ENVIRONMENTAL TAXES, INEQUALITY AND TECHNICAL CHANGE[1]

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Environmental innovations heavily depend on government policies and consumers' behaviour. This paper addresses the issue of how these two factors interact in shaping the transition to a green technology. We extend models of technological selection with heterogeneous agents and learning by including a weak hierarchy between green and polluting goods. For general distributions of agents' income and the explicit inclusion of a carbon tax, the model is not analytically tractable so we derive our results using numerical simulations. Given the level of income, carbon taxes are more effective when technological improvements brought about by wealthy pioneer consumers suffice in inducing the remaining population to buy the green good. In this case, a negative relationship between income inequality and tax effectiveness emerges. Taxes on polluting production have a regressive effect since they are mainly paid by poorer people who consume less of the green good. For these people, a negative wealth effect strongly contrasts the standard substitution effect of the tax. Finally, both lower inequality and taxes have the expected effect for intermediate levels of the learning parameter.

Keywords: Environmental Innovation, Inequality, Demand, Simulation Models.

Concerns for quality of life, sustainability of growth and environmental issues occupy an increasingly important position in the set of citizens' values, especially in developed countries where basic needs have been met (Inglehart 1995). Technical change is at

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the centre of the political discourse being the unique way of reconciling current consumption patterns with both natural resources preservation and environmental quality. In the case of environmental technologies, policy interventions and the spontaneous involvement of citizens-consumers are particularly important as market prices do not reward for the lower environmental impact of green goods. Furthermore, two channels are recognized to be the most important drivers of environmental innovations (Beise and Rennings 2005): a direct market demand for green products and an indirect political pressure for the approval of ambitious environmental policies.

On the political side, consumers, local communities and environmental activists play a key role in signalling harmful effects of certain economic activities, in giving political voice to ethical issues (i.e. the rights of future generations) and in reinforcing the effectiveness of government interventions (Esty 1998). For instance, cooperatives and diffused ownership characterize the industry of wind turbines in Denmark (Johnson and Jacobsson 2003), while German environmental activists played a key role in sustaining ambitious feed-in-tariff programs (Lauber and Mez, 2004). On the economic side, agents' consumption choices and willingness-to-pay (WTP, henceforth) higher prices for products with low environmental impacts allow the creation of niche markets for these products. Policies can be targeted to promote the creation of niche markets through labelling, public procurement or regulation, e.g. car sharing requiring low-emission cars (Kemp *et al.* 1998). Another example is the one of the private provision of a public good where certain consumers accept to contribute to the good independently on what the others do (Kotchen 2006). All these examples suggest that the effectiveness of environmental policies depends on the distribution of preferences for environmental quality across heterogeneous agents.

This paper focuses on a particular aspect of the complex relationship between agents' heterogeneity in preferences, technology diffusion and environmental policy. In particular, we analyse how the effect of the policies on green technologies is mediated by the distribution of agents' preferences and by the budget constraints preventing these preferences to be realized, i.e. poverty and financial distress. With this aim in mind, we develop a simple model of technological selection with heterogeneous agents and pioneer consumers generating positive spillovers on the remaining population. These ingredients are common to a wealth of models, both analytical (Matsuyama 2002, Bertola *et al.,* 2006) and computational (Frenken *et al.* 2006, Cantono and Silverberg 2010). We contribute to this literature in two ways. First, heterogeneous attitudes towards green or non-green goods, embodying technologies with different environmental impacts,[2] depend in our model on microfounded agents' behaviour. More precisely, following our previous paper (Vona and Patriarca 2011, PV henceforth), we capture the fact that wealthier households care relatively more about environmental quality by introducing a weak hierarchy between green and non-green goods. This allows us to analyse not only the decision of buying the green good or not, as in related studies (e.g. Cantono and Silverberg 2010), but also the intensity of that choice. As a result, consumers' decisions depend on two income thresholds: a low threshold when a consumer starts buying the green good, a high threshold when she shifts from a mix of goods to full green consumption. Second, we extend PV (2011) in two ways: 1. by examining technological selection for general distributions of income, 2. by looking at the effect of a tax on polluting goods under different levels of income inequality.

