testified by the political events in

Australia several years ago, where the parliamentary elections in 2013 revolved heavily around the so called ‘Carbon Tax’, and the incumbent government that instituted the tax was subsequently voted out (Rootes 2014).[1]

In light of the drawbacks associated both with emissions trading and with taxing emissions, a mix of the two policies could be an attractive alternative. While installing an ongoing tax on emissions in a previously unregulated jurisdiction may be seen as a politically impractical venture, a temporary tax that would subsequently convert to a tradable permit scheme at a pre-specified time might pass more easily through a contentious political process. Indeed, this type of transitional regulation did become law in Australia (Rootes 2014 and Appendix S1). A key benefit of this policy design is that the temporary emissions tax could reduce the uncertainty about future compliance costs by providing a price signal during the initial stages of regulation implementation. If set properly, this signal would conceivably lead to production and abatement investment decisions on the part of emitters that are in line with socially optimal outcomes. Once the tax stage expires, an ongoing emissions trading scheme are implemented over the long-term.

The main question pursued in this paper is whether an inter-temporally mixed regulation, comprised of an emissions tax temporarily enforced for several periods prior to an implementation of a tradable permit scheme, would improve the performance of emission regulation in comparison to an outright tradable permit scheme. The performance of the regulation is evaluated along key criteria of interest, such as optimality of investment in abatement technology and emission permits prices. The overall performance of each regulation is evaluated by its efficiency in relation to the theoretical optimum.

The use of a mix of policy instruments in a static sense is widely reported in the literature (e.g. Roberts and Spence 1976; Pizer 2002; Liao 2007; Krysiak and Oberauner 2010; also Shobe *et al.* 2014 write about a ‘hybrid approach’ implemented in California), but an inter-temporal mix, or an inter-temporal hybrid of an emissions tax and a tradable permit scheme has not yet been investigated in detail. This represents an important gap in our understanding of how the combination of two or more policy instruments over time could deliver improved outcomes in terms of lower cost GHG emissions abatement. As far as the authors are aware, the present paper is the first study that explicitly examines the inter-temporally hybridised policy design in which a tradable permit scheme sequentially follows an emissions tax. Our findings help to bridge the existing gap in the literature on the effects of such inter-temporal hybrid policies.

This paper reports findings from a laboratory economics experiments studying economic behaviour under three types of regulation: tax-only, tradable permit scheme only, and an inter-temporal policy mix of a tax followed by tradable permit scheme. Following Smith (1962) defining work

[1] See Appendix S1 for a brief overview of the history of GHG emissions reduction policy (and politics) in Australia.

with laboratory experiments as useful test beds for market-based solutions as policy alternatives, several experimental studies that focused specifically on emissions regulation emerged in the 1990s (Cason and Plott 1996; Cronshaw and Kruse 1999). Muller and Mestelman (1998) provide a comprehensive review of the early experiments related to emissions regulations, which laid a foundation for the contemporary work in the field. The more recent literature reporting on experimental studies in the context of regulation of emissions is reviewed by Cason (2010) and by Friesen and Gangadharan (2013). The work presented in the current paper is most closely related to the experiment reported by Camacho-Cuena *et al.* (2012), who focused directly on the effects that permit allocation schemes have on participants' decisions to abate. We go beyond the work reported in Camacho-Cuena *et al.* (2012) by considering alternative types of emission abatement regulations, including a hybrid inter-temporal policy mix of a tax and a tradable permit scheme, as opposed to considering alternative permit allocation schemes as in their work.

The paper is organised as follows: the next section outlines the theoretical underpinnings of the experiment, which is followed by a description of the experimental setup and procedures. The discussion proceeds with a section that presents the results, and the final section concludes by offering some policy implications of the findings and avenues for future research.

2. Conceptual framework

To set the stage for the experimental economics work presented in the subsequent sections, we rely on a standard theoretical framework of environmental economics. Let us assume that a benevolent regulator representing societal preferences for environmental quality aims to regulate emissions of GHGs. The regulator employs incentive-based regulations to achieve the objective of effective emissions regulation at the lowest social cost. The regulator could use a constant tax per unit of emissions imposed on individual emitters; a tradable permit scheme, where an overall cap is imposed on emissions and tradable permits are distributed among emitters in some way;[2] or a tax for a specified initial period followed by a tradable permit scheme. We focus on these three specific regulations here because the emissions taxes and tradable permits are the most widely used incentive-based

[2] Initial distribution of permits can be conducted by 'grandfathering' or by auctioning permits off in a primary auction market. Auctioning permits is likely to lead to a more efficient outcome than grandfathering (e.g. Thaler 1980; Cramton and Kerr 2002; Camacho-Cuena *et al.* 2012), in particular because it might provide the desired initial signal about abatement costs of various emitters (Betz *et al.* 2010). However, auctioning of permits has not been very popular in practice. In this paper, we implement proportional permit 'grandfathering' on optimal pre-regulation production levels since many newly implemented emissions trading schemes grandfather initial permit allocations. For example, California GHG emission regulation allocates significant amount (but not all) of permits based on grandfathering (Shobe *et al.* 2014).

regulations for emissions control, whereas the inter-temporal hybrid between them is of direct and specific interest to the current paper.

The ensuing empirical study focuses on the effects of alternative types of regulation on optimality of production and investment decisions of emitters. Each emitter is aiming to maximise their profit from producing goods/services subject to the particular type of regulation on their GHG emissions:

$$\max \pi_i(A_i, q_i, e_i) = pq_i - C_i(A_i, q_i, e_i) - k_i(A_i)A_i - te_i \tag{1}$$

where π_i denotes profit to emitter i, A_i denotes a technology available to emitter i that could be deployed in order to reduce emissions e_i ; q_i denotes the level of output chosen by emitter i ; p is an exogenous output price, as it is assumed that an emitter cannot influence the price in the output market; C_i (A_i, q_i, e_i) is a joint cost of production and abatement cost function; the product k_i $(A_i)A_i$ is the cost of investment in abatement technology, where k denotes the marginal cost per unit of increment of deployed technology;[3] t denotes the 'price' on emissions, which is equivalent to the marginal tax rate under an emissions taxation policy. In the case of a tax, the price on emissions is completely exogenous to each emitter as it is set by the regulator. However, when the policy is based on a tradable permit scheme, the price on emissions is endogenous, in a sense that it is determined by the level of emissions by individual emitters within the cap on emissions set by the regulator. The cap is exogenous to the emitters, but the price on emissions is not. In the case of tradable permits, the price on emissions is denoted as $t(e_j, A_j)$, where $j = 1, \ldots, i, \ldots, N$, is an index of emitters.

The endogeneity/exogeneity of the price on emissions is a fundamental difference between an emissions tax regulation, and a tradable permit scheme regulation. Under a tax regulation, and given the tax rate is set exogenously by the regulator, each emitter has an optimal response, which is to invest in abatement technology and/or to adjust its production plan, up to the point where the cost of reducing an additional unit of emission is just equal to the tax rate. Moreover, this optimal response is independent of the actions of any other emitters. Every individual emitter only interacts with the regulator, and not with any of the other emitters.

Things are very different under a regulation based on a tradable permit scheme. In this case, the price on emissions may appear exogenous to an individual emitter, but in fact it is determined by the production choices and investment in abatement technology of all emitters. Consequently, the abatement decisions of each emitter under a tradable permit scheme have bearing on the permit market price that affects all other emitters. This is

[3] This expression models the possibility of varying levels of abatement technology being deployed. The level of technology deployment can be continuous or discrete, as modelled in the empirical work below. The cost varies with the increments of deployed technology.

particularly significant when the emitters are heterogeneous in their production and abatement cost structures, as is normally the case in practice. Given this heterogeneity, it is difficult for an individual emitter to have a good *ex ante* assessment of the abatement cost of others, and of the position of their own abatement cost relative to those of others.

