Green trade unions. Structure, wages and environmental technology.*

Elias Asproudis — University of Northampton†

Maria J. Gil-Moltó — University of Sheffield‡

Abstract

This paper investigates the effect of trade union structure on firms' technological choices when the unions care about environmental protection. We compare a decentralized with a centralized union structure in a Cournot duopoly. Our results suggest that a decentralized structure provides higher incentives for the investment in cleaner technologies, although emissions may be lower under a centralized structure. The effect of the environmental damage parameter on wages and output may be non-monotonic.

Keywords: trade union structure; environmental concerns; emissions; technology; wages; employment.

JEL Codes: J51; L13; Q5; O31

*We are grateful for the comments by two anonymous referees and the editor, which have substantially helped us improve this paper. We are also grateful for comments and suggestions by Tom Weyman-Jones, Stuart McDonald and participants at RES 2010, ASSET 2012 and EAERE 2012. All remaining errors are our own.

†Northampton Business School, University of Northampton, Northampton, Park Campus, Boughton Green Road NN2 7AL, UK. E-mail: ilias.asproudis@northampton.ac.uk

‡Dpt Economics, University of Sheffield, Sheffield, 9 Mappin Street, S1 4DT, UK. E-mail: m.j.gil-molto@sheffield.ac.uk

1 Introduction

An increasing number of studies recognize that unions may be strongly motivated by environmental concerns. As Obach (1999) reports, 'Starting with the wave of environmentalism that began in the late 1960s, we see that a number of unions were supportive of this environmental mobilization'. Moreover, according to Silverman (2006), 'Union environmentalism is based in the particularist purpose of unions to protect members and in their more-universalist purpose to promote class mobilization based on solidarity'.

There are many examples of trade unions' environmentalism and alliances between trade unions and environmental groups to target common objectives. For example, Obach (1999) reports the case of the Wisconsin Labor-Environmental Network, which was a coalition between trade unions and environmental groups during the 80s and 90s, as well as other examples involving unions such as United AutoWorkers and Oil, Chemical and AtomicWorkers.[1] Bonanno and Blome (2001) documented a case where a coalition between trade unions and environmental groups was established as a reaction against the degradation of the Headwaters forest in Northern California.[2] Other examples involve unions such as the United Automobile Workers,

[1] Obach, 1999. p.51 "The United AutoWorkers union was one of the sponsors of the first Earth Day in 1970, which served as a springboard for a number of environmental groups at the beginning of the decade. Other international unions, such as the Oil, Chemical and AtomicWorkers, formed links early on with those in the environmental community and engaged in mutual support efforts (Truax, 1992)" cited in Obach, 1999. For a theoretical analysis on the relationship between labor and environmental groups with more case studies and a further literature review see Obach (2002, 2004).

[2] Particularly, p.377 "In May of 1999, labor unions and environmental activists created the "Alliance for Sustainable Jobs and the Environment," whose primary objective was to demand that Maxxam, a Houston based corporation, was held accountable for its questionable environmental and labor practices. The Alliance included various environmental groups, such as Earth First!, Sierra Club, Earth Island Institute,Worldwatch Institute, Friends of the Earth, Institute for Agriculture and Trade Policy, Rainforest Action Network, and Labor unions such as the United Steelworkers of America, The Newspaper Guild Communications Workers of America, and the American Federation of Government Employees. "

United Steel Workers of America or United Mine Workers (see Dewey, 1998; Rose, 2004; Mayer, 2009; and Gordon. 1998). [3]

Interestingly, at an international level, organizations like the United Nations or the International Trade Union Confederation also cooperate to achieve environmental sustainability. An important outcome of this type of cooperation is the joint document by the International Labour Organization and the United Nations (in its Environmental Program) entitled 'Labour and the Environment: A Natural Synergy'.[4] It is also relevant to note that the International Trade Union Confederation regularly takes part in initiatives such as the United Nations Conference on Sustainable Development (so called Rio+20) and in other initiatives pertaining social justice and environment, sustainable development etc.[5,6]

From an economic perspective, the environmental concerns and activities of trade unions raise important questions about the effects of trade unions' behavior on firms' technological choices, output and pollution levels. For example, how do trade unions react to pollution given that workers participate and therefore benefit from production but at the same time are harmed by pollution, which is a by-product of production? Or what is the effect of unions' environmental concerns on wages, production, pollution and profits? And finally, which union structure induces more investment in cleaner technologies and lower emissions levels? The aim of this research is to shed some light on these issues.

[3] For Australian examples see Snell and Fairbrother (2010).

[4] Available at http://www.unep.org/labour_environment/PDFs/UNEP-labour-env-synergy.pdf

[5] http://www.ituc-csi.org/rio-20.html (date of access 16/09/2012).

[6] See for example the United Nations Environmental programme (http://www.unep.org) date access 23/03/2013. Silverman (2004) provides evidence on the participation and involvement of the International Confederation of Free Trade Unions, the International Trade Secretariats (Global Union Federations) and the European Trade Union Confederation "...in a variety of international conferences and institutions such as the 1972 Stockholm Conference on the Environment, the 1992 Rio Earth Summit and the 2002 Johannesburg World Summit on Sustainable Development."

It is relevant to note that the effect of the trade union structure on firms' technological choices is an important topic of research in labour and industrial economics.[7] However, neither the empirical or the theoretical literature has given clear-cut results about the effects of unionization on firms' technology, innovation or R&D. For example a strong negative relationship between unionization and innovation has been reported in North America whereas no studies have confirmed this result in a European context (e.g. Menezes-Filho and Van Reenen, 2003).

Following recent theoretical studies on oligopoly, union structure and innovation, we compare firms' technological choices in the case of a decentralized union structure (that is, an independent union for each firm) with those in a centralized union structure (that is, an industry-wide union). Our main point of departure from the previous literature is that we allow the trade unions to have environmental concerns and behave accordingly. To the best of our knowledge, this has been neglected in the literature so far, despite the empirical evidence and the relevance of this issue for environmental economics and policy.[8] Specifically, we include pollution in the objective function of the union, so that to reflect the fact that unions will not only take into account wages and output when bargaining with firms, but also pollution levels. Our results indicate that the decentralized union structure provides higher incentives for firms to adopt cleaner technologies. Wages are higher and output is lower in the case of a centralized union. Firms prefer the decentralized union structure (because it allows them to obtain higher profits), although unions may prefer the centralized structure, in particular if the environmental damage parameter is not too high. Furthermore, emissions levels will be lower (higher) under the centralized structure for relatively small (large) market

[7] For some references see Ulph and Ulph (1998), Dobson (1994) and for surveys, see Menezes-Filho *et. al.* (1998) and Menezes-Filho and Van Reenen (2003).

[8] The interaction between the application of environmental policy and unionisation has been considered in Stavins (1998) and Fredriksson and Gaston (1999), for example. However the literature has mostly focused on the case where unions opposed to the environmental policies under the threat of higher unemployment.

sizes.

In the next section, we review the literature on unionization and firms' incentives to invest on innovation.

2 Theoretical background and relevant literature

The literature so far has focused on the effect of unionization and union structure on firms incentives to invest in innovation. In this section, we provide a review of this literature, which as noted earlier has abstained from any environmental considerations. A seminal contribution on the issue of unionization and innovation incentives is Ulph and Ulph (1989), who model a duopoly engaged in a patent race for a labour-saving technology. They show that the strength of the union and the timing of the firms-unions negotiations could affect negatively firms' incentives to investment on R&D. In a similar study, Ulph and Ulph (1994) compare the Right to Manage model (bargaining over wages, while the firm decides employment levels) with Efficient Bargaining (bargaining over both wages and employment). In both these contributions, the unions are assumed to be decentralized.

Tauman and Weiss (1987) examine the effect of unionization on firms' decisions to invest on a labour-saving technology in the context of a patent race, where only the workers of one of the firms are unionized. The authors show that the firm whose workers are unionized has more incentives to invest in the labour-saving technology in order to defend itself against the higher costs (higher wages) set by the union.

More recently, the literature has turned its attention to the effect of unionization structure on innovation incentives. For example, Calabuig and Gonzalez-Maestre (2002) compare the incentives to adopt a new technology provided by two unionization structures (centralized and decentralized). They conclude that a centralized union may provide stronger incentives for innovation, particularly of the market size is small. In the context of a patent race, Haucap and Wey (2004) compare the incentives to invest in innovation to reduce labour-costs across three possible union structures: A centralized union which sets a uniform wage, a decentralized union and the case where the union is centralized but sets different wages to each firm (this is the case of coordination, as labelled in their paper). Moreover, decentralization delivers the highest while centralization delivers the lowest levels of employment. According to their results, innovation incentives are non-monotonic in the degree of the centralization.

Manasakis and Petrakis (2009) examined firms' incentives to invest in cost-reducing R&D (in a non-tournament model) across different union structures. Two scenarios are considered: R&D competition and R&D cooperation. In the first case, their results indicate that if spillovers are low, the centralized union (with a uniform wage) encourages more R&D investment than the decentralized structure. In contrast, in the case of cooperation, the incentives to invest on R&D are always higher under the decentralization structure than under the industry-wide union (centralized).

As discussed before, the literature so far has studied the effect of unionization and union structure on firms' incentives to innovate, absconding from any environmental considerations. In this paper, we aim at covering (at least partially) this gap, by allowing unions to have environmental concerns. In particular, we introduce pollution into the utility function of the union. The rationale behind the inclusion of this additional element is that either the union cares about the environment (and internalizes the negative effect of pollution) or that the union cares about the impact of pollution on the health of unionized workers,[9] or even a combination of both. We analyze the effect of union structure on the incentives of firms to invest in an environmental technology in a non-tournament setting. We will focus on the case where

[9] For example, emissions from a given firms' production could influence negatively the health of the firm's workers, due to higher concentration of pollutants in the local environment.

both firms are unionized and will compare two different structures (centralized and decentralized). In the extensions section, we will also consider the case where a centralized union sets a uniform wage across firms.

The rest of the paper is structured as follows: In section 3, we introduce the model. In sections 4 and 5, we solve respectively the cases with a decentralized and a centralized union. In section 6, we compare the equilibrium outcomes across the two cases. Section 7 presents three extensions (centralized union structure with a uniform wage, and Cournot and Bertrand competition with product differentiation). Section 8 concludes.