These two extensions require a substantial departure from the methodology used in our original paper as it is difficult to preserve analytical tractability with many heterogeneous consumers not uniformily distributed and two thresholds moving endogeneously with technological learning. Besides, numerical simulations help in quantifying the effect of the tax in scenarios characterized by different learning speeds and levels of income inequality. Results of computer simulations not only generalize our previous theoretical and empirical findings on the reversion of the effect of inequality on the diffusion of the green good, but also contribute to explain the heterogeneneity in the effect of environmental policies on technological development (e.g. Vona *et al.*, 2012). In particular, we show that, given the initial level of income per capita, environmental taxes are more effective when positive

2. We assume that each good is produced with only one technology. Green (resp. non-green) goods are produced using a technology with low-(resp. high-) environmental impact.

spillovers from pioneer consumers can effectively trigger a second wave of demand for the green good. Thus, a negative relationship between income inequality and tax effectiveness emerges. In extreme cases, the regressive impact of polices like carbon taxes may have the paradoxical effect of reducing the number of consumers of green products. Our final contribution is methodological as we develop a model that has an analytically tractable core and an extension solved numerically. With respect to closely related percolation models of technology adoption (e.g. Cantono and Silverberg, 2010) and to ABM in general, this extension seems particularly promising as it enables to anchor simulation results to analytical ones.

The paper is organized as follows. Next section reviews the literature on inequality, environmental technologies and consumers' behaviour. In section 2, we remind the model and extends it for general distribution of income, Section 3 presents the main results, while section 4 concludes.

1. Related literature

Understanding the determinants of environmentally friendly behaviour represents the point of departure to entrench theoretical analyses on well-established stylized facts. Two strands of literature analyse the formation of green preferences: at the micro level, the empirical evidence on the determinants of the WTP for green goods; at the macro level, the one on the determinants of environmental regulation.

The macro strand of literature is quite scant given the lack of reliable time-varying data on environmental policies and regulation. Among the few exceptions, Dasgupta *et al.* (2001) and Easty and Porter (2002) show that GDP per capita is positively correlated with two independently built indicators of environmental policies, even when adding proxies of government efficiency and of costs of bureaucracy.[3] Interestingly, too, the index built by Easty and

3. The composite indicator used in Dasgupta et al. (2001) includes both environmental policy and environmental awareness and it is based on a survey conducted by the United Nation. The indicator used in Easty and Porter (2002) attempts to measure environmental regulation and uses data sources from the ESI project and the Global Competitiveness Report. Data sources: http://www.yale.edu/esi/ and http://www.weforum.org/issues/global-competitiveness

Porter tends to be significantly higher in more equal Nordic and central European countries. Recent work of Nicolli and Vona (2012) develops time-varying aggregate indicators of renewable energy policy[4] that are positively correlated with GDP per capita. Moreover, they show that lowering inequality positively affects the policy support for renewable energy, especially in high income countries and using policy indicators built with factor analysis. Inequality has a strong negative impact on public expenditures in green R&D as found by Magnani (2000) and by PV (2011), where the effect of inequality appears even stronger in the longer time span considered. Both in PV (2011) and in Nicolli and Vona (2012) a reversion in the relative effect of income levels and inequality emerge, that is: whereas for rich countries inequality negatively affects public policies and demand for green technologies, per-capita income is paramount in poorer ones. This evidence supports our claim that environmental quality is a good relatively higher in the hierarchical ranking.

At the micro level, several studies have shown that wealthier and more educated households are generally more willing to pay higher prices for green goods (Roe *et al.,* 2001; Wiser, 2007; Diaz-Rainey and Ashtonn 2009),[5] to participate voluntarily to the provision of green public goods (Rose *et al.* 2002, Wiser 2007, Kotchen and Moore 2007, Kotchen 2010) or to effectively buy green goods (OECD 2008, Kahn 1998, Gilg *et al.* 2005). It is worth noticing that the overall impact of richer households on the environmental quality can be either positive or negative as long as richer households consume more. However, their impact on technology through the demand of green goods is certainly positive. Also micro-evidence is consistent with our claim that environmental quality is a good relatively higher in the hierarchical ranking. In particular, sociological studies using value and social surveys show that "[the] concern for quality-of-life issues, such as free of speech, liberty and environmental protection... arise only after individuals