The conventionally advanced argument addressing this problem is that permit markets are reasonably competitive and that over time participants in an emissions trading scheme will gain some sense about the abatement cost structure of others by observing the market price for permits. This will allow them to adjust their own production and abatement decisions efficiently without directly observing the production and abatement cost structures of other emitters, but by making implicit inferences on the basis of the observed permit prices.

This view that relies on the permit market as a signalling device ignores two important features of actual markets. One is that for there to be a permit market, some emitters have to make their abatement and production decisions before they observe any market prices for permits. In other words, there has to be a 'first mover'. Unfortunately, there is no guarantee that this first mover is going to be making optimal abatement and production decisions, given that it has not observed any permit prices, and therefore cannot accurately assess its own abatement cost structure relative to that of others. Another feature is that abatement decisions are often irreversible and cannot be reverted in response to the observed permit price. This means that those 'first movers' that perhaps should have not invested in abatement are likely to be stuck with an irreversible investment. The disadvantage for the 'first mover' in this context has been discussed in the literature (Moretto 2000).

When these two features of actual permit markets are taken into account, it becomes likely that a socially optimal allocation of abatement across emitters is not going to materialise. The reason is that abatement and production decisions have to be made, by at least some emitters, prior to the market prices of permits becoming observable. As there is no mechanism for an individual emitter to recognise whether their own abatement costs are high or low relative to the others, individual emitters are not able to correctly calibrate their abatement decisions. Some emitters will invest in abatement technology and undertake substantial abatement when they should not, and others will not when they should.[4] One way to rectify this problem is via primary auction of permits, when the prices achieved in the primary market for permits can provide signals about relative abatement costs of individual

[4] Shobe *et al.* 2014 discuss the same phenomenon in the sense that inability to correctly calibrate abatement investment decisions '. . .harms the market's price discovery function', and sends '. . . incorrect signals about which units of abatement are worthwhile and which ones are not.' (p. 408).

emitters (see footnote 2), and consequently help emitters to correctly calibrate their decisions to invest in abatement technology.[5]

Another possible regulatory approach is to implement a temporary tax prior to the implementation of a tradable permit scheme, to provide an initial price signal to the emitters. Suppose that the regulator decides to use a mix of instruments over time: start with a tax and after some time switch to a tradable permit scheme. Let us assume that emitters only know their own cost of abatement and have no knowledge of the abatement cost of others. Further, assume that at the start of the temporary tax regulation prior to the implementation of a tradable permit scheme, the regulator sets an initial tax rate per unit of emissions. Under those circumstances, consider an individual emitter who observes the tax rate, and has to decide what to do in response. Given that they know their own abatement cost, their decision can be based on that knowledge and on the knowledge of the tax rate, without explicitly considering the expected effects of the switch to a tradable permit scheme in the future. A temporary tax over a period prior to the implementation of the tradable permit scheme can significantly lower the uncertainty about the adequacy of investing in abatement. Given the knowledge of the tax rate and their own abatement cost, emitters can optimally decide on the level of abatement, if any, that they are going to undertake.

This is in contrast to a situation under an outright tradable permit scheme, where no initial signal exists that can suggest to the emitters where they might stand in terms of abatement costs relative to others, creating the ‘first mover disadvantage’ as discussed above. Under a tradable permit scheme, an emitter would know the quantity of emissions that they will be entitled to, and their own abatement cost, but this is not sufficient information to make an optimal decision about how much to abate, if any. Additional information about where one’s own abatement costs stand relative to that of others is needed but is not available *ex ante*. That information starts becoming available once trading in permits commences. However, for trading to start, some emitters must make abatement decisions in the first place, without having sufficient information. Those decisions are not likely to be optimal.

A policy design consisting of an inter-temporal mix of a tax on emissions followed by a tradable permit scheme is theoretically expected to provide the needed additional information signal to emitters that should help induce more optimal abatement decisions. This theoretical expectation has so far not been tested empirically, and to fill this gap we conducted experimental economics study in the laboratory to test it. The experimental treatments were commensurate with the three types of regulations of interest: emissions tax; tradable permit scheme; and an inter-temporally mixed regulation

[5] Game theory literature has modelled situations similar to the one described here where outcomes for individual players are dependent on the actions of other players in a coordination game (Van Huyck *et al.* 1990; Nagel 1995). This literature has defined a notion of strategic uncertainty, which in our case pertains to the tradable permit scheme regulation, in contrast to a tax-based regulation where there is no such strategic uncertainty.

comprising of an emissions tax followed by a tradable permit scheme. These three regulations were compared in terms of optimality of decisions made by emitters to invest in abatement technology and in terms of realised permit prices in the experiment. They were also compared using an overall efficiency metric articulated as an optimal surplus (S^*), calculated as follows:

$$S^* = \sum_i \pi_i^* + GR^* - MDC \sum_i e_i^* \tag{2}$$

where the first term on the right-hand side is the aggregate profitability across all emitters, with π_i defined in Equation 1; the second term accounts for the government revenue, comprised of receipts from emissions taxes, or penalties for insufficient permits, as applicable; and the last term represents the cost of environmental damage, where MDC is the marginal damage cost. The subscript i denotes an individual emitter. The asterisk denotes a theoretically optimal level.

Based on Equation 2, and utilising the data obtained from the experiment, the performance under each of the three tested regulations was compared using the following total efficiency (TE) measure:

$$TE^m = \frac{\sum_i \pi_i + GR - MDC \sum_i e_i}{\sum_i \pi_i^* + GR^* - MDC \sum_i e_i^*} \times 100 \tag{3}$$

where the superscript m is used to index the observed levels of production, investment in abatement technology, and emissions for each of the three regulations (m = 1, 2, 3) that were tested. The higher the observed value of TE^m, the closer the regulation m is to the theoretically optimal outcome.

3. Experimental design and procedures

The design of the study was motivated by the electricity sector, one of the largest greenhouse gas emitting sectors in Australia and globally. However, the experiments were conducted without a mention of this particular context. Furthermore, the language used during the sessions was intentionally decontextualised from typical environmental or regulatory vocabulary in order to minimise the chance of association of the experimental environment with the CO2 emissions regulation that was in place in Australia at the time. Permits were referred to as *inputs* and the tax was framed as an *input price*.[6] Technology upgrades were referred to as *investments*.

The experiment was designed around eight hypothetical heterogeneous emitters. Each participant in the experiment was assigned a role of one of those eight emitters. The tasks that participants faced were to make production, investment, and permit buying/selling decisions so as to

[6] The *input price* was set to an amount different from the carbon tax that was in place in Australia at the time.

maximise their profits (Equation 1) and accordingly their own actual payoff. These decisions were to be made taking into account individual production characteristics, possibilities to invest in abatement technology, and the regulation that participants faced. Participants could form expectations about the cost of complying with regulation based on a known marginal tax rate or based on an expected price of a permit. In particular, and crucial for the key research question of this study, in the inter-temporally mixed-regulation treatment the tested hypothesis was whether the sequential implementation of an emissions tax and a tradable permit scheme improved participant's ability to form more accurate expectations about future permit prices relative to their own cost of abatement, as compared to an outright tradable permit scheme treatment.

Each participant faced the same linear production function where a unit of input could produce a unit of output and implicitly entailed emitting a unit of emissions. The maximum quantity of output that could be produced by each participant in any given period within a round of play was ten units. Participants could invest into upgrades of their production technology in order to reduce emissions. Generating emissions in this setup was articulated as using required *inputs*, as in Gangadharan *et al.* (2005). Emitters can reduce emissions either by cutting back production, by investing into a less emission-intensive technology, or both.