3 The model

We consider a Cournot oligopoly with two unionized firms indicated by $i, j = 1, 2$ with $i \neq j$ producing a homogeneous product facing an inverse demand function $p = a - q_i - q_j$ where $a > 0$ is a related to the size of the market (a larger a implies a larger market). Firms transform labour into output, using the production technology $q_i = L_i$ where q_i, L_i are firm i's levels of output and labour respectively.[10] w_i is the wage rate per unit of labour. Production is polluting with firms' emissions given by $y_i = k_i q_i$, where $k_i \in (0, 1]$ is the emission intensity of firm i. Firms have at their disposal a continuum of anti-pollution technologies which allow them to effectively choose their emission intensities k_i.[11] A cleaner technology (or a technology which is more efficient against pollution) is associated with a lower k.[12] The

[10] This modelling implies that there are constant returns to scale, which is a usual assumption in bargaining models (Manasakis and Petrakis, 2009; Petrakis and Vlassis, 2004). An alternative modelling could be a quadratic relation like $q_i = \frac{1}{a} L_i^2$ where parameter a represents the level of the technical efficiency (e.g. Menezes-Filho et al. 1998). However, for tractability reasons we favour the constant returns to scale assumption.

[11] We assume the absence of a technology which can eliminate completely emissions from production, that is $k_i > 0$.

[12] The technology could be a i) production technology, therefore any change in the technology could influence the level of the production or ii) an environmental technology without any direct relation to production. For example the number of the filters in a

technology costs are given by $F_i = \gamma(1 - k_i)^2$ with $\gamma > 0$. This implies that the adoption of cleaner technologies requires higher (fixed) costs and that there are diminishing returns to investment in technology. The parameter γ simply scales up the differences in the adoption costs between two different technologies. Hence each firm's cost function is given by $C_i = w_i q_i - \gamma(k_i - 1)^2$. Therefore, firms' profits are

$$\pi_i = (a - q_i - q_j)q_i - w_i q_i - \gamma(k_i - 1)^2 \quad (1)$$

The union sets the wage level to maximize its utility while firms choose the level of output (and therefore employment) to maximize profits.[13] When the trade union does not care about the environment, its utility function is typically assumed to follow a Stone-Geary equation $U_i = (w_i - w_o)L_i$ where w_0 is the reservation wage (that is, the wage that the workers could gain in a competitive industry). This utility function implies that the union of workers in firm i cares both about the level of the wages and about the level of employment in firm i.[14] In our paper, we assume that unions also care about environmental quality (or about the health of unionized members, which could be harmed by pollution). Hence, we introduce environmental damage as an additional term into the trade union's utility function. The environmental damage derived from firm i's emissions is given by $D_i(y_i) = ey_i$, where $e > 0$ is the marginal damage from pollution (e.g. the environmental damage for each tonne of CO_2).[15] The parameter e can also be interpreted

refinery's pipe for CO_2 reduction or 'scrubbers' to remove of SO_2 from a fuel gas coal fired electric plant. For references on the latter see Keohane (2001), Chao and Wilson (1993) and Srivastava (2001).

[13] This is the so-called Monopoly Union model (Dunlop, 1944, and Petrakis and Vlassis, 2004), which is a special case of the Right to Manage model (see Nickell and Andrews, 1983; Espinosa and Rhee, 1989; Booth, 1995; Lopez and Naylor, 2004 and Mukherjee, 2008), where the union has full power to set wages while the firm has full power to choose the level of employment.

[14] Another usual assumption is that all workers are unionised, homogeneous and have equal opportunities to be employed (e.g. Oswald, 1985).

[15] The linear damage or constant marginal damage function has been widely used in the

as the relative strength of the environmental preferences of the union (that is, a higher e would imply that the union is more environmentally oriented). To guarantee positive output, we impose $a > e$. All in all, the trade union's utility function becomes $U_i = (w_i - w_o)L_i - D = (w_i - wo)L_i - ey_i$. [16] Given that $y_i = k_i q_i$ and that firms produce one unit of labour to produce one unit of output ($q_i = L_i$), we can rewrite U_i as:

$$U_i = L_i(w_i - (w_0 + ek_i)) \tag{2}$$

Interestingly, if unions are environmentally concerned, workers' reservation wage is $w_0 + ek_i$. That is, the opportunity cost of working is increasing in the externality produced by work. Hence, the higher the environmental damage (e) is or the more polluting the technology used by firm i (k_i) is, the higher the wage that the union will demand to compensate for the disutility caused by pollution. Following Lommerud et al. (2005) we set $w_0 = 0$ for the sake of simplicity and without loss of generality.

We will solve our model under two possible unionization structures: First, a decentralized structure, where workers are unionized at firm level. That is, there are two unions, one for each firm. Each union chooses w_i to maximize $U_i = L_i(w_i - (w_0 + ek_i))$. Second, a centralized structure, where workers in both firms are members of the same union. That is, there is only one union. In this case, the union chooses wages to maximize the sum of utilities derived from wages and employment across firms: $U = \sum(w_i - w_o)L_i$. We will use superscripts D and C respectively to identify the outcomes of the decentralized and centralized structures.

As in Haucap and Wey (2004), our timing is the following: Firms choose technology in the first stage. In the second stage, wages are set by the unions

literature. For example, see Kennedy (1999), Kennedy and Laplante (1999) and Requate (2005).

[16] One could consider that union members have a mission - oriented characteristic which is environmental protection and press the firm to adopt a less polluting technology (Besley and Ghatak, 2005).

(union). In the final stage, firms decide on production (and employment). In all stages, decisions are taken simultaneously. We impose that $e^2 < 9\gamma$, so that to guarantee an interior solution in the technology choice stage in both cases. We solve the game by backwards induction to find the subgame perfect Nash equilibrium solutions. All proofs to lemmata and propositions are relegated to the appendix.

In stage 3, firms simultaneously choose q_i (and therefore L_i) to maximize profits, given the outcomes in the previous stages. The solutions to this final stage are therefore common to the two cases. Applying the First Order Condition (FOC henceforth) for maximization and solving the system, we obtain the Cournot - Nash equilibrium output, employment and profits:[17]

$$q_i^C = L_i^C = q_i^D = L_i^D = \frac{a - 2w_i + w_j}{3}, \tag{3}$$

Note that firm i's equilibrium output (and consequently, employment level) is decreasing in the own wage ($\frac{\partial q_i}{\partial w_i} < 0$) but increasing in the rival firm's wage ($\frac{\partial q_i}{\partial w_j} > 0$). A higher wage implies a higher marginal cost of production. It follows that while the own wage (that is, the own marginal cost) will affect negatively firms' own output, the competitor's wage (that is, the competitors' marginal cost) will affect it positively. Moreover, the equilibrium output, and therefore the employment level, is also increasing in the size of the market ($\frac{\partial q_i}{\partial a} > 0$). That is, the larger the market is, the more firms produce and therefore, the more workers they hire.

In the next sections we will solve stages one and two for the two cases (decentralized and centralized union structure).

[17] The SOC for maximization is met: $\partial \pi_i / \partial q_i = -2 < 0$.

4 Decentralized unions

4.1 Stage two: Unions set wages

In stage two, the unions simultaneously set the level of the wages to maximize utility, $U_i = w_i L_i - e y_i$. After substituting the equilibrium level of employment, the utility function becomes

$$U_i = (w_i - ek_i)(\frac{a - 2w_i + w_j}{3}) \tag{4}$$

Applying the FOCs for maximization ($\frac{\partial U_i}{\partial w_i} = 0$), we obtain[18]

$$\frac{\partial U_i}{\partial w_i} = \frac{1}{3}(a + 2ek_i - 4w_i + w_j) = 0. \tag{5}$$

Note that $\frac{\partial^2 U_i}{\partial w_i \partial w_j} > 0$; that is, wages are strategic complements. As in Petrakis and Vlassis (2004) if the union j sets higher wages, the level of the output of firm j will decrease ($\frac{\partial q_j^D}{\partial w_j} < 0$) but firm i will produce more ($\frac{\partial q_i^D}{\partial w_j} > 0$). This induces union i to set higher wages to firm i when the rival firm deals with higher wages from the union j.

Solving the system of FOCs, the equilibrium wages for each firm are given by:

$$w_i^D = \frac{1}{15}(5a + 2e(4k_i + k_j)). \tag{6}$$

Thus, the wage level for each firm depends positively on how polluting not only the own but also the competitor's technology choices are, as long as $e > 0$. The effect of the own technology choice on the equilibrium wage is clear: The more polluting the technology used by firm i is, the higher the reservation wage of workers in firm i will be, which will push the wage level set by union i up. The same logic applies to firm j (a higher k_j leads to

[18] The SOC for a maximum if fulfilled: $\frac{\partial^2 U_i}{\partial w_i^2} = -4/3$.

a higher w_j). However, the increase in w_j will have an additional indirect effect on the w_i. An increase in w_j makes firm i relatively more competitive, increasing its output level. As a consequence, the union will demand a higher wage from firm i. This explains why the equilibrium wage level in firm i depends positively not only on the technology chosen by firm i but also on the technology chosen by firm j, even though the emissions produced by firm j do not directly feature in union i's utility function. The following lemma summarizes this result:

Lemma 1 *In a decentralized union structure, the wages set by the unions to each firm depend positively not only on the technology choices by that firm ($\partial w_i^D/\partial k_i > 0$) but also on the technology choices by the competing firm ($\partial w_i^D/\partial k_j > 0$).*

4.2 Stage one: Firms choose technology

In stage one, firms simultaneously choose k_i to maximize profits. After substituting (6) into (3), we obtain

$$q_i^D = L_i^D = \frac{2}{45}(5a - 7ek_i + 2ek_j). \tag{7}$$

Note that, other things being equal, each firm produces more when it uses a greener technology ($\frac{\partial q_i^D}{\partial k_i} < 0$). In addition, each firm produces more when its competitor adopts a dirtier technology ($\frac{\partial q_i^D}{\partial k_j} > 0$). The intuition for this is related to the reaction of the unions to firms' technological choices. As we have shown before, when firms adopt greener technologies, the unions will set lower wages. This leads to lower labour costs, which in turn induce firms to produce more and hire more workers.

Substituting q_i^D and w_i^D into (1), we obtain

$$\pi_i^D = (\frac{2}{45}(5a - 7ek_i + 2ek_j))^2 - \gamma(1 - k_i)^2 \tag{8}$$

Applying the first order conditions for maximization ($\frac{\partial \Pi_i^D}{\partial k_i} = 0$) and solving the system, we obtain firms' equilibrium technology choices[19]

$$k_i^D = \frac{405\gamma - 28ae}{405\gamma - 28e^2} \tag{9}$$

It is interesting to note that k_i^D is decreasing in the size of the market ($\frac{\partial k_i^D}{\partial a} < 0$); that is, other things being equal, firms tend to invest more in greener technologies when the size of the market is larger. The intuition is that the larger the market is, the more firms produce ($\frac{\partial q_i^D}{\partial a} > 0$). This, in turn, makes the investment in cleaner technologies more profitable. In addition, k_i^D is decreasing in the parameter γ. As usual, higher adoption costs (higher γ) will discourage the adoption of cleaner technologies ($\frac{\partial k_i^D}{\partial \gamma} > 0$).