4. Data source: http://www.iea.org/textbase/pm/?mode=re
5. Peer effects in consumption are also found to be very relevant in the Contingent Evaluation of the WTP for clean energy carried out by Wiser (2007). In particular, the expected contribution of the others is found to be significantly correlated with the individual willingness to contribute. This result becomes relevant for the relationship between inequality and environmental quality if, as well known in the literature on peer effect in education, peer effects enter nonlinearly in the utility function.

have met their more basic materialist needs for food, shelter, and safety" (Gelissen, 2007; p. 393, see Diekmann and Franzen 1999, Franzen 2003).

On the theoretical side, the standard way to examine the relationship between income inequality and environmental quality is to look at the political-economy determinants of environmental regulation. Using a median voter argument, Magnani (2000) claims that income inequality and expenditures for environmental R&D can be negatively correlated if richer households prefer more environmental quality than poorer ones. Eriksson and Persson (2003) also derive a partial negative relationship between inequality and pollution in a political economy model where heterogeneous agents decide the optimal level of pollution control under the assumption that wealthier individuals are less affected by pollution.[6] Kempf and Rossignol (2007) study a similar problem but allow for a dynamic trade-off between growth and environmental quality. There, the median voter jointly decides the taxes devoted to finance two public goods: environment and infrastructures, which are conductive to growth. In line with previous studies, if the weight assigned to the "environment" in the utility function is low enough with respect to the one assigned to "consumption," a more unequal society would privilege production rather than the environment. Among the channels that support a negative impact of inequality and social segregation on the environment, recent studies (e.g. Rothman 1998, Roca 2003) claim that rich people are often able to divert the monetary benefits out-of-pollution from the cost of it. For instance, in a model of spatial sorting of agents by skills, Gawande *et al.* (2001) show that hazardous waste sites tend to be located in neighbourhoods with a higher fraction of poorer workers willing to accept higher pollution in exchange of jobs in the polluting sector.

All these models examine settings where technology does not change and hence neglect the role of environmental innovations, especially of those innovations that imply a redesign of the whole production process rather than the mere adoption of end-of-pipe solutions. Environmental innovations can be conviniently distin-

6. As in Magnani (2000), the result hinges upon the fact that, given the average income, a richer median voter can afford both more pollution control and more consumption.

guished between end-of-pipe and cleaner (or integrated) technologies: "Cleaner production reduces resource use and/or pollution at the source by using cleaner products and production methods, whereas end-of-pipe technologies curb pollution emissions by implementing add-on measures" (Frondel *et al.,* 2004, pp.1). The former are true innovations, both from the perspective of reducing net energy and material flows and from the one of economic agents, who have to change their behaviour to adopt these technologies.[7] More in general, a transition from polluting to a cleaner technology is best understood as a complex phenomenon involving changes in many institutional layers and the building of new social constituencies (Kemp 1994). Particularly important is the process through which new technologies acquire social legitimacy and become cost-effective. Overall, these socio-cultural features of new technologies are particularly important for green products that involve radical changes in habits and convey an intrinsic ethical motivation.

Following this argument, it is convenient to think at the dynamic interaction between consumers' behaviour and technological development as a prototypical feature of green technological transitions. Standard growth models are not well-equipped to deal with the path dependency emerging from demand-supply interactions. This weakness of standard models is even more relevant when consumers are heterogeneous and hence the dynamics of demand results from the aggregation of different evolving behaviour (e.g. Faber and Frenken 2009 on this argument in relation to environmental issues).

With regards to the diffusion of green products, agent-based computational models (ABM) have been applied to capture the intrinsic socio-cultural aspects of green technologies by introducing a richer set of assumptions on consumers' behaviour. These models typically analyse diffusion patterns of green goods in complex environment characterized by rich supply-side dynamics (Bleda and Valente 2009, Windrum *et al.* 2009) and using calibrated data to build scenarios for technological transitions

7. Examples of significant behavioural changes are: production of energy from renewable sources involving greater decentralization and self-production; change in the ownership structure to enlenght the durability of certain goods, e.g. cars; recycling and reusing activities; creation of consumers' networks to ensure steady demand to local producers of biofood.