Participants differed by their net revenues per unit of output and consequently per unit of emission (Table 1). Based on these differences, individual emitters were characterised as 'producer types'. For any given value of net revenue to be attained, producer types described on the left-hand side of Table 1 had to produce more units of output and thereby more emissions than the producer types on the right-hand side of Table 1. For instance, to attain a net revenue of 100, producer type 2 had to emit 10 units of emissions (corresponding to 10 units of output that requires 10 units of inputs/permits), whereas producer type 8 would only need to emit 4 units of emissions (corresponding to 4 units of output that requires 4 units of input/permits). Based on this, we define emission intensity per unit of net revenue, as displayed in the second row of Table 1. Producer types 1, 2 and 3 can be consequently labelled as relatively high emission intensity producers, producer types 4 and 5 as medium emission intensity, and producer types 6, 7 and 8 as low emission intensity per unit of net revenue.

Participants could invest in a single discrete unit of abatement technology upgrade per period up to a maximum of four upgrades in a round (13 periods). Each unit of abatement technology upgrade reduces that participant's emission intensity per unit of net revenue by 10 per cent. Participants differed by their individual cost structures for abatement technology upgrades (Table 1). The high emission intensity producer types (1, 2 and 3) had relatively low nominal investment cost of technology upgrades. However, given that each technology upgrade only reduces emissions per unit of net revenue by 10 per cent, the investment cost per unit of emission intensity

Table 1 Production characteristics of participants and theoretically optimal number of abatement technology upgrades

	Producer type assigned to individual participants							
	1	2	3	4	5	6	7	8
Net revenue per unit of output (or per unit of emissions)†	7.5	10	12.5	15	17.5	20	22.5	25
Emission intensity per unit of net revenue	1/7.5	1/10	1/12.5	1/15	1/17.5	1/20	1/22.5	1/25
Cost of upgrade 1	12.5	12.5	12.5	25	25	50	75	125
Cost of upgrade 2	62.5	75	50	75	75	100	150	200
Cost of upgrade 3	112.5	137.5	150	125	125	200	225	250
Cost of upgrade 4	162.5	200	250	175	175	250	300	300
Optimal number of upgrades	0	0	0	3	3	2	1	1
Optimal expenditure on upgrades	0	0	0	225	225	150	75	125

Note: †Each unit of output requires using a unit of input, which is equivalent to a unit of emissions.

improvement was still high for these producer types. Consequently, it was optimal for these producer types not to invest in abatement technology upgrades (Table 1).[7]

Producer types 4 and 5 with medium emission intensity had low investment costs for technology upgrades, especially for the higher level of upgrades (the third and fourth upgrade). This makes them the lowest cost producer types in terms of investment cost per unit of emission intensity improvement, which in turn meant that they should invest the most in upgrades out of all producer types, optimally at three technology upgrades each. By the same token, producer type 6 should optimally invest in two technology upgrades, and producer types 7 and 8 in a single upgrade each (Table 1).

The experiments were programmed in z-Tree (Fischbacher 2007) and conducted in an experimental laboratory at the University of Sydney in the period October 2012 to April 2013. All 144 participants (Eight participants per session, six sessions per treatment and three treatments) that took part in the experiment were students at the University of Sydney who were recruited via the University's ORSEE database of student volunteers (Greiner 2004). Each of the three treatments was replicated in six experimental sessions; a total of 18 experimental sessions were conducted. Each participant took part in only one session. An experimental session consisted of four rounds. Each of the 13 periods in a round consisted of a series of stages as summarised in Table 2. All four rounds in a session were identical in that the same treatment and producer characteristics were induced for the duration of the whole experimental session. The reasons for conducting four identical rounds per experimental session were to allow for sufficient time and repetition of tasks so that participants become proficient in performing the tasks they were

[7] The theoretically optimal investment in abatement technology in terms of optimal number of upgrades and optimal expenditure on upgrades is given in the last two rows of Table 1.

required to perform. In addition, the repetition of four identical rounds allowed the researchers to observe the effects of learning over consecutive rounds and to discern these effects from the treatment effects. This is discussed in more detail in section 4.4 below.

The first five periods of each round comprised a pre-liability phase in which participants were free to choose a level of production without facing any costs associated with emissions. Participants could also make investments in technology upgrades in anticipation of regulation on emissions that takes effect in subsequent stages of the experiment. This pre-liability phase was designed so that participants can become familiarised with their production and emissions characteristics (i.e. how much input is needed to produce output) and with their investment options in abatement technology (i.e. how much it costs them to undertake technology upgrades, and by how much incremental upgrades reduce emissions). This allows participants to carefully consider the decisions about production and investment in abatement without the pressure of being exposed to a regulation. The experimental environment was relatively complex, and these five 'training' periods were introduced as a pre-liability phase in order to avoid participants making erroneous decisions in the liability phases due to unfamiliarity with the characteristics of the roles that they are playing.

Table 2 Description of the decision stages within a period in the experiment

Decision stage	Procedures
Investment stage (60 seconds)	Each production level required a certain number of inputs. The inputs are costless in the pre-regulation phase, and costly in the regulation phase. The costs of these inputs represent a component of production costs attributable to the cost of emissions. At the start of the second period, and at the start of all subsequent periods, producers could invest in a technological upgrade that would reduce their emissions intensity by 10%. Producers could select at most one incremental upgrade per period and up to four upgrades in total per round. Choosing the maximum of four upgrades would give a cumulative 40% reduction in required inputs. All upgrades lasted for the remaining periods in the round and were irreversible.
Production and trading stage (60 seconds)	Participants selected a production level between 0 and 10 each period. Participants knew their input costs and revenues associated with each production level. In the treatments with trading, a single-unit double auction for inputs was also active during this stage. Participants placed bids and asks, and transacted within the trading period. Each bid or ask was for a single input. The best current bid and ask were displayed on the screen at all times. To execute a trade, buyers or sellers clicked on the bid or ask that they were willing to transact for. A record of each transacted price from the current period was displayed on participants' screens.
Summary stage (15 seconds)	Participants were shown a summary of their personal performance for the previous period and the cumulative number of upgrades undertaken by all producers up to date.

The emissions regulation was implemented from period 6 onwards in each round (Table 3). In each of the 13 periods within a round, participants had the task of selecting a production level in order to generate revenue.[8] The choice of production level directly implied a given level of emissions that was articulated as an *input* (Appendix S3, Screenshot 1). In addition to the task of choosing a production level, from period 2 onwards participants had an opportunity to invest in abatement technology upgrades (Appendix S3, Screenshot 2). At the end of each period they received information about the total number of technology upgrades (*investments*) undertaken by all participants in that round (Appendix S3, Screenshot 3). During the regulated phase of the tax-only treatment (periods 6–13, Table 3), a tax on emissions was applied, articulated as a 'price for insufficient inputs'. Participants could see this information and the corresponding reduction of their balance, but there were no additional tasks that they could undertake in this regard. The same occurred in the mixed-regulation treatment during the tax component of the regulated phase (periods 6–8, Table 3). Participants faced an additional task of trading permits (*inputs*) in the trade phase of the mixed-regulation (periods 9–13, Table 3), and during the whole regulated phase of the trade-only treatment (periods 6–13, Table 3). This task involved participating in the single-unit double auction for permits by placing bids to buy permits or ask price to sell permits (Appendix S3, Screenshot 4).

The information given to participants that described their own production characteristics (net revenues, cost of investing in technology upgrades, and their profits) was completely private. On the other hand, the information on the total number of abatement technology upgrades undertaken by all participants, and the information related to permit trading – such as the highest current bid price and lowest current ask price – and the quantity and price of traded permits, were provided publicly.

In the treatments with tax (tax-only and mixed regulation) the tax rate was set at the level of E$16 to induce optimal emissions of 320 units on aggregate over the periods 6–13 (eight periods). The optimal aggregate emissions were computed at the point where the sum of the cost of reducing emissions and the cost of environmental damages from emissions was minimised. The environmental damage cost was modelled as a linear function of emissions, ensuring *ex-post* optimality of the tax rate.