After the necessary substitutions, the equilibrium levels of output and emissions are given by

$$q_i^D = L_i^D = \frac{90(a-e)\gamma}{405\gamma - 28e^2} \tag{10}$$

$$y_i^D = \frac{90(a-e)(405\gamma - 28ae)\gamma}{(405\gamma - 28e^2)^2} \tag{11}$$

Interestingly, the derivative of the emissions with respect to the size of the market $\frac{\partial y_i^D}{\partial a}$ may be positive or negative depending on the size of the market, a. Specifically, there is a critical value of the size of the market $a_{cv}^D = \frac{28e^2+405\gamma}{56e}$ before (beyond) which emissions are increasing (decreasing) in the size of the market. The intuition is straightforward if one considers the effect of the market size on emissions. Recall that firms' emissions are given by $y_i^D = k_i^D q_i^D$, where both k_i^D and q_i^D are functions of a. In particular, a has a positive effect on emissions through output (q_i^D is proportional to output) but it has a negative effect through the technology choice (higher a

[19] The SOC is $\frac{\partial^2 \Pi_i}{\partial k_i^2} < 0$ for any e and γ such that $e^2 < 9\gamma$. Hence the conditions for a maximum are fulfilled.

means lower k_i^D). This second effect will outweigh the firms effect for large enough values of a. In fact, the total effect of a on emissions is given by:

$$\frac{\partial y_i^D}{\partial a} = k_i^D \frac{\partial q_i^D}{\partial a} + \frac{\partial k_i^D}{\partial a} q_i^D$$

where $\frac{\partial q_i^D}{\partial a} = \frac{90\gamma}{405\gamma - 28e^2} > 0$ and $\frac{\partial k_i^D}{\partial a} = -\frac{28}{405\gamma - 28e^2} < 0$. Hence, $k_i^D \frac{\partial q_i^D}{\partial a} > 0$ and $\frac{\partial k_i^D}{\partial a} q_i^D < 0$. As k_i^D is decreasing in a while output is increasing in a, it follows that the negative effect ($\frac{\partial k_i^D}{\partial a} q_i^D$) will outweigh the positive effect ($k_i^D \frac{\partial q_i^D}{\partial a}$) for sufficiently large values of a. Thus, the relationship between emissions and market size follows an inverted U-shape.[20] The following lemma summarizes this finding.

Lemma 2 *In the decentralized case, the relationship between the level of pollution and the size of the market follows an inverted U-shape. The value of a which makes y_i^D reach its maximum is $a_{cv}^D = \frac{28e^2 + 405\gamma}{56e}$.*

For completeness, we compute the equilibrium profits, wages and union's utility levels, by substituting k_i^D:

$$\pi_i^D = \frac{4(a-e)^2(2025\gamma - 196e^2)\gamma}{(405\gamma - 28e^2)^2} \tag{12}$$

$$w_i^D = \frac{135(a+2e)\gamma - 28ae^2}{405\gamma - 28e^2} \tag{13}$$

$$U_i^D = \frac{12150(a-e)^2\gamma^2}{(405\gamma - 28e^2)^2} \tag{14}$$

Before concluding this section, it is relevant to analyze the effect of the environmental damage parameter on both the equilibrium level of output and wages. The following result summarizes.

Proposition 1 *In the decentralised case, the following holds: i. If $a^2 \leq 14.46\gamma$, w_i^D is increasing while q_i^D is decreasing in e. ii. If $a^2 > 14.46\gamma$,*

[20] It is intuitive and straightforward to check that as e increases, y_i^D decreases.

w_i^D is initially increasing and then turns decreasing in e, while the opposite applies to q_i^D. The critical value of e which makes w_i^D and q_i^D reach their maximum and minimum respectively is $e_{cv}^D = \frac{1}{14}(14a - \sqrt{7}\sqrt{28a^2 - 405\gamma}$.

The intuition behind this lemma is as follows: A more serious environmental damage (higher e) induces the unions to demand higher wages (see eq. 6), through the increased reservation wage. As labour costs increase, firms hire fewer workers, produce and pollute less. The reduction in pollution will eventually lead to a reduction in the reservation wage of workers and therefore to a lower wage in equilibrium, which will induce firms to raise their production levels again. So that the turning point in wages and output arises, it is necessary that the technology costs are low relative to the size of the market (specifically $a^2 > 14.46\gamma$). Otherwise, firms will keep reducing output.[21]

5 Centralized unions

5.1 Stage two: Union sets wages

With a centralized unionization structure, there is only one union which sets the wages for both firms. Hence the utility function of the union is given by $U^C = w_i L_i + w_j L_j - e(y_i + y_j)$. Substituting the equilibrium levels of employment into the utility equation and applying the FOCs for maximization yields:[22]

$$\frac{\partial U^C}{\partial w_i} = \frac{1}{3}(a + 2ek_i - ek_j - 4w_i + 2w_j) = 0 \tag{15}$$

[21] The lemma depicts two possible scenarios. In scenario i, the technology costs (γ) are high relative to the size of the market (a). Hence, it is comparatively cheaper for firms to reduce pollution by reducing output. In contrast, in scenario ii, the technology costs are low relative to the size of the market. Thus, firms have stronger incentives to invest in cleaner technologies (hence, the equilibrium k_i^D will tend to be lower in this scenario).

[22] The SOC is $-4/3$. Hence, the conditions for a maximum are fulfilled.

After solving the system of FOCs, we obtain the equilibrium wages

$$w_i^C = \frac{1}{2}(a + ek_i) \tag{16}$$

Note that, as in the decentralized case, the wage set to firm i depends positively on firm i's technology choice (since this increases the reservation wage of workers, through the emissions caused by their work). However, in contrast with the decentralized case, w_i does not depend on the technology choice by firm j. The reason for this is that the union maximizes its utility across the two firms and is therefore able to internalize the effect originated from the competition between the two firms.

Lemma 3 *In a centralized union structure, the wages set by the unions to each firm depend positively on the technology choices by that firm ($\partial w_i^C/\partial k_i > 0$) but are independent of the technology choices by the competing firm ($\partial w_i^C/\partial k_j = 0$).*

5.2 Stage one: Firms choose technology

In this stage, firms simultaneously choose k_i to maximize profits. After substituting (16) into (3), we obtain

$$q_i^C = L_i^C = \frac{1}{6}(a - 2ek_i + ek_j). \tag{17}$$

As in the case of decentralization, the equilibrium output (and employment) is decreasing in k_i and increasing in k_j. Substituting q_i^C and w_i^C into (1), we obtain

$$\pi_i^C = (\frac{1}{6}(a - 2ek_i + ek_j))^2 - \gamma(k_i - 1)^2 \tag{18}$$

The FOCs for maximization are:

$$\frac{\partial \pi_i^C}{\partial k_i} = \frac{1}{9}(-ae - 18\gamma(k_i - 1) + e^2(2k_i - k_j))$$

Solving the system of FOCs, we obtain firms' equilibrium technology choices:[23]

$$k_i^C = \frac{18\gamma - ae}{18\gamma - e^2} \tag{19}$$

Like in the decentralized case, firms' technological choices less polluting the larger the market is ($\frac{\partial k_i^C}{\partial a} < 0$). Again, higher technology costs will discourage the adoption of cleaner technologies ($\frac{\partial k_i^C}{\partial \gamma} > 0$). Substituting k_i^C into q_i^C and y_i^C yields

$$\begin{aligned} q_i^C &= \frac{3(a-e)\gamma}{18\gamma - e^2} \\ y_i^C &= \frac{3(a-e)(18\gamma - ae)\gamma}{(18\gamma - e^2)^2} \end{aligned}$$

As in the case with a decentralized union structure, the equilibrium level of emissions follows an inverse U-shape in the size of the market. As explained in the case of decentralization, two effects are at play: A higher a leads to higher output but also to the adoption of a cleaner technology. It turns out that for large enough market sizes, firms will produce more but using a less polluting technology, yielding lower pollution levels.[24]

Lemma 4 *In the centralized case, the relationship between the level of pollution and the size of the market follows an inverted U-shape. The critical value of a which makes pollution turn decreasing in a is $a_{cv}^C = \frac{e^2+18\gamma}{2e}$.*

After the necessary substitutions, the equilibrium levels of wages, the utility of the union and firms' profits are

[23] The SOC is $\frac{\partial^2 \Pi_i^C}{\partial k_i^2} < 0$ for any e and γ such that $e^2 < 9\gamma$. Hence, the conditions for a maximum are fulfilled.

[24] As in the case of decentralization, it is intuitive and straightforward to check that as e increases, y_i^C decreases.

$$\pi_i^C = \frac{(a-e)^2(9\gamma - e^2)\gamma}{(18\gamma - e^2)^2} \quad (20)$$

$$w_i^C = \frac{9(a+e)\gamma - ae^2}{18\gamma - e^2} \quad (21)$$

$$U^C = \frac{54(a-e)^2\gamma^2}{(18\gamma - e^2)^2} \quad (22)$$

To conclude this section, we wish to study the effect of the environmental damage parameter on wages and output (employment). We can establish the following:

Proposition 2 *In a centralised case, the following holds: i. If* $a^2 \leq 18\gamma$, w_i^C *is increasing while* q_i^C *is decreasing in* e*. ii. If* $a^2 > 18\gamma$, w_i^C *is initially increasing and then turns decreasing in* e*, while the opposite applies to* q_i^C*. The critical value of* e *which makes* w_i^C *and* q_i^C *reach their maximum and minimum respectively is* $e_{cv}^C = a - \sqrt{a^2 - 18\gamma}$.

As in the case with decentralization, wages initially increase and output initially decreases in the environmental damage parameter. However, after a certain point, the wages may start declining and output start increasing. As explained before, a more serious environmental damage (higher e) induces the union to compensate for the negative effects of pollution with an increase in the wage through a higher reservation wage (see eq. 16). As a consequence, firms will produce less given that their labour costs go up (they hire fewer workers). After a certain point, when production is very low, the union will decrease the wage rates to induce firms to hire more workers. This will then lead firms to raise their production levels again. So that the turning point in the wage and output levels arises, it is necessary that the technology costs are low relative to the size of the market ($a^2 > 18\gamma$); otherwise, firms will keep reducing output.

6 Comparisons

In this section we compare the equilibrium results across the two unionization structures.