(Schwarz and Ernst 2010). Within the broad class of simulation and ABM models, percolation models (Antonelli 1996, Silverberg and Verspagen 2005, Frenken *et al.* 2008) represent the most parsimonious approach to study technology selection with economies of scale and network externalities (e.g. Geroski 2000) when consumers are heterogeneous. Cantono and Silverberg (2010) apply these models to the case of the diffusion of environmentally friendly goods and analyse the effectiveness of a green subsidy. Diffusion of green consumption is constrained by both the heterogeneity in individual WTPs and the consumers' network structure, which affects the spread of information diffusion across potential adopters. To capture learning, the price of the new good decreases with the number of adopters. In this simple setting, the subsidy is effective only within an internal range of the learning parameter: when learning is too slow consumption does not take off, when it is too fast diffusion takes place anyway.

The logic of our model is related to the one of Cantono and Silverberg (2010) as lead-users and consumers' heterogeneity are also essential. Our paper, however, provides a different microfoundation for agent's adoption decision that depends explicitly on the opportunity cost of giving up consumption of the polluting good,[8] through income, and on the initial price gap between the two goods. As will be clearer in the next section, our model also analyses the relationship between the shape of the distribution of WTP for environmental quality and the final outcome.

2. The model

To analyze the choice between polluting and non-polluting goods, we adopt the framework of PV (2011). The simplest setting to address this issue is to consider two goods and two wants. Both goods satisfy a basic need, like food or shelter. The green good,

8. It is interesting to note that, in sociological surveys measuring the values for environmental quality, result strongly depends on the way the demand is made. In terms of absolute preferences developed and developing countries do not differ much. In turn, the higher propensity to spend in environmental quality of developed countries clearly emerges when the opportunity cost of environmental protection in terms, for instance, of foregone income is explicitly mentioned in the survey questionnaire (Inglehart 1995, Diekmann and Franzen 2003). Therefore, this opportunity cost should be also considered in building theoretical models.

indexed by 2, is more expensive but it also satisfies a non basic want like environment preservation. The green good enables agents to enjoy the same direct utility of the old one plus an additional utility linked to an "eco-friendly" motif. This is a convenient way to model preferences for the environment as it encompasses both the case in which "eco-friendly" goods are of better quality, and the one where they are consumed for "altruistic" reasons or moral obligations (see Eriksson 2004, Conrad 2005, OECD 2008).

The weak hierarchy between the two wants, the second being not necessary in an Inada sense, is essential to derive the particular shape of the Engel curve that, in turn, is crucial to derive our main results. As discussed in previous section, this assumption is also empirically founded.

More in details, we adopt the simplified framework of a utility function $w(.)$ that is continuous and additively separable in the two wants. In particular, $w(.)$ is concave in the basic want and linear in the second one. Thus[9]:

$$w(x_1; \mathrm{x}_2) = u(x_1 + x_2) + x_2\,; \tag{1}$$

where x_i is the quantity of the good i and $u(.)$ is a strictly concave function. Note that each unit of the second good gives a greater utility than each unit of the first one, so the first good is consumed only if the price of x_2 is sufficiently higher than the price of x_1. Now let m be the total income to be allocated between the two goods, δ_p the relative price gap, *i.e.* $p_2–p_1 / p_1$ that represents a proxy of technological expertise in the production of the two goods. Under the previous hypotheses on the utility function, the first order condition for the internal solutions of this simple constrained optimization problem gives:[10]

$$u'(x_1 + x_2) = \frac{1}{\delta_P}\,; \tag{2}$$

9. Further details are discussed in PV (2011) where we also show that the linearity of the utility function in the second want is not necessary to derive our results. Note that the more general form $w_i(x_1; x_2) = u(x_1 + x_2) + \upsilon_i x_2$ would allow to capture heterogeneity in individual preferences for the environment.