In the treatments with trading (trade-only and mixed regulation), five emissions permits per period were allocated to each participant starting in the initial period when trading of permits became active under the specific regulation. This was commensurate with the theoretically optimal level of emissions of 40 per period (eight participants times five permits), which was the same under all three regulations considered. A single-unit double auction was implemented as the permit trading mechanism due to its low transaction

[8] Screenshots of computer screens as displayed by ZTree software that participants were looking at can be found in the Appendix S3.

Table 3 Description of experimental treatment

Treatment	Non-liability phase (Periods 1–5)	Regulated phase (Periods 6–13)	
Tax-only	Pre-liability	Tax	
Mixed (Staged transition)	Pre-liability	Tax (Periods 6–8)	Trade (Periods 9–13)
Trade-only	Pre-liability	Trade	

costs and easily understood and utilised design, particularly the ease of placing and accepting bids and asks.[9] Figure 1 represents the theoretically predicted permit equilibrium price under the optimal investment. Given that a primary aim was to study the efficiency under alternative regulations for controlling emissions, care was taken not to induce a narrow permit price range, as it could result with inefficient outcomes occurring during the emissions permit trading phases. Therefore, a relatively wide permit price range was induced to facilitate efficient exchange of permits at a wide spectrum of prices.

If a participant held less than the required number of permits at the end of a period, a fine of E$32 was levied for each insufficient permit. This was observed in 14 per cent of permit trading periods amounting to a shortage of 1.3 and 1 permits on average per period under the trade-only and mixed-regulation treatments, respectively.

On entering the lab, each participant was randomly assigned a role of one of the eight producer types (Table 1). Comprehensive experimental instructions were shown in a video and complemented by a hard copy.[10] After viewing the video, participants retained the written instructions and completed a quiz to demonstrate their understanding of the tasks.

Participants' earnings were calculated based on their performance in all four rounds. Participants were privately informed of their personal exchange rates before the beginning of the session. The Experimental dollars to Australian dollars exchange rate was adjusted according to the characteristics of a specific producer type of a participant, so that in equilibrium each participant had equal opportunity to earn a A$30 performance-based payout.[11] In the actual experiment, participants earned an average of

[9] Smith (1962) provides extensive evidence that double auctions elicit best-possible market results in experimental environments. However, Camacho-Cuena *et al.* (2012) suggest that the type of auction used after an initial distribution of permits does not have a significant effect on the pattern of technology adoption in an experimental environment similar to the one reported in this paper.

[10] The video instructions are available to view online: tax treatment (http://youtu.be/zJvOwsEbuHo), emissions trading treatment (http://youtu.be/E8UdoCjbMTA), hybrid treatment (http://youtu.be/o904wrJqBwo), input trading (http://youtu.be/XO09KoVHp2k). We included the text of the instructions in Appendix S2.

[11] Australian dollar to US dollar exchange rate at the time when the experiment was conducted (i.e. late 2012, early 2013) was about 1:1.

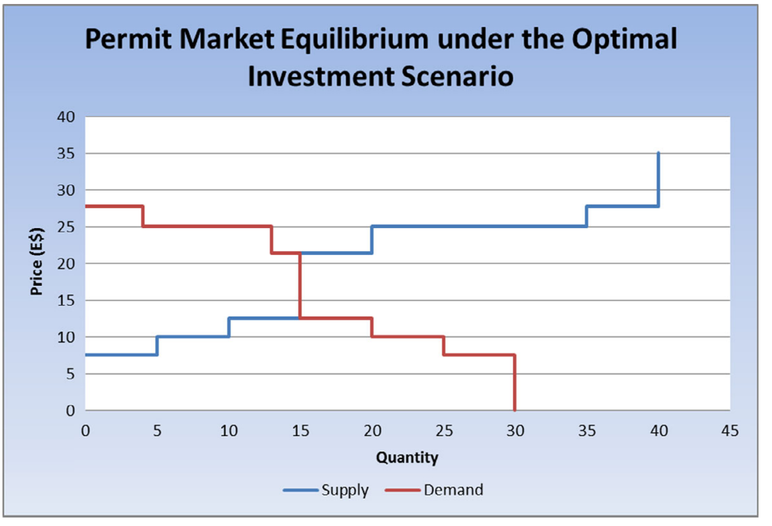

Figure 1 Equilibrium in the permit market under the optimal investment scenario*. * The market equilibrium price range is in the interval from E$12.50 to E$21.43. [Colour figure can be viewed at wileyonlinelibrary.com]

A$24.35 in addition to the A$10 participation fee for a total of A$35.35 over a session that lasted one-and-a-half hours.

4. Results

This section reports the findings from the experimental sessions that are used to compare the three alternative regulatory treatments: tax-only, tradable permit scheme only, and inter-temporally mixed regulation (staged transition from tax to tradable permits). Comparisons were conducted in terms of optimality of investment in abatement technology, overall efficiency of regulation, and in terms of observed market prices for emission permits. A standard Wilcoxon–Mann–Whitney two-sample rank-sum test was used to test the significance of the observed differences in these outcomes between treatments. Significance of these results was double checked with a robust Fligner-Policello (FP) test for differences in the medians of treatments (Fligner and Policello 1981).[12] P-values reported throughout this section are based on the Wilcoxon-Mann-Whitney tests. Significance refers to $P \leq 0.05$ as validated by the robust FP test unless otherwise noted. In addition, a regression analysis was used to test whether there is a difference in the level of departure from the theoretically optimal investment in abatement technology

[12] Asymptotic p-value provided by the FP test may not be adequate when the sample size of each treatment is less than 12. In this case, Fligner and Policello provide critical values of significance. The asymptotic p-values generated in Stata 11 using the FPRank module (Benmamoun (2006)) that are presented here have been cross-referenced with these small-sample critical points. Actual values of the conducted Wilcoxon–Mann–Whitney tests are available from the authors upon request.

upgrades across the production types (high, medium, and low cost of improving emission efficiency) and across the three tested regulations.

4.1 Investment in abatement

Comparisons along investment behaviour were particularly important for this study, as the key effect from implementing a tax before rolling out a tradable permit scheme is to induce emitters to more accurately determine their optimal investment in abatement. The effectiveness of investing in technology upgrades was evaluated via the difference between the observed and the theoretically optimal level of investment in technology upgrades. As described in Table 1, the theoretically optimal level of investment implied that some participants – those with high cost of improving emission intensity – should not invest in technology upgrades at all, while others – those with low costs of improving emission intensity – should invest considerable amounts. The theoretically optimal sets of investment levels, as given in Table 1, were identical for all three treatments. The individual optimal levels of investment for each producer type were also identical in all treatments subject to optimal market prices of the traded permits.

The propensity of participants in economics experiments in a laboratory to overact or over enter (in the present context, overinvest) as documented by Gangadharan and Nemes (2005) and Camacho-Cuena *et al.* (2012) was also observed in this experiment. This phenomenon of over entry has been documented in market entry games (Rapoport 1995; Erev and Rapoport 1998) especially under certain parametrisations of the market characteristics (Camerer and Lovallo 1999). In addition, experiments on auctions with endogenous entry also exhibit over entrance as a commonly observed outcome (Aycinena *et al.* 2016). In our case, this behaviour is exhibited by participants who invested in aggregate abatement more than they should have in all three treatments.

Aggregate number of, and expenditure on, abatement technology upgrades were consistently higher and further away from the optimum under the trade-only treatment than under the mixed-regulation or tax-only treatments (Table 4 and Table 5). This implies that participants formed expectations for higher permit prices under the trade-only treatment, compared to the expectations formed under the mixed regulation. It is an indication that the mixed regulation that starts with a tax and transforms into a tradable permit scheme could help emitters form more accurate expectations about permit prices, which in turn enables them to make better decisions about investment in abatement technology upgrades.