6.1 Output, employment and and wages

Comparing the equilibrium levels of output and wages across the two structures, we can state the following result:

Proposition 3 *Comparing a centralized union structure with a decentralized union structure, we can establish the following:* $q_i^D > q_i^C$ *(and therefore* $L_i^D > L_i^C$*) and* $w_i^C > w_i^D$*.*

Proposition 3 states that the equilibrium levels of output and employment are higher while wages are lower under the decentralized structure than under the centralized structure. A more powerful union (centralized) union will be able to set higher wages. Thus from the point of view of the employed workers, a centralized union is preferable ($w_i^C > w_i^D$). However, a higher wage level in the case of centralization will inevitably induce firms to reduce employment and to produce less ($q_i^D > q_i^C$ and $L_i^D > L_i^C$).

6.2 Technology choices and Emissions

Next, we compare both structures in terms of technology choices and emissions. In terms of technology choices, we can establish the following result:

Proposition 4 *Comparing a centralized union structure with a decentralized union structure, we can establish the following:* $k_i^C > k_i^D$*.*

The above proposition states that under a centralized unionization structure, firms choose more polluting technologies than in a decentralized structure. As firms anticipate that a more powerful union structure is more able to obtain the rents associated with a lower emission damage (by increasing the wage), they are less interested in investing in cleaner technologies.

In terms of emissions, the following can be stated:

Proposition 5 *Comparing a centralized union structure with a decentralized union structure, we can establish the following:* $y_i^C < y_i^D$ if $a < a^{cv}$ and $y_i^D < y_i^C$ if $a > a^{cv}$, where for $a^{cv} = 35\gamma A/eB$ with $A = (501.6\gamma^2 - e^2(e^2 + 14.86\gamma))$ and $B = (e^2(e^2 - 135\gamma) + 1930.9\gamma^2)$.

The above proposition implies that the effect of the unionization structure on the level of pollution depends on the market size.[25] Note that shifting from a decentralized to a centralized structure affects positively emission intensities k ($\Delta k = k_i^C - k_i^D > 0$) and negatively output ($\Delta q = q_i^C - q_i^D < 0$). The combination of these two effects will result in higher (lower) emissions in the case a centralized structure when the size of the market is relatively small (large). To illustrate the intuition for the above result, we can approximate the overall effect on pollution from the move to centralization by $\Delta y \approx k\Delta q + q\Delta k$ where $k\Delta q$ is the negative direct effect associated to lower output while $q\Delta k$ is the positive indirect effect associated to a more polluting technology in a centralized structure. Note that in equilibrium, output is increasing in a while the emission intensity is decreasing in a. Hence, it is easy to see that the direct negative effect can only outweigh the positive effect for relatively small market sizes.

6.3 Firms' profits and Unions' utility

Next, we compare profits and union's utility in equilibrium. We can state the following:

Proposition 6 *Comparing a centralized union structure with a decentralized union structure, we can establish the following: i.* $\pi_i^D > \pi_i^C$ *and ii.* $U^C > \sum U_i^D$ *if* $e^2 < 3.41\gamma$ *and* $U^C < \sum U_i^D$ *if* $e^2 > 3.41\gamma$.

As stated in Proposition 3, firms produce less with centralization. Although lower production would imply a higher price in the final market, the

[25] This general result is illustrated with some numerical examples in the appendix.

higher cost of production (due to the higher wage level with a centralized union structure) outweighs this effect. Overall, firms' profits are lower with a centralized than with a decentralized union structure. That is, $\pi_i^D > \pi_i^C$.

On the other hand, the decentralized union structure offers a higher level of aggregate utility to the unions if the environmental damage parameter is large enough. Note that, in general, the centralized structure allows unions to set higher wages. However, the unions do not only care about wages (and employment) but also about the environment and firms invest more in cleaner technologies in the decentralized case. If the environmental damage parameter is relatively low, the unions reach higher levels of utility with a decentralized structure (in this case, the environmental damage is a relatively less important component of the utility function of the union). Hence, the unions prefer one, single and centralized structure in those circumstances rather than two separate unions ($U^C > \sum U_i^D$), while the opposite applies to firms. When the environmental damage parameter is relatively large, emissions carry a greater weight in the utility function of the union. In this case, the union obtains higher utility with a decentralized structure ($U^C < \sum U_i^D$). Hence, when the environmental damage parameter is large enough, the preferences of the firms and the unions (in terms of bargaining structure) are aligned.

6.4 Social Welfare

To conclude, we bring together the findings in this section so that to compare social welfare across the two structures. We define social welfare as the aggregation of consumer surplus, producer surplus and the unions utility. Hence, social welfare in the decentralized and in the centralized case are given respectively by $W^D = CS^D + PS^D + U_i^D + U_j^D$ and $SW^C = CS^C + PS^C + U^C$, where $CS^D = \frac{1}{2}(q_i^D + q_j^D)^2$, $CS^C = \frac{1}{2}(q_i^C + q_j^C)^2$ and $PS^D = \pi_i^D + \pi_j^D$,

$PS^C = \pi_i^C + \pi_j^C$.[26] The equilibrium levels of social welfare in these structures are:

$$SW^D = \frac{28(a-e)^2(2025\gamma - 56e^2)\gamma}{(405\gamma - 28e^2)^2} \quad (23)$$

$$SW^C = \frac{2(a-e)^2(45\gamma - e^2)\gamma}{(18\gamma - e^2)^2} \quad (24)$$

The following result can be established:

Proposition 7 *Comparing a centralized union structure with a decentralized union structure, we can establish the following:* $SW^D > SW^C$.

The above proposition shows that a decentralized union structure attains higher levels of welfare than a decentralized structure. Firms invest more in cleaner technologies with a decentralized structure and also produce more. Hence, consumer surplus and profits are higher with a decentralized structure. Pollution may also be lower with a decentralized structure for relatively large market sizes. Even when decentralization yields more pollution, the effect through (producer and consumer) surplus will compensate for the increased emissions. Thus, a decentralized structure is preferable from the point of view of the welfare. This result can therefore be seen as complementary to those in Manasakis and Petrakis (2009) and Haucap and Wey (2004), where unions are not driven by any environmental motivations.

Before concluding this section, we wish to investigate the effect of the different market failures which could arise in this context on the result in Proposition 7. Typically in oligopoly model, underproduction will take place. In our context, market failures related to technology investments and pollution (externalities) could also arise in addition. To the purpose of this analysis, we calculate the socially optimal level of output (q_i^O and emission

[26] We do not introduce the damage function in the social welfare in order to avoid double counting since it is already part of the unions' utility function.

intensities k_i^O). The objective function of the regulator (SW) is given by the aggregation of the two firms profits (1), unions' utility (2) and consumer surplus ($CS = \frac{1}{2}\sum_{i=1}^{2} q_i$) which can be simplied as:

$$SW = P\sum_{i=1}^{2} q_i - \gamma\sum_{i=1}^{2}(1-k_i)^2 - \sum_{i=1}^{2} ek_iq_i + \frac{1}{2}(\sum_{i=1}^{2} q_i)^2$$

The regulator chooses q_i and k_i to maximize social welfare, yielding:[27]

$$k_i^O = \frac{4\gamma - ae}{4\gamma - e^2}\ ;\ q_i^O = \frac{2(a-e)\gamma}{4\gamma - e^2}$$

As long as it is socially optimal to produce (that is, $q_i^O > 0$),[28] it is straightforward to check that $k_i^O < k_i^D < k_i^C$ and $q_i^O > q_i^D > q_i^C$. Thus, both with centralization and with decentralization, there is both underinvestment in cleaner technologies and underproduction. However, the gap between the socially optimal and the equilibrium levels of technology and output is smaller in the case of decentralization. Therefore, decentralization would be preferred from the point of view of the regulator as it delivers outcomes closer to the social optimum. Interestingly, both under centralization and decentralization, it is possible that emissions are too high. The reason for this is that even though firms underproduce, they also underinvest in cleaner technologies. This can render too much or too little pollution, depending on which of the two effects dominates. Interestingly, for small market sizes, the equilibrium level of emissions are too high compared to the social optimum, while the opposite applies to relatively large market sizes. The following lemma summarizes this result:

[27] Note that w_i has disappeared as a variable because wages are a direct transfer from firms to unions, which do not affect directly the level of social welfare.

[28] We focus on $4\gamma > e^2$ to focus on positive outputs (otherwise, the social planner would simply close down the firms and stop producing). All the results derived in the previous sections still hold even if we impose $4\gamma > e^2$.

Lemma 5 *Both with decentralization and with centralization, firms underinvest ($k_i^O < k_i^D < k_i^C$) and underproduce ($q_i^O > q_i^D > q_i^C$) relative to the social optimum. This may result in socially excessive levels of pollution, particularly for relatively small a.*

7 Extensions

In this section we present several extensions of our main model. In particular, we solve the case of a centralized union with uniform wage and compare the equilibrium outcomes of this case with the other two. Then, we present and discuss our benchmark with product differentiation under both quantity (Cournot) and price competition (Bertrand).[29]

7.1 Centralized trade union with uniform wage

In our benchmark model we assumed that the centralized union will set different wages to each firm, this is the centralised-coordinated case (see also Manasakis and Petrakis, 2009 and Haucap and Wey, 2004). In this subsection we analyze the case where the centralized union sets the same wage to both firms (that is, it will set a uniform wage). In this case, the utility function of the union is $U^{UN} = w(L_i + L_j) - e(y_i + y_j)$ where the superscript UN indicates the centralization with uniform wage structure. The rest of the model remains the same. As in the main sections of the paper, we assume $a > e$ for positive outputs and $e^2 < 9\gamma$ to guarantee an interior solution in the second stage across all the cases.[30] Setting $w_i = w_j = w$ in (3), we obtain the solution to the third stage:

$$q_i^{UN} = L_i^{UN} = \frac{a - w}{3} \tag{25}$$

[29]The detailed calculations are available from the authors upon request.
[30]The SOCs for maximisation are fulfilled in all the stages.