10. The first order condition in Equation (2) states that $\tilde{x}$ corresponds to the level of consumption at which the ratio between the marginal utilities of the basic want $u'(x_1 + x_2)$ and of the other want (1) equals the marginal cost of substitution between the two goods

Considering the properties of u, and defining the function ϕ as the inverse of u', this condition has the following solution:

$$x_1 + x_2 = \phi\left(\frac{1}{\delta_P}\right) = \tilde{x} .; \qquad (3)$$

Equation (3) implies that a mixed bundle is chosen only within an income thresholds $m \in (m^-, m^+)$. If income is not enough to buy the quantity $\tilde{x}$ of the cheapest good ($m < m^- = p_1\tilde{x}$) the green good is not consumed. When agents are rich enough to buy a quantity of good 2 ($m > m^+$), they will consume only that good which satisfies also the other want.

Figure 1. Engel's curves for the two goods

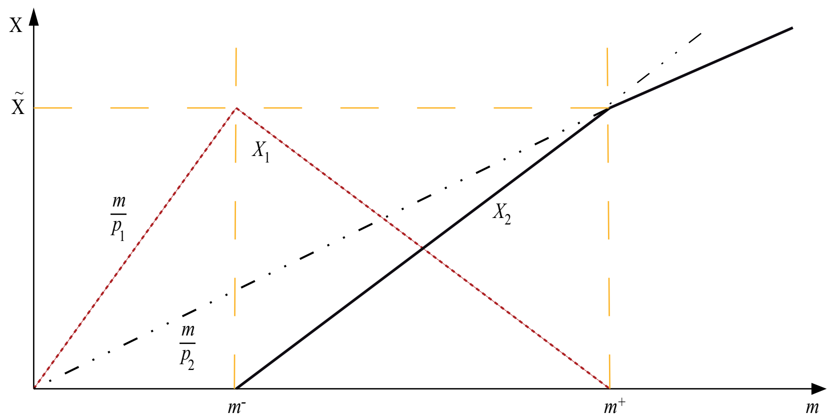


Figure 1 shows the Engel's curve derived by this analysis. The particular S-shape of the Engel's curve of x_2 is the main driver of all further developments. To give a preliminary intuition, it is worth to recall an important property of this curve (see PV 2011 for details). It is steeper in the region (m^-, m^+) than above m^+ Between m^- and m^+, the gradual substitution of the old good with the new one reinforces the positive effect on the consumption of due to the income expansion itself, while in the third region ($m > m^+$) substitution no longer occurs.

In what follows, it is useful to recall that the income thresholds (m^-, m^+) have a "dual" counterpart in the price domain. The "price gap" thresholds are important to analyse technological change in so far as, under standard competitive conditions in all markets, prices reflect costs and the inverse of the price gap reflects technological levels. Moreover, the two price gap thresholds, that correspond to a shift in consumers' behaviour, depend on m. The richer the consumer, the lower the two price gap thresholds required to start consuming the green good. Put it differently, rich consumers buy the green good even if the way of producing it is relatively inefficient.

2.1. The effect of a tax on the first good

In this section, we derive the basic analytical results on the effect of a tax that increases the price of good 1, *i.e.* a carbon tax. The non linearities in the income-demand curves derived in previous section imply that higher income people consume lower shares of the taxed good. Thus, the tax has a regressive impact. For consumers with incomes above m^+, the tax has clearly no effects since they do not consume the taxed good. Conversely, for consumers with incomes below m^+, the tax will have, as usual, the two contrasting substitution and income effects. The strength of each of these effects varies according to agents' shares of consumption, hence according to their income. To analyze the combined impact of these two effects, let us consider the effect of the tax on the two thresholds. A higher p_1 entails a lower δp. Since the marginal utility is a decreasing function (see Equation (2)), it is straightforward to show that this implies a lower $\tilde{x}$. That is, a tax on the old good always decreases the income threshold of consumption at which agents start consuming the new good. In formulas we have.[11]

$$\frac{\partial \tilde{x}}{\partial p_1} = \frac{1}{u''} \frac{p_2}{(p_2 - p_1)^2} < 0. \tag{4}$$