The observed abatement technology upgrade decisions over the four rounds of the experiment demonstrate that participants learn with experience. Aggregate number of upgrades and investment expenditure move closer towards the theoretically optimal level across the four rounds under all treatments (Table 4 and Table 5). Nevertheless, the expenditures are

Table 4 Average aggregate expenditure on investment in abatement by round and treatment (standard deviations in parentheses)

Treatment	Round				Optimal	Overall average by treatment
	1	2	3	4		
Tax-only	3042 (469)	2329 (726)	1819 (707)	1521 (422)	800	2178 (810)
Mixed (Staged transition)	2979 (663)	2304 (358)	1738 (355)	1592 (553)	800	2153 (727)
Trade-only	2933 (649)	2373 (787)	1821 (750)	1667 (814)	800	2198 (868)

Table 5 Average number of aggregate technology upgrades by round and treatment (standard deviations in parentheses)

Treatment	Round				Optimal	Overall Average by Treatment
	1	2	3	4		
Tax-only	26 (2.9)	19.33 (5.4)	15.33 (3.4)	13.83 (1.5)	10	18.63 (5.9)
Mixed (Staged transition)	25.67 (3.4)	19 (3.0)	14.83 (1.0)	14 (2.8)	10	18.38 (5.3)
Trade-only	25.83 (2.8)	21.83 (5.0)	18.83 (5.2)	17 (5.7)	10	20.88 (5.6)

considerably higher than the theoretical optimum even in the tax-only treatment, which was closest to the optimum in the final round. As discussed above, this can be attributed to the noted propensity of participants in economics experiments in the lab to overact (Gangadharan and Nemes (2005) and Camacho-Cuena *et al.* (2012)).

In light of the tendency for participants to overact, it is important to consider the role that risk aversion and regret might play in decision making. As we did not measure individual risk preferences in this study, it is not possible to identify the effects of risk aversion, if they exist. However, we do not believe that risk aversion can explain observed behaviour here. With risk-averse participants, we would expect to observe underinvestment rather than overinvestment. Given the framing of our experiment, it is straightforward for participants to avoid losses from insufficient inputs, and we indeed observe that the participants succeed in that. In the tax-only treatment, if the net revenue per input is lower than the tax, one simply can choose not to produce. In the trade-only treatment, one could easily avoid substantive financial penalties for insufficient inputs since the production levels can be adjusted until the very last second of each period. Such experimental framing limits confounding effects due to uncertainty of compliance. Also, while the participants are choosing production levels to maximise their net revenues, a decision to invest introduces a risk of potential losses. A participant could experience a loss if profits from additional production would not cover the investment costs for technology upgrade. Therefore, if anything, our experimental evidence implies that the participants who overinvest might be risk takers.

We also find that ‘regret’ is nearly impossible to discern from ‘learning’ (section 4.4 below). Under the experimental setup, participants could easily both under- or overinvest. Overinvestment can induce regret through the realisation that one could have spent less on abatement. Underinvestment can induce regret as the participant forgoes potential net revenues due to the lack of inputs.

We find that as participants go through more rounds and gain more experience along the way, they actually tend to invest less in abatement technology (see Table 6, estimated coefficients on ‘Round’); that is, the difference between observed and theoretically optimal abatement investment decreases. This result could be interpreted as being consistent with both learning and regret.

Looking at the individual level, participants with high costs of improving emission intensity (those who should not have invested at all in order to maximise their profits, i.e. producer types 1, 2 and 3 in Table 1) invested significantly more in abatement technology upgrades under an outright tradable permit regulation relative to the mixed regulation (two-tailed $P \leq 0.01$) (Figure 2). The investment decisions of participants with moderate costs of improving emission intensity (producer types 6, 7 and 8 in Table 1) did not vary significantly across treatments. Participants with the lowest cost of improving emission intensity (producer types 4 and 5 in Table 1) invested closest to the optimum, and their investment decisions did not vary significantly across treatments. This is an important result as it indicates that a tax predating a tradable permit scheme is particularly beneficial for adjusting expectations of emitters with high emission intensity who face high costs of improving that intensity, and less useful for those emitters who have lower emission intensity and can improve that intensity at low cost. In combination with the finding that overall investment activity is closer to the optimum under the mixed regulation than under the trade-only regulation, it suggests that the benefits to the high emission intensity emitters from the extra information carried by the tax predating a tradable permit scheme could be substantial.

In order to further examine this point, a regression analysis was conducted to evaluate the effects of regulation on abatement investment decisions of participants of particular type. The difference between the observed investment in abatement technology upgrades made by an individual participant and the theoretically calculated optimal number of upgrades for the producer type assigned to that participant (Table 1) was the dependent variable in the

Table 6 Results from a regression analysis (dependent variable: difference between observed and theoretically optimal number of upgrades in abatement technology)

	Estimated coefficients
Constant	1.90***
	(0.22)
Regulation	
Tax-only	−0.23
	(0.29)
Trade-only	−0.25
	(0.29)
Cost of improving emission intensity	
High	0.55**
	(0.26)
Low	0.60**
	(0.26)
Cost × regulation	
High cost	
Tax-only	−0.104
	(0.37)
Trade-only	1.29***
	(0.37)
Low cost	
Tax-only	0.22
	(0.37)
Trade-only	0.04
	(0.37)
Round	−0.35***
	(0.03)
Log likelihood	−826.7904
n	576

Note: Standard errors in parentheses. Significance is identified by asterisks: *indicates $P < 0.1$, **$P < 0.05$, ***$P < 0.01$.

regression analysis.[13] The dependent variable was regressed on the following indicator variables: regulation type (tax-only, trade-only, and mixed regulation); cost of improving emission intensity: high costs (producer type 1, 2 and 3), low costs (producer type 4 and 5), and medium costs (producer type 6, 7 and 8); an interaction term between these two indicator variables; and an experimental round (round 1, 2, 3 and 4). The mixed regulation, the medium cost producer type and round 1 were treated as baselines. The regression equation is specified as follows:

$$(A_{i,g} - A^*_{i,g}) = \beta_0 + \beta_1 D_{1,i,g} + \beta_2 D_{2,i,g} + \beta_3 (D_{1,i,g} x D_{2,i,g}) + \beta_4 D_{4,i,g} + \varepsilon_{i,g} \tag{4}$$

where A_i denotes the observed investment in abatement technology upgrades made by participant i, in experimental session g, and asterisk denotes the optimal investment in technology upgrades. The betas are the coefficients to

[13] Data for experimental periods 2 through to 13 were used in the regression analysis, as participants could make abatement investment decisions in each of those periods.