In the second stage, the union chooses w to maximize U^{UN}. The solution to this stage is given by:

$$w^{UN} = \frac{1}{4}(2a + e\sum k_i) \tag{26}$$

In the first stage, firms choose k_i to maximize profits. The solution is given by:

$$k_i^{UN} = \frac{72\gamma - ae}{72\gamma - e^2} \tag{27}$$

And therefore the (rest of the) equilibrium outcomes of the centralized case with uniform wage are given by:

$$q_i^{UN} = \frac{12(a-e)\gamma}{72\gamma - e^2}$$

$$y_i^{UN} = \frac{12(a-e)(72\gamma - ae)\gamma}{(72\gamma - e^2)^2} \tag{28}$$

$$\pi_i^{UN} = \frac{(a-e)^2(144\gamma - e^2)\gamma}{(72\gamma - e^2)^2} \tag{29}$$

$$w_i^{UN} = \frac{36(a+e)\gamma - ae^2}{72\gamma - e^2} \tag{30}$$

$$U^{UN} = \frac{864(a-e)^2\gamma^2}{(72\gamma - e^2)^2} \tag{31}$$

$$SW^{UN} = \frac{2(a-e)^2(720\gamma - e^2)\gamma}{(72\gamma - e^2)^2} \tag{32}$$

The comparison of the equilibrium results in this case (centralized union with a uniform wage) with the previous two cases (decentralized union and centralized union with wage discrimination) allows us to make several remarks:

i. The equilibrium wage in this case is higher than in any of the two previous cases, while the opposite applies to output ($w^{UN} > w^C > w^D$ and

$q_i^D > q_i^C > q_i^{UN}$).

ii. The chosen technology is more polluting with a uniform wage than in any of the other cases ($k_i^D < k_i^C < k_i^{UN}$).

iii. Pollution may be lower with a centralized union setting a uniform wage than in any of the other cases ($y_i^{UN} < \min[y_i^C,\ y_i^D]$), but this requires relatively small market sizes.

iv. Firms prefer a centralized union with a uniform wage than with wage discrimination, although a decentralized union is preferred to both those cases ($\pi_i^D > \pi^{UN} > \pi^C$).

v. The centralized structure with a uniform wage is never the regime preferred by the unions ($U_i^{UN} < \max[U_i^C, U_i^D]$).

vi. From the point of view of welfare, a centralized union with a uniform wage delivers the lowest levels of welfare ($SW^D > SW^C > SW^{UN}$).

As the reader can see, wages are increasing and output (employment) decreasing in the degree of centralization. Firms' incentives to undertake environmental innovation are monotonically decreasing in the degree of centralization, given that the resulting emission intensities are the lowest with decentralization and the highest with a centralized structure and a uniform wage. Firms anticipate that a more powerful structure will allow the unions to capture a greater part of the rents derived from the investment in environmental technologies. As a consequence, firms are less interested in investing in environmental innovation. This does not imply that emissions are necessarily higher in the case of centralization with a uniform wage than in any of the other cases. In fact, given that output is at the lowest, it is also possible that emissions are also at the lowest in this case despite the higher emission intensities. Even though wages are higher in the case of the uniform wage, unions will not always prefer this regime, as it may result in lower employment and even higher emissions. All in all, we can state that social welfare is also monotonically decreasing in the degree of centralization.[31]

[31] Given lemma 6 and remarks i. and ii. here, it is straightforward to see that $k_i^O <$

7.2 Differentiated product

We extend our benchmark model by allowing differentiation. We will solve the model using both quantity (Cournot) and price (Bertrand) competition. In both cases, the rest of the model stays the same.

7.3 Quantity competition

Firms face an (inverse) demand function such as $p_i = a - q_i - bq_j$ where the parameter $b \in [0, 1]$ indicates how close substitutes the goods are. $b = 1$ corresponds to the case where the good is homogenous, which has been solved in the main sections of the paper, whereas $b = 0$ would correspond to the case where goods are independent (hence, firms are monopolists of their own demand). We solve the case of the Cournot duopoly model with product differentiation following the same steps as in the benchmark model. Firms' profits are given by $\pi_i = p_i q_i - w_i q_i - \gamma(k_i - 1)^2 \; C_i$. As in the main part of the paper, we impose $a > e$ and $e^2 < (4 - b^2)^2\gamma$ to guarantee respectively positive outputs and interior solutions in the technology choice stages in both cases (centralization and decentralization).[32] In the last stage firms choose output (employment) to maximize profits. The solution to the third stage is common to both cases and is given by:

$$q_i^C = q_i^D = L_i^C = L_i^D = \frac{a(2-b) - 2w_i + bw_j}{4 - b^2} \tag{33}$$

As before, output and employment are increasing in the own wage and decreasing in the competitor's wage. The effect of the competitor's wage on the own output depends on b. The closer the substitutes are (the higher b is), the fiercer the competition and therefore the stronger the impact of the competitors' wage on the own level of output. Moreover, in the symmetric

k_i^{UN} and $q_i^O > q_i^{UN}$. Thus, underproduction and underinvestment also take place in a centralised structure with uniform wage.

[32] The SOCs for maximization are fulfilled in all stages.

equilibrium, we can establish that firms will produce less, the closer substitute goods are.[33]

In the second stage, the unions (union) choose wages to maximize profits. The solutions for the decentralized and centralized cases are respectively:

$$w_i^D = \frac{a(2-b)(4+b) + 2e(4k_i + bk_j)}{16-b^2} \quad ; \quad w_i^C = \frac{1}{2}(a + ek_i) \tag{34}$$

As can be seen from the above expressions, the wage imposed by the centralized union, w_i^C, does not depend on the parameter of differentiation. The intuition is that the union can internalize the effect of competition in the final market by discriminating firms in terms of wages. Evaluating the derivative of w_i^D in symmetry, we can establish that b affects negatively wages ($\partial w_i^D / \partial b < 0$). That is, as competition intensifies, a decentralized union will set lower wages to firms. In other words, the union has more incentives to set higher wages in cases where firms face less competition so that to capture their rents.

Solving the first stage we find:

$$k_i^D = \frac{\gamma T - 4a(8-b^2)e}{\gamma T - 4(8-b^2)e^2} \quad ; k_i^C = \frac{\gamma Z - ae}{\gamma Z - e^2} \tag{35}$$

where $T = (4-b)^2(2-b)(b+2)^2(b+4)$ and $Z = 2(2-b)(2+b)^2$.

It is tedious but straightforward to establish that firms invest more in cleaner technologies when the union is organized in a decentralized manner than in a centralized manner (that is, $k_i^C - k_i^D > 0$) for any $b \in (0,1]$. (If $b = 0$, that is the goods are independent, $k_i^D = k_i^C$). Moreover, firms produce more in the decentralized case than in the centralized case ($q_i^D - q_i^C > 0$), irrespectively of how close substitutes goods are. In fact, q_i^D and q_i^C can be written as:

[33] The intuition for this last statement can be easily understood if one thinks about the two extreme cases: If goods are perfect substitutes ($b = 1$), it is as if firms are sharing one market while if goods are independent ($b = 0$), it is as if firms were monopolists in two separate markets.

$$q_i^D = \frac{2(a - ek_i^D)}{(4-b)(2+b)} \ ; \ q_i^C = \frac{(a - ek_i^C)}{2(2+b)} \tag{36}$$

Given that $k_i^D < k_i^C$, we know that $(a - ek_i^D) > (a - ek_i^C)$, and it is easy to see that $\frac{2(a-ek_i^D)}{(4-b)(2+b)} > \frac{(a-ek_i^C)}{2(2+b)}$ for any $b \in (0,1]$. (If $b = 0$, that is if goods are independent, $q_i^D = q_i^C$). Thus, the results we obtained in the main sections of the paper related to the effect of the union structure on firms' incentives to innovate and output (and employment) do not depend on the differentiation between the goods (Except in the extreme case where goods are completely independent, when the decentralized and centralized structure provide the same outcomes). As a consequence, we argue that the rest of the comparisons presented in section 6 (which are directly or indirectly related to either k or q or both) do not qualitatively depend on the degree of product differentiation.

7.4 Price competition

In this subsection we consider the case of a Bertrand duopoly with product differentiation. We start from the system of inverse demand functions presented in the previous section ($p_i = a - q_i - bq_j$), after inverting it, we obtain $q_i = \frac{a(1-b)-p_i+bp_j}{1-b^2}$, which is the demand function faced by each firm, where b measures how close substitutes goods are, with $b \in [0,1)$. Firm i's profits are given by $\pi_i = p_i q_i - w_i q_i - \gamma(k_i - 1)^2$. As before, we require $a > e$ for positive output. We also require that $e^2 < \frac{4(4-b)^2(1-b^2)\gamma}{(2-b^2)^2}$ so that to find an interior solution for the technology choices in both cases.[34] In the last stage, firms choose prices to maximize profits. The solution to the last stage (which is common for centralization and decentralization) is:

$$p_i^C = p_i^D = \frac{a(2 - b - b^2) + 2w_i + bw_j}{4 - b^2} \tag{37}$$

That is, firm's equilibrium prices are increasing in the wages set by the

[34] Given our parameter restrictions, the SOCs for maximization are fulfilled in all the stages.

unions (that is, in firms' marginal costs). From now on, the model is solved in the same way as in the main sections of the paper. In the second stage, the unions (union) choose wages to maximize utility. The solution to the second stage (equilibrium wages) for the decentralized and the decentralized cases are:

$$\begin{aligned} w_i^D &= \frac{a(1-b)(b+2)(4-b(2b-1))) + (2-b^2)e(-2(2-b^2)k_i + bk_j)}{16-17b^2+4b^4} \\ w_i^C &= \frac{1}{2}(a+ek_i) \end{aligned} \tag{38}$$

As before, w_i^C does not depend on the degree of differentiation. Finally, in the first stage, firms choose technologies to maximize profits. The solution to the last stage yields:

$$k_i^D = \frac{ae(b^2-2)^2(8-9b^2+2b^4)+N}{e(b^2-2)(8-9b^2+2b^4)+N} \ ; \ k_i^C = \frac{a(b^2-2)e+\Lambda}{(b^2-2)e^2+\Lambda} \tag{39}$$

where $N = (b-2)^2(1+b)(2+b)(2b^2+b-4)^2(b(2b-1)-4)\gamma$ and $\Lambda = 4(b-2)^2(1+b)(2+b)\gamma$. It is tedious but straightforward to check that in this case, as well as in the Cournot case, $k_i^D < k_i^C$ for any value of b. Then, the equilibrium outputs can be written as:

$$q_i^D = \frac{(2-b-b^2)(a-ek_i^D)}{2(4-5b^2+b^4)} \ ; \ q_i^C = \frac{(a-ek_i^C)}{(4+2b-2b^2)} \tag{40}$$

Given that $k_i^C > k_i^D$, we know that $(a-ek_i^D) > (a-ek_i^C)$. Moreover, it is easy to check that $\frac{(2-b-b^2)}{2(4-5b^2+b^4)} > \frac{1}{(4+2b-2b^2)}$, given that $0 < b < 1$. Hence, as in the case of quantity competition, we can state that $q_i^D > q_i^C$, irrespectively of the degree of product differentiation. Thus, we argue that the rest of the comparisons presented in section 6 (which are directly or indirectly related to either k or q or both) do not depend qualitatively on the type of competition either.