However, the effect of the tax on the income thresholds is not so trivial. Indeed, we have:

11. The continuity and differentiability of all functions considered give:

$$\frac{\partial \tilde{x}}{\partial p_1} = \frac{\partial \tilde{x}}{\partial \delta_P} \frac{\partial \delta_P}{\partial p_1} = \frac{\partial \phi(\frac{1}{\delta_P})}{\partial \delta_P} \frac{\partial \delta_P}{\partial p_1} = -\phi' \frac{1}{\delta_P^2} \frac{\partial \delta_P}{\partial p_1};$$

the definition of ϕ and the properties of the derivative of an inverse function gives Equation (4). .

$$\frac{\partial m^{+}}{\partial p_1} = p_2 \frac{\partial \tilde{x}}{\partial p_1} < 0. \tag{5}$$

$$\frac{\partial m^{-}}{\partial p_1} = p_1 \frac{\partial \tilde{x}}{\partial p_1} + \tilde{x} \gtrless 0. \tag{6}$$

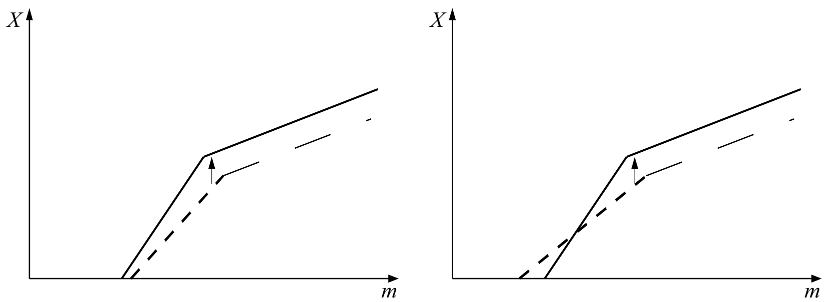
While the upper threshold will always diminish with the tax, thus favoring the demand shift to the green good, the effect on the lower threshold, *i.e.* the minimal income needed to consume the new good, deserves to be further discussed. The first term in Equation (6) represents the substitution effect. It is always negative and, according to Equation (4) is decreasing in the concavity of the utility function and increasing in the price gap. The second term of Equation (6) is the income effect, it is positive and, according to Equation (3), is increasing in the price gap. As a result, for not very concave utility functions and high price gap, the tax may increase the income threshold at which agents start consuming good 2. In this case, some households in the neighborhood of m^{-} are induced to consume less of the second good because the income effect associated with the higher cost of satisfying the basic need offset the substitution effect associated with a lower price gap. Although this can be seen as an extreme case, it is important to be aware of such possible reversing effects when designing incentive schemes to foster environmental preservation.[12] In the more general cases, the tax increases the demand of the new good of all agents but such an increase is much lower for poorer people that have a stronger negative income effect. Figure 2 summarizes the two possible effects of the tax on the Engel curves.

The case represented on the right panel of Figure 2 allows to visualize the range of middle-low incomes for which the tax has the paradoxical effect of reducing consumption of the green good. The left panel of Figure 2 displays instead the well-behaved case. It is also important to remark that, in both cases, the environmental tax has the standard regressive effect of benefiting wealthier households more than poorer ones (e.g. OECD 2004). In our model, this

12. For instance, this paradoxical result provides a different, simpler rationale to justify the joint adoption of a carbon tax and a subsidy for the green good The standard justification is that the tax is needed for the environmental externality, while the subsidy for the learning or knowledge externality (Jaffe *et al.* 2005). Mix of taxes and subsidies are also commonly observed in practice. The subsidy here can be used to offset the negative income effect of the tax.

result depends on a simple compositional effect. Poorer households consume a large fraction of the dirty good that becomes more expensive. Notice also that subsidizing the consumption of the green good cannot be enough to offset this regressive effect as long as poorer households keep buying a greater fraction of the dirty good. Income transfers are hence required to offset the redistributive effects of environmental policies.