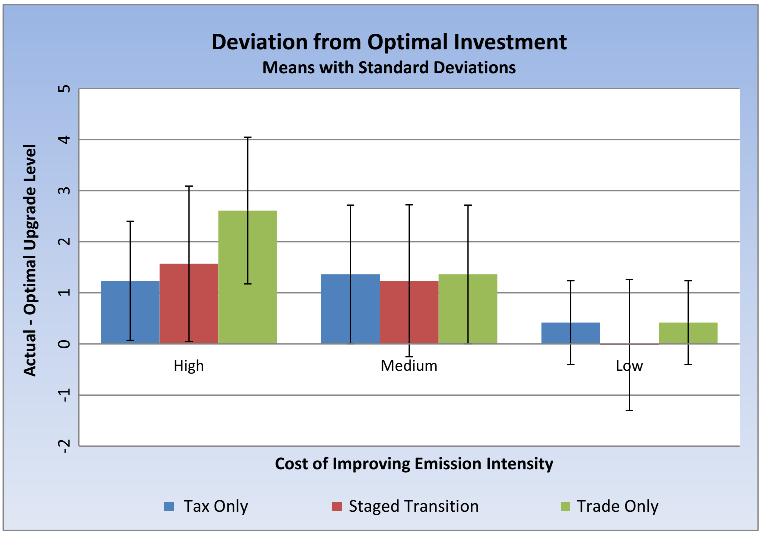

Figure 2 Difference between actual and theoretically predicted number of investment upgrades for the three types of regulation. [Colour figure can be viewed at wileyonlinelibrary.com]

be estimated. $D_{1,i,g}$ is an indicator variable for the regulation type (tax-only, trade-only, and mixed regulation), $D_{2,i,g}$ is an indicator variable for the costs of improving emission intensity (high, low and medium), and $D_{4,i,g}$ is an indicator variable for the experimental round (rounds 1, 2, 3 or 4). We estimated the regression with a maximum likelihood estimation procedure using clustered standard errors estimator (Cameron and Miller 2015). The errors were clustered by an identifier for the experimental session (g), in order to isolate any effects that might have occurred in individual sessions.
The results from the regression estimation are reported in Table 6. They are in line with the findings reported above based on comparisons using the non-parametric tests, confirming the previous finding that emitters who faced high costs of improving emission intensity made investment decisions closer to the optimum under the mixed regulation, as opposed to the trade-only regulation. This is evidenced by the magnitude of the estimated coefficient on the interaction term between the trade-only regulation and the high cost indicator variable, which is also highly statistically significant (Table 6). This result further strengthens the finding that implementing an inter-temporally mixed regulation comprised of a tax followed by a tradable permit scheme is likely to help high intensity emitters to better calibrate their expectations about permit prices, and to consequently make more accurate abatement technology investment decisions.

4.2 Overall efficiency

The efficiency measure presented in Equation 3 was computed using data from the experimental treatments corresponding to the three regulations that were tested. A high efficiency score indicates an observed outcome that is close to the theoretically optimal outcome and vice-verse for a low efficiency score. Overall efficiency was consistently higher under the inter-temporally mixed regulation than under trade-only regulation (Figure 3). These findings conform well to the expectations and to the theoretical predictions that the inter-temporally mixed regulation would be at least as efficient as an outright tradable permit regulation.

In addition, under the tax-only treatment participants achieved significantly higher efficiency levels than under the trade-only treatment (one-tailed $P \leq 0.05$ for rounds 1, 2, 3; $P \leq 0.1$ for round 4) and marginally significantly higher efficiency than under the mixed regulation (one-tailed $P \leq 0.1$ for rounds 2, 3 and 4) (Figure 3).

4.3 Permit prices

Mean transaction prices observed in the permit market (Table 7) were within the theoretically predicted permit price range under both regulations that involved permit trading. Average permit prices under the mixed regulation and trade-only regulation were somewhat higher than the tax rate under the tax-only regulation (E$16), whereas it is theoretically expected that permit prices should converge to the tax rate given that all the parameters were the same across the treatments. Indeed, we observe such convergence in round 4 of the mixed regulation, where the permit price is only marginally and not statistically significantly higher than E$16 (Table 7).

However, transacted prices for permits were significantly higher on average in the trade-only treatment than in the mixed-regulation treatment (one-tailed $P \leq 0.05$ for round 1) (Table 7). As is evident from Table 7, participants had

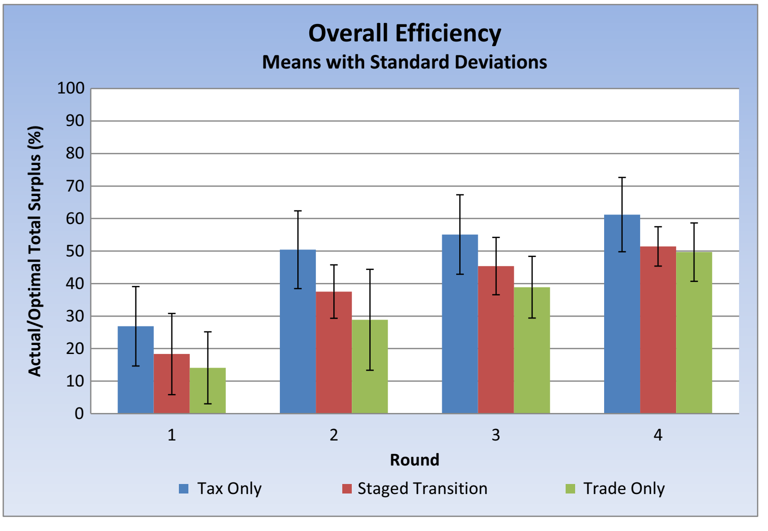

Figure 3 Overall efficiency of the three types of regulation. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 7 Average permit prices under the staged transition and trading only treatments by round (standard deviations in parentheses)

Treatment	Round				Overall average by treatment
	1	2	3	4	
Mixed (Staged transition)	17.71 (3.21)	17.29 (3.95)	17.04 (3.46)	16.74 (3.78)	17.20 (3.39)
Trade-only (All Periods)	21.69 (3.30)	19.97 (3.16)	19.15 (2.69)	17.79 (4.09)	19.65 (3.44)
Trade-only (first 5 trading periods)	21.06 (3.60)	20.75 (3.70)	19.65 (2.59)	18.05 (3.85)	19.88 (3.45)

formed expectations of significantly higher permit prices under the trade-only regulation compared to the mixed regulation. This is most evident in round 1, when the difference in permit prices between trade-only and mixed regulation is some 3-4 experimental dollars. With participant learning, this difference reduced to only one experimental dollar in round 4. This discrepancy indicates that initial expectations about permit prices tend to be much more inflated under the trade-only regulation. It also indicates that the tax component of the mixed regulation helps participants to form more accurate understanding about the relative position of their own costs of improving emission intensity and the expected permit price.

To conduct further comparison on an even more 'like-to-like' basis between the mixed regulation and trade-only regulation, we look only at the first five trading periods under the trade-only regulation (Table 7, last row). In this way, we can compare the observations on permit prices in the five initial periods of trading under both mixed and trade-only regulation. For the mixed regulation, those are periods 8–13, and for the trade-only regulation, those are periods 6–10. This allows us to examine the effects of a tax implemented prior to permit trading taking place as opposed to implementing tradable permits outright. The results show that average permit prices tended to be significantly higher (i.e. further away from the optimum) in the first five trading periods of the trade-only treatment compared to the mixed-regulation treatment. Moreover, the difference in average permit prices is much greater between the first five trade-only periods and mixed regulation then the difference between the first five trade-only periods and all trade-only periods (Table 7). This is further evidence that the treatment that included a tax prior to implementing a tradable permit scheme enabled the participants to make decisions closer to the optimum, which resulted in lower permit prices reflecting the overall lower abatement cost.

4.4 Learning

The experimental design provided ample opportunity for learning and information gathering by participants over the four rounds of an experimental session. Learning, as measured by participants' propensity to invest closer to theoretically optimal predictions, occurred faster in the tax-only and mixed regulation than in the trade-only treatment (Tables 4 and 5). This is evidenced by the marginally significant difference in aggregate technology upgrade expenditures between the first two rounds in the tax-only (two-tailed $P \leq 0.1$) and in the mixed regulation ($P \leq 0.1$), but no significant reduction in expenditure under the trade-only regulation ($P \geq 0.1$) (Table 4). Similar trends are observed between the second and third rounds and between the third and fourth rounds (Table 4).