8 Discussion and Conclusions

In this paper we have analyzed the effect of unionization structure on the incentives to invest in environmental technologies by a duopoly. In our model, investing in environmental technologies allows firms to reduce their emission intensities; that is, to make their production cleaner. The main point of departure of our paper from the previous literature is that we have assumed that unions are environmentally concerned. Despite substantial evidence of this type of preferences, the literature so far has largely assumed that unions do not take into account the environment when deciding upon wages and/or employment. In our model, we have assumed that the utility function of the union includes pollution as an additional argument. That is, unions do not only care about wages and employment but also about environmental protection.

We have considered two main types of unionization structures: Decentralized, where each firm faces a separate union and centralized, where firms face an industry-wide union. Our results indicate that the unions set higher wages the more polluting firms' technologies are, irrespectively of the type of unionization structure. Wages are higher in the centralized case. As a consequence, output and therefore employment are lower in the centralized case. Our findings also show that the centralized structure reduces firms' incentives to invest in cleaner technologies. However, a centralized union structure may lead to lower levels of pollution, but this requires the market to be relatively small. For higher market sizes, the decentralized structure leads to lower pollution than a centralized structure. All in all, social welfare is lower with a centralized structure than with a decentralized structure.

Given our findings, we argue that if the regulator's objective is to maximize welfare, he/she should create the conditions for decentralized union structures, since according to our findings, this structure delivers the highest levels of welfare. For example, by introducing a labour market reform supporting bargaining at firm level (rather than at industry or even higher level).

However, one can envisage cases where the regulator may give more weight to emissions in its objective function (for example, if the environmental problem is very severe). In such cases, a centralized structure may be preferable, in particular, if the size of the market is small, as in those circumnstances, a centralised structure may lead to lower emissions levels than a decentralised structure.

We have also extended our benchmark model by allowing the centralized union to set a uniform wage. Our results indicate that this structure provides the lowest incentives to invest in environmental innovation. This allows us to state that the incentives to invest in environmental technologies when unions care about the environment are monotonically decreasing in the degree of union centralization. Finally, we have also allowed for differentiated goods and different types of competition (price vs. quantity). Our main results regarding environmental innovation incentives and output (employment) levels are robust to these modelling modifications.

A word of caution is needed here. Our results have been derived in a rather streamlined context. It would be interesting to consider the effect of unionization structure under more general demand and technology conditions, or under different bargaining settings. For example, we have assumed that unions have all power to choose wages while firms have all power to choose output (and therefore employment). It would be interesting to consider the case where firms and unions bargain over both wages and employment. Additionally, it would be also interesting to study the interaction between environmental policy tools (emission taxes, subsidies to innovation) and the presence of green unions. We leave these topics for future research.

References

1. Besley, T. and Ghatak, M. (2005) Competition and incentives with motivated agents. *American Economic Review*, 95, 616–636

2. Bonanno, A. and Blome, B. (2001) The environmental movement and labor in global capitalism: Lessons from the case of the Headwaters Forest. *Agriculture and Human Values,* 18, 365–381.

3. Booth, A.L. (1995) *The economics of the trade union.* Cambridge University Press, Cambridge.

4. Calabuig, V. and Gonzalez-Maestre, M. (2002) Union structure and incentives for innovation. *European Journal of Political Economy*, 18, 177–192.

5. Chao, H-P. and Wilson, R. (1993) Option value of emission allowances. *Journal of Regulatory Economics*, 5, 233–249.

6. Dewey, S. (1998) Working for the environment: Organized labor and the origins of environmentalism in the United States: 1948–1970. *Environmental History*, 1:45–63

7. Dobson, P. (1994) Multifirm unions and the incentive to adopt pattern bargaining in oligopoly. *European Economic Review*, 38, 87–100.

8. Dunlop, J. (1944) *Wage determination under trade unions.* New York: Macmillan.

9. Espinosa, M.P. and Rhee, C. (1989) Efficient wage bargaining as a repeated game. *Quarterly Journal of Economics*, 104, 565–588.

10. Fredriksson, P.G. and Gaston, N. (1999) The ‘greening’ of trade unions and the demand for eco-taxes. *European Journal of Political Economy*, 15, 663–686.

11. Gordon, R. (1998) Shell no! OCAW and the labor-environmental alliance. *Environmental History*, 3, 460–487.

12. Haucap, J. and Wey, C. (2004) Unionization structures and innovation incentives. *Economic Journal*, 114, 149–165.

13. Kennedy, P.W. (1999) Learning about environmental damage: Implications for emissions trading. *Canadian Journal of Economics*, 32, 1313–1327.

14. Kennedy, P.W. and Laplante, B. (1999) Environmental policy and time consistency: emission taxes and emissions trading, in E. Petrakis, E.S. Sartzetakis, and A. Xepapadeas (eds) *Environmental regulation and market power*, Edward Elgar, Cheltenham. pp. 116-144.

15. Keohane, N.O. (2002) Environmental policy and the choice of abatement technique: Evidence from coal-fired power plants. Paper presented at 2nd World Congress of Environmental and Resource Economists, June 2002, Monterrey, CA.

16. Lommerud, K.E., Straume, O. R., and Sorgard, L. (2005) Downstream merger with upstream market power. *European Economic Review*, 49, 717–743.

17. Lopez, M.C. and Naylor, R.A. (2004) The Cournot-Bertrand profit differential: a reversal result in a differentiated duopoly with wage bargaining. *European Economic Review*, 48, 681–696.

18. Manasakis, C. and Petrakis, E. (2009) Union structure and firms' incentives for cooperative R&D investments. *Canadian Journal of Economics*, 42, 665–693.

19. Mayer, B. (2009) Cross-movement coalition formation: bridging the labor-environment divide. *Sociological Inquiry*, 79, 219–239.

20. Menezes-Filho, N. and Van Reenen, J. (2003) Unions and innovation: a survey of the theory and empirical evidence. CEPR Discussion Paper No. 3792, London.

21. Menezes-Filho, N., Ulph, D., and Van Reenen, J. (1998) The determination of R&D: empirical evidence on the role of unions. *European Economic Review*, 42, 919–930.

22. Mukherjee, A. (2008) Unionized labour market and strategic production decision of a multinational. *Economic Journal*, 118, 1621–1639.

23. Mukherjee, A., Broll, U., and Mukherjee, S. (2008) Unionized labor market and licensing by a monopolist. *Journal of Economics*, 93, 59–79.

24. Nickell, S.J. and Andrews, M. (1983) Unions, real wages and employment in Britain 1951-1979. *Oxford Economic Papers*, 35, 183–206.

25. Obach, B.K. (1999) The Wisconsin labor-environmental network: a case study of coalition formation among organized labor and the environmental movement. *Organization and Environment*, 12, 45–74.

26. Obach, B.K. (2002) Labor-environmental relations: an analysis of the relationship between labor unions and environmentalists. *Social Science Quarterly*, 83, 82–100.

27. Obach, B.K. (2004) *Labor and the environmental movement: the quest for common ground*. MIT Press.

28. Oswald, A.J. (1982) The microeconomic theory of the trade union. *Economic Journal*, 92, 576–595.

29. Oswald, A.J. (1985) The economic theory of trade unions: an introductory survey. *Scandinavian Journal of Economics*, 87, 160–193.

30. Petrakis, E. and Vlassis, M. (2004) Endogenous wage bargaining institutions in oligopolistic sectors. *Economic Theory*, 24, 55–73.

31. Requate, T. (2005) Dynamic incentives by environmental policy instruments — a survey. *Ecological Economics*, 54, 175–195.

32. Rose, F. (2004) Labor-Environmental Coalitions, in D. Reynolds (ed.) *Partnering for change: unions and community groups build partnerships for economic justice*. M.E. Sharpe, New York. pp. 3–18.

33. Silverman, V. (2004). Sustainable alliances: The ideology of international labor environmentalism. *International Labor and Working Class History*, 66, 118–135.

34. Silverman, V. (2006) Green unions in a grey world. *Organization and Environment*, 19, 191–213.

35. Snell, D. and Fairbrother, P. (2010) Unions as environmental actors. *Transfer: European Review of Labour and Research*, 16, 411–424.

36. Srivastava, R. K., Jozewicz, W., and Singer, C. (2001). SO_2 scrubbing technologies: A review. *Environmental Progress*, 20, 219–227.

37. Stavins, R.N. (1998) What can we learn from the grand policy experiment? Lessons from SO_2 allowance trading. *Journal of Economic Perspectives*, 12, 69–88.

38. Tauman, Y. and Weiss, Y. (1987) Labor unions and the adoption of new technology. *Journal of Labor Economics*, 5, 477–501.

39. Ulph, A. and Ulph, D. (1989) Labour markets and innovation. *Journal of Japanese and International Economics*, 3, 403–423.

40. Ulph, A. and Ulph, D. (1994) Labour markets and innovation: ex-post bargaining. *European Economic Review*, 38, 195–210.

41. Ulph, A. and Ulph, D. (1998) Labour markets, bargaining and innovation. *European Economic Review*, 42, 931–939.

9 Appendix

9.1 Proofs

9.1.1 Proofs to lemmata and propositions in sections 4, 5 and 6.

PROOF LEMMA 1:

It follows immediately from the analysis of the first derivatives with respect to k_i and k_j: $\frac{\partial w_i^D}{\partial k_i} = \frac{8e}{15} > 0$, $\frac{\partial w_i^D}{\partial k_j} = \frac{2e}{15} > 0$. QED.