Figure 2. The effect of a tax on the Engel curve



Grounded on these analytical results, the next section address the issue of the effectiveness of environmental taxes on the diffusion of the green good in a context of heterogeneous agents, drawn from a left-skewed distribution of income. Before this, the next sub-section briefly summarizes the relationship between aggregate demand of x_2 and the shape of the income distribution.

2.2. Income Distribution and aggregate demand

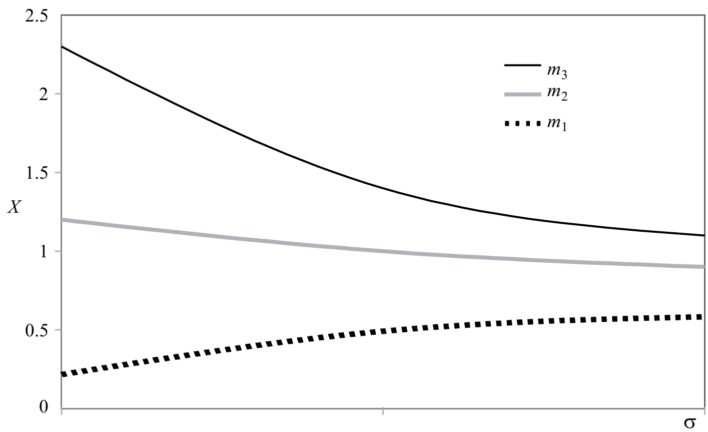
In an economy where agents are heterogeneous in their incomes, the non-linearities in the Engel curves imply that the diffusion of good 2 jointly depends on the average income and on the level of income inequality. With the purpose of giving preliminary insights on this process, let us consider numerical examples drawn from a log-normal distribution of income with a concave shaped utility for the basic want.[13] This is also the distribution of consumers' characteristics chosen by Cantono and Silverberg (2010), which, however, do not analyse the role played by the second moment of the distribution.[14]

13. In particular, we take: $u(x) = ln(x)$ and $\delta p = 2$.

14. Also the functional distribution of income matters on the diffusion pattern of a new good (see Patriarca and Vona 2009).

In Figure 3, we plot the aggregate demand X_2 as a function of the variance in income distribution for different mean income levels ($m_1 < m_2 < m_3$). If the mean income is relatively high, an unequal distribution implies an increase in the number of agents with income under the threshold m^-. For the characteristics of the Engel curve for x_2, that is steeper in ($m^- < m^+$), a redistribution would have in this case a positive impact on the diffusion of the green good. Conversely, in relatively poorer economies, higher income dispersion enables fewer rich people to consume the green good, which can at most emerge as niche consumption.

Figure 3. Variance of the income distribution and diffusion of the green good for different levels of the mean income



This reversal effect of inequality on the diffusion of x_2 is a consequence of the S-shaped feature of the Engel curve of the new good. In turn, the S-shaped relationship depends both on the assumption of a weak hierarchy between the two goods and on the fact that very poor consumers do not buy the green good. It is interesting to note that the S-shaped feature of our Engel curve does not allow to sketch a uniform relationship between inequality and the diffusion of x_2 as it would be for concave—or convex-shaped curves considered in the previous literature on the "aggregation argument" (e.g. Heerink *et al.* 2001). For a standard aggregation argument, if the rich buy relatively more of the green good, higher inequality would generate more consumption of green goods. In our model, instead, middle income households are the only ones for which an income expansion translates in a more than proportional increase of x_2. Hence, there is a reversal in the effect of inequality on the diffusion of the green good for sufficiently high levels of average income.

3. The effect of a tax on the diffusion of green technologies

3.1. The dynamic setting

To analyse the effectiveness of the carbon tax, we consider an environment where technology improves endogenously. As well-documented in the literature on demand-driven innovation (e.g. von Hippel 1988), initially pioneer consumers are willing to buy more expensive innovative products. Their consumption is a source of positive externalities as long as it triggers price reductions that may enable low-budget consumers to adopt these products (pioneer consumer effect, PC henceforth). However, an "excessive income distance" between pioneer consumers and the remaining population prevents the process of diffusion to fully trickle down (consumption polarization effect) to other consumers. The overall effect of the heterogeneity in consumers' characteristics, notably the variance, on the diffusion pattern depends on which of the two effects prevails.