It was expected that learning would occur in all treatments, but the extent and speed of learning was expected to vary across the three treatments. The experimental results are in line with these expectations. Observed learning occurred faster in the tax-only and mixed regulation than in the trade-only regulation. Case in point is the aggregate number of average technology upgrades (Table 5), where the observed behaviour was very similar in the first round across all three treatments (investment in around 26 upgrades). However, the behaviour changed sizably in magnitude, but without statistical significance in the subsequent rounds for the tax-only and the mixed regulation, moving quickly in the direction of the theoretically optimal behaviour (i.e. investment in 10 upgrades). This change occurred much more slowly under the trade-only regulation, where average aggregate number of abatement technology upgrades remained high in the second and third rounds and did not approach optimum even in the fourth round. Observing these differential dynamics across treatments allows us to discern the effects of learning from the treatment effects. Each experiment offered an equal number of repeated rounds and thus equal opportunities for learning. However, the learning outcomes are much poorer under the trade-only regulation than under the other two regimes.

This is likely due to the limited capacity of participants to form accurate expectations about permit prices in the trade-only regulation, and subsequently their inability to correctly calibrate investment decisions in abatement technology under this regulation. This impedes and slows down their learning process. The implication for actual permit markets is significant: the argument that over time participants in emissions trading schemes will be able to work out how their own abatement cost structure stands in relation to others by observing the competitive market price for permits is supported by the empirical evidence gathered here. However, the empirical evidence suggests that this argument holds much more strongly for an inter temporally mixed regulation where the exposure to a tax in the early stages of the regulation allows participants to make adjustments much faster and with much less variability compared to an outright tradable permit regulation.

5. Conclusion

In light of the potentially strong political backlash associated with an emissions tax, and the uncertainty associated with tradable permit schemes, a new type of inter-temporally mixed GHG emissions regulation consisting of a staged transition from a tax to a tradable permit scheme has been proposed and indeed partially implemented in Australia. This paper evaluates this new regulatory approach *vis-a-vis* the more traditional tax-only and tradable permit-only regulations on a range of criteria of interest, including optimality of investment in abatement technology, overall regulation efficiency, and prices in permit markets. The comparisons were undertaken through economics experiments conducted in a computer laboratory. The findings indicate that a mixed regulation may enable emitters to make better investment decisions in abatement technology and may bring about greater overall efficiency and lower permit prices when compared to a tradable permit scheme implemented outright.

The overall efficiency under the mixed regulation was greater than the efficiency under the trade-only regulation. The key driver of this are the non-optimal investments in abatement technology made by emitters. Emitters with high costs of improving emission intensity were found to invest heavily in abatement when they should not have, especially under the trade-only regulation. This is adversely affecting the permit market, eliminating the opportunities for low cost emitters to abate the most, as their abatement is crowded out by the abatement carried by high abatement cost emitters. The result is low overall efficiency realised under the trade-only regulation.

Findings from the mixed-regulation treatment were an improvement on the trade-only regulation. The existence of an emission tax prior to the introduction of a tradable permit scheme significantly improved the ability of participants to make abatement investment decisions that were more in line with the theoretical optimum. This subsequently resulted in lower permit prices, and higher overall efficiency under the mixed regulation when compared to the trade-only regulation. The mixed regulation is particularly beneficial to those emitters that have relatively higher costs of improving emission intensity, as it helps them to better calibrate their decisions about investment in abatement technology. Under the trade-only regulation, emitters with high costs of improving emission intensity tend to invest in abatement much more than they should. The excess investment in high cost abatement results with high cost of permits as permit prices reflect the abatement costs, and subsequently with lower efficiency. The mixed regulation rectifies this problem by incorporating a more accurate price-signalling device (the tax rate) in the early stages of the regulation.

The fundamental reasons for this overall performance of the mixed regulation relative to the trade-only regulation are more profound. They are related to the differences between an emissions tax regulation and a tradable permit scheme regulation in terms of the strategic interactions among emitters. These differences are general and not specific to the experiment reported in this paper. In general, under a tax regulation, there are no strategic interactions among emitters – the behaviour of one emitter does not affect the outcomes that other emitters face. From a perspective of an individual emitter the only strategic interaction is with a regulator. This is very different under a tradable permit scheme regulation where non-optimal decisions of some individual emitters prior to, or in the early stages of, regulation's implementation affect the outcomes for the other emitters irrespective of the optimality of those emitters' own actions. Put differently, under a tradable permit scheme, emitters have to form expectations about what other emitters will do, as everyone will be affected by everyone else's decisions via the permit price. Irreversibility of investment in abatement technology makes this problem even more serious. This general situation is also apparent in our experiment, where overinvestment in abatement by high cost emitters significantly affects the outcomes for all. The strategic difference between an emissions tax regulation and a tradable permit scheme in the context of optimality of investment in abatement has not drawn much attention in the literature thus far, but in the light of the findings of the current paper, further investigations in this direction are warranted.

The findings in this paper suggest that the use of a fixed price instrument such as an emissions tax, prior to the introduction of a tradable permit scheme is likely to be a good policy, as it is likely to reduce the total social costs of regulation. The benefits of this policy are particularly apparent in the short run, as it provides signals to emitters about the adequacy of investment in abatement technology and about expected permit prices in the future. In the long run, a tradable permit scheme may well be a regulatory instrument of choice, but the inefficiencies as a result of non-optimal decisions made prior to, or in the early stages of its implementation could be alleviated by an introductory emissions tax.

Like other empirical studies, and in particular experimental economics studies, the present work has several limitations that should be taken into account when interpreting the findings. Specifically, the results are derived from experiments where there were only few market participants, which might influence the results, even though the relatively large number of replications of individual treatments (six replications) should mitigate this issue to some extent. In addition, some of the design features (e.g. the discrete nature of the abatement cost curve, or the absence of banking of permits) that were implemented in order to simplify the experimental procedure might not represent adequately situations in real markets. Also, the dynamics of the global optimum outcomes are not further investigated in this paper. There was a global optimum for the experiment *ex ante*. However, once participants started to make decisions, some of which are clearly not optimal, there is a new global optimum contingent on those past sub-optimal decisions. Taking into account these iterative optima in a dynamic way would require further careful and extensive modelling, which was well beyond the scope of this paper, but it is something worth pursuing in future research.

Notwithstanding these limitations, this study provides useful findings that can be drawn upon in practical applications by pollution regulating agencies, legislators and businesses, as it sheds light on the benefits that a regulation based on an inter-temporal policy mix, consisting of an emissions tax predating a tradable permit scheme, could bring to a wide swath of stakeholders. Key benefits of the inter-temporal policy mix regulation are that it allows achieving GHG abatement at lower costs compared to the tradable permit regulation only and is more politically palatable than a tax-only regulation. These benefits suggest that the policy mix regulation could deliver significant reduction in GHG emissions in those jurisdictions that apply it. Curbing GHG emissions effectively on a global scale requires creative solutions: applications of innovative regulatory approaches, such as the inter-temporally mixed regulation investigated here, may be a step forward in that direction.

Data availability statement

Data available on request from the authors: The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Aldy, J. and Stavins, R. (2012). The promise and problems of pricing carbon: theory and experience, *The Journal of Environment & Development* 21, 152–180.

Aycinena, D., Gomberg, A., Elbittar, A. and Rentschler, L. (2016). When should the jurors talk? An experimental study of timing and information acquisition, PET 16 Conference, Rio de Janeiro.

Betz, R. and Gunnthorsdottir, A. (2009). Modeling emissions markets experimentally: The impact of price uncertainty. Paper presented at the 18th World IMACS / MODSIM Congress, Cairns, 13-17 July 2009.

Betz, R. and Sato, M. (2006). Emissions trading: lessons learnt from the 1st phase of the EU ETS and prospects for the 2nd phase, *Climate Policy* 6, 351–359.

Betz, R., Seifert, S., Cramton, P. and Kerr, S. (2010). Auctioning greenhouse gas emissions permits in Australia, *The Australian Journal of Agricultural and Resource Economics* 54, 219–238.