PROOF LEMMA 2:

It is straightforward to calculate that $\frac{\partial y_i^D}{\partial a} = \frac{90\gamma(28e(e-2a)+405\gamma)}{(28e^2-405\gamma)^2}$. Setting $\frac{\partial y_i^D}{\partial a} = 0$ and solving with respect to a we calculate the $a_{cv}^D = \frac{28e^2+405\gamma}{56e}$. The second order derivative is $\frac{\partial \overline{y}_i^D}{\partial a} = \frac{-90\gamma(56ea))}{(28e^2-405\gamma)^2} < 0$. Hence y_i^D reaches its maximum at a_{cv}^D.QED

PROOF PROPOSITION 1:

It is straightforward to check that $\frac{\partial q_i^D}{\partial e} = \frac{90(56ae-28e^2-405\gamma)\gamma}{(28e^2-405\gamma)^2}$ and $\frac{\partial w_i^D}{\partial e} = -\frac{270(56ae-28e^2-405\gamma)\gamma}{(28e^2-405\gamma)^2}$. Hence, the signs of $\frac{\partial q_i^D}{\partial e}$ and $\frac{\partial w_i^D}{\partial e}$ depend on the sign of $(56ae - 28e^2 - 405\gamma)$, which is continuous in e. Recall that $a > e > 0$. At $e = 0$, this term is negative. Hence, initially $\frac{\partial q_i^D}{\partial e} < 0$ and $\frac{\partial w_i^D}{\partial e} > 0$. The derivative of $(56ae - 28e^2 - 405\gamma)$ with respect to e is $56(a - e)$, which is positive. Thus, $(56ae - 28e^2 - 405\gamma)$ may turn positive (and therefore $\frac{\partial q_i^D}{\partial e}$ and $\frac{\partial w_i^D}{\partial e}$ positive and negative respectively) as e increases. In fact, at $a = e$, $\frac{\partial q_i^D}{\partial e} = \frac{90\gamma}{(28e^2-405\gamma)^2} > 0$ and $\frac{\partial w_i^D}{\partial e} = -\frac{270\gamma}{(28e^2-405\gamma)^2} < 0$. Setting $56ae - 28e^2 - 405\gamma = 0$, we find $e_{cv}^D = \frac{1}{14}(14a - \sqrt{7}\sqrt{28a^2 - 405\gamma}$ (we can discard the other root as it implies $e > a$). e_{cv}^D is only a real root if $a^2 > 405/28 = 14.46$. Thus, if $a^2 \leq 14.46$, $\frac{\partial q_i^D}{\partial e} < 0$ and $\frac{\partial w_i^D}{\partial e} > 0$. If $a^2 > 14.46$, $\frac{\partial q_i^D}{\partial e}$ and $\frac{\partial w_i^D}{\partial e}$ move from negative to positive and from positive to negative respectively as e increases, with the turning point at e_{cv}^D.QED

PROOF LEMMA 4:

It follows immediately from the analysis of the first derivatives with respect to k_i and k_j: $\frac{\partial w_i^c}{\partial k_i} = \frac{1e}{2} > 0$, $\frac{\partial w_i^D}{\partial k_j} = 0$. QED.

PROOF LEMMA 5:

It is easy to check that $\frac{\partial y_i^C}{\partial a} = \frac{3\gamma(e^2-2ae+18\gamma)}{(e^2-18\gamma)^2}$. Setting $\frac{\partial y_i^C}{\partial a} = 0$, we find $a_{cv}^D = \frac{e^2+18\gamma}{2e}$. The second derivative is $\frac{\partial^2 y_i^C}{\partial a^2} = -\frac{6\gamma e}{(e^2-18\gamma)^2} < 0$. Hence, y_i^C reaches a maximum at a_{cv}^D.QED.

PROOF PROPOSITION 2:

Calculating the derivatives of the equilibrium levels of output and wages with respect to e yields $\frac{\partial q_i^C}{\partial e} = \frac{3(2ae-e^2-18\gamma)\gamma}{(e^2-18\gamma)^2}$ and $\frac{\partial w_i^C}{\partial e} = -\frac{9\gamma(2ae-e^2-18\gamma)}{(e^2-18\gamma)^2}$. Hence, the signs of $\frac{\partial q_i^C}{\partial e}$ and $\frac{\partial w_i^C}{\partial e}$ depend on the sign of $(2ae-e^2-18\gamma)$, which is continuous in e. Recall that $a > e > 0$. At $e = 0$, this term is negative. Hence, initially $\frac{\partial q_i^C}{\partial e} < 0$ and $\frac{\partial w_i^C}{\partial e} > 0$. The derivative of $(2ae - e^2 - 18\gamma)$ with respect to e is $2(a-e) > 0$, which implies that $(2ae - e^2 - 18\gamma)$ may potentially turn positive (and therefore $\frac{\partial q_i^C}{\partial e} > 0$ and $\frac{\partial w_i^C}{\partial e} < 0$ turn positive and negative respectively) for a sufficiently large e. In fact, at $e = a$, $\frac{\partial q_i^C}{\partial e} = \frac{3\gamma}{(e^2-18\gamma)^2} > 0$ and $\frac{\partial w_i^C}{\partial e} = -\frac{9\gamma}{(e^2-18\gamma)^2} < 0$. Setting $(2ae - e^2 - 18\gamma) = 0$, we find $e_{cv}^C = a - \sqrt{a^2 - 18\gamma}$ (we can discard the other root as it implies $e > a$). Note that e_{cv}^D is only a real root if $a^2 > 18\gamma$. Thus, if $a^2 \leq 18\gamma$, $\frac{\partial q_i^D}{\partial e} < 0$ and $\frac{\partial w_i^C}{\partial e} > 0$. If $a^2 > 18\gamma$, $\frac{\partial q_i^D}{\partial e}$ and $\frac{\partial w_i^D}{\partial e}$ move from negative to positive and from positive to negative respectively as e increases, with the turning point taking place at e_{cv}^C. QED.

PROOF OF PROPOSITION 3:

It is easy to check that $q_i^C - q_i^D = \frac{3(a-e)(2e^2-135\gamma)\gamma}{(28e^2-405\gamma)(e^2-18\gamma)} < 0$ and $w_i^C - w_i^D = 3\frac{3(a-e)(135\gamma-2e^2)\gamma}{(28e^2-405\gamma)(e^2-18\gamma)} > 0$ given that $a > e > 0$, $\gamma > 0$ and $e^2 < 9\gamma$. QED.

PROOF OF PROPOSITION 4:

It is immediate to check that $k_i^C - k_i^D = (99(a-e)e\gamma)/((28e^2-405\gamma)(e^2-18\gamma)) > 0$ since $a > e > 0$ and $e^2 < 9\gamma$. QED.

PROOF OF PROPOSITION 5:

Note that $y_i^C - y_i^D = \frac{3(a-e)\gamma R}{(28e^2-405\gamma)^2(e^2-18\gamma)^2}$ where $R = 56ae^5 - 7560ae^3\gamma + 1962e^4\gamma + 108135ae\gamma^2 + 29160e^2\gamma^2 - 984150\gamma^3$. Given that $a > e > 0$, the sign of $y_i^C - y_i^D$ depends on the sign of R. Note that at $a = 0$, $R =$

$1962e^4\gamma + 29160e^2\gamma^2 - 984150\gamma^3 < 0$ for $e^2 < 9\gamma$. Moreover, $\frac{\partial R}{\partial a} = 56e^5 - 7560e^3\gamma + 108135e\gamma^2 > 0$ for $e^2 < 9\gamma$. Thus, R may change sign as a increases. Setting $R = 0$ and solving for a, we get $a = 35\gamma A/eB$ where $A = (501.6\gamma^2 - e^2(e^2 + 14.86\gamma))$ and $B = (e^2(e^2 - 135\gamma) + 1930.9\gamma^2)$ where both $A > 0$ and $B > 0$ for $e^2 < 9\gamma$. All in all, $R < 0$ if $a < 35\gamma A/eB$ and positive if $a > 35\gamma A/eB$. Therefore, $y_i^C < y_i^D$ for $a < 35\gamma A/eB$ and $y_i^C > y_i^D$ for $a > 35\gamma A/eB$. At $35\gamma A/eB$, $y_i^C = y_i^D$. QED.

PROOF OF PROPOSITION 6:

Note that $\pi^C - \pi^D = -\frac{27(a-e)^2\gamma^2(244e^4 - 6573e^2\gamma + 42525\gamma^2)}{(28e^2 - 405\gamma)^2(e^2 - 18\gamma)^2}$. Given that $a > e$, $\gamma > 0$ and $e^2 < 9\gamma$, the sign of $\pi^C - \pi^D$ depends on the sign of $(244e^4 - 6573e^2\gamma + 42525\gamma^2)$. Moreover, at $e = 0$, this term is positive. This term will be zero if $e^2 = 16.14\gamma$ or $e^2 = 10.79\gamma$. Given that $e^2 < 9\gamma$, we know $(244e^4 - 6573e^2\gamma + 42525\gamma^2) > 0$. As a consequence, we can state that, $\pi^C - \pi^D < 0$.

Furthermore, $U_i^C - \sum U_i^D = \frac{54(a-e)^2\Psi}{(405\gamma - 28e^2)^2(18\gamma - e^2)^2}$ where $\Psi = (334e^4 - 6480\gamma e^2 + 18225\gamma^2)$. Hence, the sign of $U_i^C - \sum U_i^D$ is determined by the sign of Ψ. At $e = 0$, $\Psi = 18225\gamma^2 > 0$. Evaluating Ψ for $e^2 = 9\gamma$, we have $-13031\gamma^2 < 0$. The derivative of Ψ with respect to e is $e(1336e^2 - 12960\gamma)$ which is negative for any $e > 0$ such that $e^2 < 9\gamma$. Hence we know that Ψ moves from positive to negative and will cross only once in the interval $e \in (0, \sqrt{9\gamma})$. Setting $\Psi = 0$ if $e^2 = 3.41\gamma$. Thus, if $e^2 < 3.41\gamma$, $U_i^C - \sum U_i^D > 0$ and if $e^2 > 3.41\gamma$, $U_i^C - \sum U_i^D < 0$. At $e^2 = 3.41\gamma$, $U_i^C - \sum U_i^D = 0$. QED.

PROOF OF PROPOSITION 7:

It is straightforward to check that $SW^D - SW^C = 2(a-e)^2\gamma\varsigma$ where $\varsigma = -\frac{99\gamma(140e^4 + 909e^2\gamma - 18225\gamma^3)}{(405\gamma - 28e^2)^2(18\gamma - e^2)^2} > 0$ for any e such that $e^2 < 9\gamma$. Hence, $SW^D - SW^C > 0$. QED

PROOF OF LEMMA 6:

It is straightforward to see that $k_i^D - k_i^O = \frac{293(a-e)e\gamma}{(405\gamma - 28e^2)(4\gamma - e^2)} > 0$ since $a > e > 0$ and $(4\gamma - e^2) > 0$ (otherwise $q_i^O < 0$). Hence, we also know that $k_i^C - k_i^O > 0$ since from proposition 4, we know that $k_i^C - k_i^D > 0$.

Hence, $k_i^C > k_i^D > k_i^O$. Likewise, it is straightforward to see that $q_i^D - q_i^O = \frac{2(a-e)\gamma(17e^2+225\gamma)}{(405\gamma-28e^2)(4\gamma-e^2)} > 0$. Hence, we also know that $q_i^C - q_i^O < 0$ since from proposition 5, we know that $q_i^C - q_i^D < 0$. Hence, $q_i^C < q_i^D < q_i^O$.

