

## Responses to the referee's comments on manuscript

### "Timing of adoption of clean technologies, transboundary pollution and international trade"

We thank you for your very constructive comments and suggestions, which have significantly improved our paper. Below we provide further details on how we take into account each of the points raised in your report (marked in red).

1. There are two market failures-monopoly and environmental externalities- and the paper's results are driven by the interaction between these externalities. However, this is rarely worked out in a clear way.

When the polluting technology is used, there are two market failures, which are monopoly (or duopoly) and environmental externalities. Since the levels of pollution and production are proportional, a per-unit emission tax is sufficient to correct the two market failures. When the clean technology is used, there is only one market failure (monopoly or duopoly), which is corrected by a per-unit production subsidy. In the revised paper, we have better explained the interaction between these externalities.

We have inserted the following phrases after equations (6), (9) and (30):

"With the polluting technology there are two market failures, which are monopoly and environmental externalities. As the levels of pollution and production are proportional, an emission-tax per-unit of pollution  $t_{idd}^a$  is sufficient to correct the two market failures and induce the socially optimal levels of production and pollution."

"Therefore, the emission-tax, which is used to correct monopoly and environmental externalities market failures, is positive when environmental externalities are high and is negative when environmental externalities are low."

"Therefore, under a common market, the emission-tax, which is used to correct duopoly and environmental externalities market failures, is always positive because

the duopoly market failure is less important than the environmental externalities market failure.”

2. Moreover, the authors use very simple functional forms and calculate closed form solutions for certain parameter restrictions. Therefore, it would be all the more important to explain the results intuitively.

By using general functions for demand, production and damage, we may not be able to compare the instantaneous social welfares or the socially optimal adoption dates under autarky and a common market, etc. Almost all our main results may not be shown with a general model.

A general model for the studied problem will lead a completely different paper and could be subject to further research. Finally, many papers cited in our article employ simple functional forms (Fujiwara 2011, Milliou and Petrakis 2011, Nasiri and Zaccour 2009, Soest 2005).

3. The literature review is often too unspecific, simply citing papers that have been written on some topic. Moreover, I would suggest to reverse the order of presentation: First, explain the papers idea and main result. Thereafter compare it to the literature.

We have improved the literature review and reversed the order of presentation by explaining the paper’s idea and main results, and then comparing them with the literature.

4. Propositions 1 and 6 depend on a specific tax / subsidy schedule. This should be included in the propositions, which otherwise sound more general than they actually are.

We have included in propositions 1 and 6 the per-unit emission-tax and subsidy.

5. There are so many sub- and superscripts in the paper that it is very easy to get lost.

We ignore how to remove some sub- or superscripts in the paper without making more confusion. Indeed, we have to distinguish between the optimal values for firms denoted by  $*$ , those socially optimal denoted by  $\wedge$ , those obtained with the polluting and clean technologies denoted respectively by  $d$  and  $c$ , the case where both firms use the dirty technology is denoted by  $dd$ , the case where both firms use

the clean technology is denoted by cc, and the case where one firm uses the polluting technology whereas the other firm uses the clean technology is denoted by dc or cd.

6. Proposition 3 (under autarky, the optimal adoption date for firms is earlier than socially optimal) is surprising. Early adoption has a positive effect on environmental damages and on output, which is too low due to the monopolistic market. Both effects are beneficial for social welfare; hence I would rather have expected the opposite result. It is important that the authors provide a clear intuition for their result. Moreover, the ranking changes with a common market (proposition 7). What is the intuition for this result? Of course, there is a close relation to propositions 1 and 6. But these are not explained at an intuitive level either?

We have inserted the following clarifications after propositions 1 and 3, respectively:

“Indeed, under autarky, because of the monopoly power, the instantaneous net profit of a firm is very high even when it uses the polluting technology.”

“This result is different from that obtained under autarky because the monopoly power induces that the instantaneous net profit of a firm is higher than under a common market where we have a duopoly. This holds whether firms use the polluting or the clean technology.”

7. The relation between the appendix and the proposition should be clarified (e.g., proof of proposition 2 ...).

All our propositions resume what we have already showed. In the revised paper, we have clarified our proofs by indicating the subsection in the appendix when we refer to the appendix.

8. Propositions 4 and 8 are so obvious that they do not deserve the label of a proposition.

We have removed propositions 4 and 8.

9. Eq. (38) and the related discussion:  $q < 0$  suggests that one gets a boundary solution with  $q = 0$ . This should be clarified. Moreover, I don't find such a solution "unrealistic" as it is claimed in the text. In particular, the solution that maximizes aggregate welfare of both countries would look like this. The reason is simply that

marginal cost of production are constant so that it would be most efficient if only one firm invests in the new technology.

After Eq. (38), we have clarified the case of a boundary solution and removed the term “unrealistic”.

In this paper, we don't consider the case where the two regulators cooperate and maximize their joint social welfare function. In the studied non-cooperative case, if firms decide to adopt the clean technology non-simultaneously, this will lead to one active firm and one inactive firm. This latter will not choose non-simultaneous adoption, and firms will adopt the clean technology simultaneously.

10. The socially optimal output levels are the same under autarky and under the common market (eqs. 5, 11, 28, 32). Why is this so?

Production quantities are the same under autarky and a common market because these socially optimal production quantities maximize the instantaneous social welfare independently whether firms compete or not. We have clarified this point after proposition 5.

11. Similarly, what is the reason for the inversion of the ranking between the welfare gains and profits in proposition 1 and 6?

We have inserted the following clarifications after propositions 1 and 3, respectively:

“Indeed, under autarky, because of the monopoly power, the instantaneous net profit of a firm is very high even when it uses the polluting technology.”

“This result is different from that obtained under autarky because the monopoly power induces that the instantaneous net profit of a firm is higher than under a common market where we have a duopoly. This holds whether firms use the polluting or the clean technology.”

12. The authors discuss proposition 10 as "surprising" but I think there is a straightforward intuition. In the common market there is more competition. Hence there is less reason to raise output by a low emission tax or a high subsidy for renewables.

Proposition 10 (in the revision proposition 6) is surprising with respect to what we could expect from regulators that try to give competitive advantages to their

respective firms. However, with the explanations given in the paper, it is no longer “surprising”. We have removed the word “surprising”.

13. The authors should discuss why the regulator can only subsidize output of renewables, but not the implementation of the clean technology. I find that this is an important point because the marginal cost of renewable are assumed to be lower than those of fossils. Subsidizing implementation of the clean technology would also make it easier to disentangle the optimal response to the two market failures of imperfect competition and environmental externalities.

In the previous version of the paper, we have tried to consider and to compare the case where the regulators interfere and the case where the regulators don't interfere in the implementation of the clean technology. As you recommended, we considered in the revised paper only the case where regulators subsidize the implementation of the clean technology.

14. In my opinion there are too many propositions. The authors should work out their most important findings and focus on them.

We have reduced the number of propositions from 12 to 7.