Bruvoll, A. and Larsen, B.D. (2004). Greenhouse gas emissions in Norway: do carbon taxes work? *Energy Policy* 32, 493–505.

Bullock, D. (2012). Emissions trading in New Zealand: development, challenges and design, *Environmental Politics* 21, 657–675.

Camacho-Cuena, E., Requate, T. and Waichman, I. (2012). Investment incentives under emission trading: an experimental study, *Environmental and Resource Economics* 53, 229–249.

Camerer, C. and Lovallo, D. (1999). Overconfidence and excess entry: an experimental approach, *American Economic Review* 89, 306–318.

Cameron, C.A. and Miller, D.A. (2015). A practitioner's guide to cluster-robust inference, *Journal of Human Resources* 50, 317–372.

Cason, T.N. (2010). What can laboratory experiments teach us about emissions permit market design? *Agricultural and Resource Economics Review* 39, 151–161.

Cason, T.N. and Plott, C.R. (1996). EPA's new emissions trading mechanism: a laboratory evaluation, *Journal of Environmental Economics and Management* 30, 133–160.

Conefrey, T., Fitz Gerald, J.D., Valeri, L.M. and Tol, R.S. (2013). The impact of a carbon tax on economic growth and carbon dioxide emissions in Ireland, *Journal of Environmental Planning and Management* 56, 934–952.

Cramton, P. and Kerr, S. (2002). Tradeable carbon permit auctions: How and why to auction not grandfather, *Energy Policy* 30, 333–345.

Cronshaw, M.B. and Kruse, J.B. (1999). An experimental analysis of emission permits with banking and the Clean Air Act Amendments of 1990, *Research in Experimental Economics* 7, 1–24.

de Vries, F.P. and Hanley, N. (2016). Incentive-based policy design for pollution control and biodiversity conservation: a review, *Environmental and Resource Economics* 63, 687–702.

Downing, P. and White, L. (1986). Innovation in pollution control, *Journal of Environmental Economics and Management* 13, 18–29.

Erev, I. and Rapoport, A. (1998). Coordination, "magic", and reinforcement learning in a market entry game, *Games and Economic Behavior* 23, 146–175.

Fischbacher, U. (2007). z-tree: Zurich toolbox for ready-made economic experiments, *Experimental Economics* 10, 171–178.

Fligner, M.A. and Policello, G.E. (1981). Robust Rank Procedures for the Behrens-Fisher Problem, *Journal of the American Statistical Association* 76, 162–168.

Friesen, L. and Gangadharan, L. (2013). Environmental markets: what do we learn from the lab? *Journal of Economic Surveys* 27, 515–535.

Gangadharan, L., Farrell, A. and Croson, R. (2005). Investment decisions and emissions reductions: results from experiments in emissions trading, in List, J.A. and Price, M.K. (eds), *Handbook on Experimental Economics and the Environment*. Edward Elgar Publlishing, Cheltneham, UK, pp. 233–264.

Gangadharan, L. and Nemes, V. (2005). Impact of risk and uncertainty in the provision of local and global environmental goods: An experimental analysis. Research Paper 956. Department of Economics, University of Melbourne.

Garcia, A., Leal, M. and Lee, S.-H. (2018). Time-inconsistent environmental policies with a consumer-friendly firm: tradable permits versus emission tax, *International Review of Economics and Finance* 58, 523–537.

Goulder, L.H. and Schein, A.R. (2013). Carbon Taxes versus cap and trade: a critical review, *Climate Change Economics* 4, 1350010.

Greiner, B. (2004). *An Online Recruitment System for Economic Experiments*. Forschung und wissenschaftliches Rechnen 2003. V. M. E. Kurt Kremer. Ges. für Wiss. Datenverarbeitung, Göttingen, pp. 79-93.

Hahn, R. and Stavins, R. (2011). The effect of allowance allocations on cap-and-trade system performance, *Journal of Law and Economics* 54, S267–296.

International Emissions Trading Association (IETA). (2013). The World's carbon markets: a case study guide to emissions trading: Switzerland. Available from URL: http://www.ieta.org/assets/Reports/EmissionsTradingAroundTheWorld/edf_ieta_switzerland_case_study_may_2013.pdf. [accessed 15 Sep 2014].

Keohane, N.O. and Olmstead, S.M. (2016). *Markets and the Environment*. Island Press, Washington, DC.

Krysiak, F. and Oberauner, I. (2010). Environmental policy à la carte: letting firms choose their regulation, *Journal of Environmental Economics and Management* 60, 221–232.

Liao, C.N. (2007). Modelling a mixed system of air pollution fee and tradable permits for controlling nitrogen oxide: a case study of Taiwan, *The Australian Journal of Agricultural and Resource Economics* 51, 475–490.

Malueg, D. (1989). Emission credit trading and the incentive to adopt new pollution abatement technology, *Journal of Environmental Economics and Management* 16, 52–57.

Milliman, S. and Prince, R. (1989). Firm incentives to promote technological change in pollution control, *Journal of Environmental Economics and Management* 17, 247–265.

Moretto, M. (2000). Irreversible investment with uncertainty and strategic behavior, *Economic Modelling* 17, 589–617.
Muller, A. and Mestelman, S. (1998). What have we learned from emissions trading experiments? *Managerial and Decision Economics* 19, 225–238.
Nagel, R. (1995). Unraveling in guessing games: an experimental study, *The American Economic Review* 85, 1313–1326.
Pizer, W. (2002). Combining price and quantity controls to mitigate global climate change, *Journal of Public Economics* 85, 409–434.
Rapoport, A. (1995). Individual strategies in a market entry game, *Group Decision and Negotiation* 4, 117–133.
Requate, T. (2005). Dynamic incentives by environmental policy instruments—a survey, *Ecological Economics* 54, 175–195.
Roberts, M. and Spence, M. (1976). Effluent charges and licenses under uncertainty, *Journal of Public Economics* 5, 193–208.
Rootes, C. (2014). A referendum on the carbon tax? The 2013 Australian election, the Greens, and the environment, *Environmental Politics* 23, 166–173.
Ruth, M., Gabriel, S.A., Palmer, K.L., Burtraw, D., Paul, A., Chen, Y., Hobbs, B.F., Irani, D., Michael, J., Ross, K.M., Conklin, R. and Miller, J. (2008). Economic and energy impacts from participation in the regional greenhouse gas initiative: a case study of the State of Maryland, *Energy Policy* 36, 2279–2289.
Sawyer, D. and Gass, P. (2014). Regulating carbon emissions in Canada climate policy year in review and trends, 2013. International Institute for Sustainable Development. Available from URL: http://www.iisd.org/pdf/2014/canadian_carbon_policy_review_2013.pdf. [accessed 15 Sep 2014].
Shobe, W., Holt, C. and Huetteman, T. (2014). Elements of emission market design: an experimental analysis of California's market for greenhouse gas allowances, *Journal of Economic Behavior and Organization* 107, 402–420.
Smith, V. (1962). An experimental study of competitive market behavior, *The Journal of Political Economy* 70, 111–137.
Svendsen, T.G. (1999). U.S. interest groups prefer emission trading: a new perspective, *Public Choice* 101, 109–128.
Thaler, R. (1980). Toward a positive theory of consumer choice, *Journal of Economic Behavior and Organization* 1, 39–60.
Van Huyck, J., Battalio, R. and Beil, R. (1990). Tacit coordination games, strategic uncertainty, and coordination failure, *The American Economic Review* 80, 234–248.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1 History of Australian GHG mitigation policy since the turn of the century

Appendix S2 Experimental instructions

Appendix S3
Screenshot 1. Participant Production Screen, No Trading
Screenshot 2. Participant Investment Screen
Screenshot 3. End of Period Summary Screen
Screenshot 4. Participant Production Screen, with Trading