As for emissions: $y_i^C - y_i^O = \frac{(a-e)\gamma}{(18\gamma-e^2)^2(4\gamma-e^2)^2}\chi$ where $\chi = -59ae^2+96ae^3\gamma+62e^4\gamma-696ae\gamma^2-720e^2\gamma^2+3456\gamma^3$. Hence, the sign of $y_i^C - y_i^O$ depends on the sign of χ. The derivative of χ with respect to a is $e(-5e^4+96e^2\gamma-696\gamma^2) < 0$ if $4\gamma - e^2 > 0$. Hence, χ is decreasing in a. Recall that $a > e$. At the limit $(a = e)$, $\chi = 62e^4\gamma - 720e^2\gamma^2 + 3456\gamma^3 > 0$. Hence, χ is positive in the begining and may turn negative at a given value of a. Setting $\chi = 0$ and solving for a, we find: $a = \frac{2(31e^4\gamma-360e^2\gamma^2+1728\gamma^3)}{e(5e^4-96e^2\gamma+696\gamma^2).}$. If $a < \frac{2(31e^4\gamma-360e^2\gamma^2+1728\gamma^3)}{e(5e^4-96e^2\gamma+696\gamma^2).}$, $y_i^C > y_i^O$ and if $a > \frac{2(31e^4\gamma-360e^2\gamma^2+1728\gamma^3)}{e(5e^4-96e^2\gamma+696\gamma^2).}$

As for emissions: $y_i^D - y_i^O = \frac{(a-e)\gamma}{(405\gamma-28e^2)^2(4\gamma-e^2)^2}\Gamma$ where $\Gamma = -2044ae^5 + 32760ae^3\gamma + 21361e^4\gamma - 184185ae\gamma^2 - 236520e^2\gamma^2 + 947700\gamma^3$. Hence, the sign of $y_i^D - y_i^O$ depends on the sign of Γ. The derivative of Γ with respect to a is $-2044e^5 + 32760e^3\gamma - 184185e\gamma^2 < 0$ if $4\gamma - e^2 > 0$. Hence, Γ is decreasing in a. Recall that $a > e$. At the limit $(a = e)$, $\Gamma = (585\gamma - 73e^2)(405g - 28e^2)(4\gamma - e^2) > 0$. Hence, χ is positive in the begining and may turn negative at a given value of a. Setting $\Gamma = 0$ and solving for a, we find: $a = \frac{\gamma(21361e^4-236520e^2\gamma+947700\gamma^2)}{(2044e^5-32760e^3\gamma+184185e\gamma^2}$. Thus, if $a < \frac{\gamma(21361e^4-236520e^2\gamma+947700\gamma^2)}{(2044e^5-32760e^3\gamma+184185e\gamma^2}$, $y_i^D > y_i^O$ and if $a > \frac{\gamma(21361e^4-236520e^2\gamma+947700\gamma^2)}{(2044e^5-32760e^3\gamma+184185e\gamma^2}$, $y_i^D < y_i^O$. Hence, in both regimes, for sufficiently small a, the equilibrium emissions are larger than the socially optimal level of emissions.

9.1.2 Proofs of results in section 7.1.

PROOF OF REMARK i:

Note that $q_i^C - q_i^{UN} = \frac{9(a-e)e^2\gamma}{(e^2-72\gamma)(e^2-18\gamma)}$ and $w_i^{UN} - w_i^C = \frac{27(a-e)e^2\gamma}{(e^2-72\gamma)(e^2-18\gamma)}$. Given that $a > e > 0$, $\gamma > 0$ and $e^2 < 9\gamma$, it is immediate to see that $q_i^C - q_i^{UN} > 0$ and $w_i^{UN} - w_i^C$. Moreover from Proposition 1, we know that $q_i^C - q_i^D < 0$ and $w_i^C - w_i^D > 0$. It follows that $q_i^D > q_i^C > q_i^{UN}$ and $w_i^D < w_i^C < w_i^{UN}$.QED.

PROOF OF REMARK ii:

Note that $k_i^{UN} - k_i^C = (54(a-e)e\gamma)/(72\gamma - e^2)(18\gamma - e^2)$. Given that $a > e$, $\gamma > 0$ and $e^2 < 9\gamma$, it is easy to see that $k_i^{UN} - k_i^C > 0$. Moreover, we know that $k_i^C > k_i^D$, it follows that $k_i^{UN} > k_i^C > k_i^D$. QED

PROOF OF REMARK iii.

Note that $y_i^{UN} - y_i^C = -3(a-e)\gamma e\Upsilon/((72\gamma - e^2)^2(18\gamma - e^2)^2)$, where $\Upsilon = (ae^4 - 90e^3\gamma - 1296(a-2e)\gamma^2)$. Since $a > e > 0$ and $\gamma > 0$, the sign of $y_i^{UN} - y_i^C$ depends on the sign of Υ (if Υ is negative (positive), $y_i^{UN} - y_i^C > (<)0$). Note that at $a = e$, $\Upsilon = e^5 - 90e^3\gamma + 1296e\gamma^2 > 0$ for $e^2 < 9\gamma$. Moreover, $\frac{\partial\Upsilon}{\partial a} = e^4 - 1296\gamma^2 < 0$ for $e^2 < 9\gamma$. Thus, Υ may change sign as a increases. Setting $\Upsilon = 0$ and solving for a, we get $a = \frac{18e(5e^2-144\gamma)\gamma}{e^4-1296\gamma^2} > 0$ given that $e^2 < 9\gamma$. Therefore, $y_i^{UN} - y_i^C < 0$ for $a < \frac{18e(5e^2-144\gamma)\gamma}{e^4-1296\gamma^2}$ and $y_i^{UN} - y_i^C > 0$ for $a > \frac{18e(5e^2-144\gamma)\gamma}{e^4-1296\gamma^2}$.

On the other hand, $y_i^{UN} - y_i^D = -6(a-e)\gamma F/((28e^2-405\gamma)^2(e^2-72\gamma)^2)$, where $F = (1148ae^5 + 15120ae^3\gamma - 106821e^4\gamma - 1849230ae\gamma^2 + 2391120e^2\gamma^2 + 7873200\gamma^3)$. Since $a > e > 0$ and $\gamma > 0$, the sign of $y_i^{UN} - y_i^D$ depends on the sign of F (if Υ is negative (positive), $y_i^{UN} - y_i^C > (<)0$).). At $a = e$, $F = 1148e^6 - 91701e^4\gamma + 541890e^2\gamma^2 + 7873200\gamma^3 > 0$ for $e^2 < 9\gamma$. Moreover, $\frac{\partial F}{\partial a} = 1148e^5 + 15120e^3\gamma - 1849230e\gamma^2 < 0$ for $e^2 < 9\gamma$. Thus, F may change sign as a increases. Setting $F = 0$ and solving for a, we get $a = \frac{9(11869e^4\gamma - 265680e^2\gamma^2 - 874800\gamma^3)}{2e(574e^4+7560e^2\gamma-924615\gamma^2} > 0$ given that $e^2 < 9\gamma$. Therefore, $y_i^{UN} - y_i^C < 0$ for $a < \frac{9(11869e^4\gamma - 265680e^2\gamma^2 - 874800\gamma^3)}{2e(574e^4+7560e^2\gamma-924615\gamma^2}$ and $y_i^{UN} - y_i^C > 0$ for $a > (\frac{9(11869e^4\gamma - 265680e^2\gamma^2 - 874800\gamma^3)}{2e(574e^4+7560e^2\gamma-924615\gamma^2}$.

The rest of the result follows. QED.

PROOF OF REMARK iv:

It is immediate to see that $\pi^{UN} - \pi^C = \frac{27(a-e)^2\gamma^2((e^2+36\gamma)}{(e^2-72\gamma)^2(e^2-18\gamma)^2} > 0$ and $\pi^{UN} - \pi^D = -\frac{81(a-e)^2\gamma^2(180e^2+22231e^2\gamma-226800\gamma^2)}{(e^2-72\gamma)^2(28e^2-405\gamma)^2} < 0$ given that $e^2 < 9\gamma$. Thus, $\pi^D > \pi^{UN} > \pi^C$. Likewise, $U_i^{UN} - U_i^C = \frac{162(a-e)^2e^2(5e^2-144\gamma)\gamma}{(e^2-72\gamma)^2(e^2-18\gamma)^2} < 0$. Hence, irrespective of the relative ranking between U^C and U^D, we know that

$U_i^{UN} < \max[U^C, U^D]$.QED.

PROOF OF REMARK v.

It is easy to see check that $SW^C - SW^{UN} = 162(a-e)^2\gamma^2\omega$ where $\omega = \left[\frac{180e^2\gamma - 7e^4}{(72\gamma - e^2)^2(18\gamma - e^2)^2}\right] > 0$ for any e such that $e^2 < 9\gamma$. Hence, $SW^C - SW^{UN} > 0$. Given that we know that $SW^D > SW^C$, it follows that $SW^D > SW^C > SW^{UN}$. QED

9.2 Illustrations of result in Proposition 5

In the main text, we have shown that emissions are higher under the decentralized structure than in the centralized structure for low market sizes but the opposite applies to large market sizes (see proposition 5). This is a general result which we illustrate here with some numerical examples. In the tables below, we present the equilibrium results for given e and γ under a relatively small and a relatively large market size. As the reader can see from the three tables, when the market is relatively small, emissions are lower under a centralized structure than under a decentralized structure, although the opposite applies when the market is relatively large.[35]

Table 1: Equilibrium results ($e = 4$, $\gamma = 2$).

	Small market ($a = 6$)		Large market ($a = 7$)	
	Decentralized	Centralized	Decentralized	Centralized
k	0.38	0.6	0.07	0.4
q	0.99	0.6	1.49	0.9
π	0.22	0.04	0.50	0.09
y	0.379	0.36	0.107	0.36
w	3.01	4.2	2.52	4.3
U	2.96	2.16	6.66	4.86

[35] The parameter combinations e and γ used in the tables meet the condition $e^2 < 9\gamma$, to guarantee an interior solution in the technology choice stage. Note that U indicates aggregate utility in the case of a decentralized union, so that it is comparable with the utility of a centralized union.

Table 2: Equilibrium results ($e = 1.5$, $\gamma = 0.5$).

	Smaller market ($a = 3.5$)		Larger market ($a = 5$)	
$e = 1.5$, $\gamma = 0.5$	Decentralized	Centralized	Decentralized	Centralized
k	0.397	0.55	0.246	0.444
q	0.645	0.44	0.80	0.555
π	0.23	0.09	0.367	0.154
y	0.256	0.246	0.199	0.246
w	1.564	2.16	1.58	2.33
U	1.248	1.185	1.95	1.851

Table 3: Equilibrium results ($e = 1$, $\gamma = 0.3$).

	Smaller market ($a = 3$)		Larger market ($a = 3.2$).	
	Decentralized	Centralized	Decentralized	Centralized
k	0.400	0.545	0.340	0.5
q	0.577	0.409	0.635	0.45
π	0.225	0.105	0.273	0.127
y	0.231	0.223	0.216	0.225
w	1.267	1.77	1.2	1.85
U	1	1.004	1.2	1.215