The simplest way of including technological spillovers from pioneer consumers consists in introducing a positive relationship between the growth of demand for X_2 and technological change, *i.e.* a global externality. This assumption is a quite standard way to capture pioneer consumers' spillovers (e.g. Matsuyama 2002, Cantono and Silverberg 2010). Let us denote with γ_i the technological level in sector i, which is equal to the inverse of p_i *i.e.* $p_i = 1/\gamma_i$. We chose a particular linear form for the learning function:

$$\gamma_{2,t} = \gamma_{2,t-1} + c(X_{2,t-1} - X_{2,t-2}), \tag{7}$$

where c measures the effectiveness of technological change. We now analyze the process of diffusion of good 2, by considering the initial condition in which the green good appears at time 1, with a technological level $\gamma_{2,0}$ low enough as to induce a niche demand for this good by few pioneer consumers. Clearly, we also assume a positive technological gap at time 0 *i.e.* $\gamma_{1,0} - \gamma_{2,0} > 0$ being the green technology initially less developed.

Once the niche level of demand emerges, the process of technological progress involves a self-reinforcing process of decreases in p_2 and thus increases in the demand of this new good. For a given mean income, the dynamics of demand depends on the technological parameter c and on the mass of consumers that, in correspondence to each technological improvement, increase their consumption of x_2 the latter being a function of the income distribution. We consider a realistic and general distribution of incomes: the incomes of a population of 1000 agents are extracted from lognormal distributions. The higher complexity of this model with respect to the original paper requires the use of simulation methods.

We compare the diffusion patterns for the new good of two random samples with the same mean (set at a level that allows for a niche consumption of the green good at time 0) but with different variances associated with a Gini coefficient of respectively 0.22 and 0.44, which are the lower and upper bounds of Gini coefficients in OECD countries.[15] The results of this preliminary exercise are shown in Figure 4: the left panel considers a lower level of the learning parameter while the right one a middle level.[16] In the left panel, when technical change is too slow, the PC effect prevails so the unequal society guarantees greater diffusion of the green good. In the right panel, the level of c potentially allows a full diffusion of the new good and the more equal society outperforms the unequal one.

In both cases, technological progress is initially faster in less equal countries because of the stronger PC effect. When technology becomes more mature, however, the more equal population recovers and overcomes the less equal one given the larger number of potential followers, i.e. the middle class is larger. This result, jointly with the empirical evidence presented in the PV (2011), seems to confirm that pioneer consumers play an important role in explaining early stages of technological development, while the mass of potential adopters is more important in later phases. In the

15. See, e.g., OECD on-line statistics: http://stats.oecd.org
16. Respectively, c and $c = 0.2$.

right-hand panel of Figure 4, the crossing-point between the two diffusion curves corresponding to different levels of inequality highlights this leap-frogging effect that—it is worth to remark—occurs only for a sufficiently high learning potential. Finally, Figure 5 replicates the analysis of Figure 4 for a lower level of income per capita. In this case, the green good diffuses less in the equal society also in correspondence to higher levels of the learning parameter. This further exercise generalizes our analytical result on the reversion in the effect of inequality depending on the level of income per capita (see PV 2011).

Figure 4. Dynamics of consumption of the green good

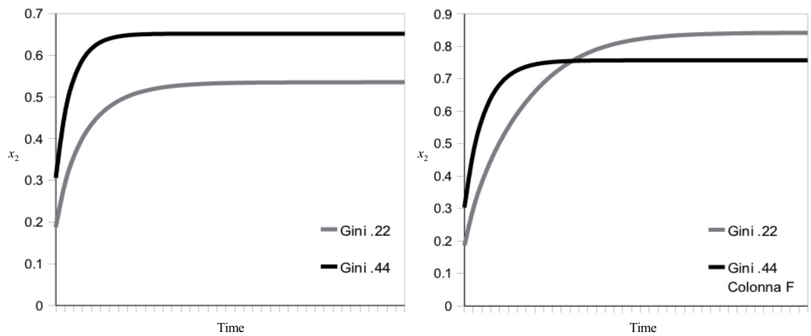
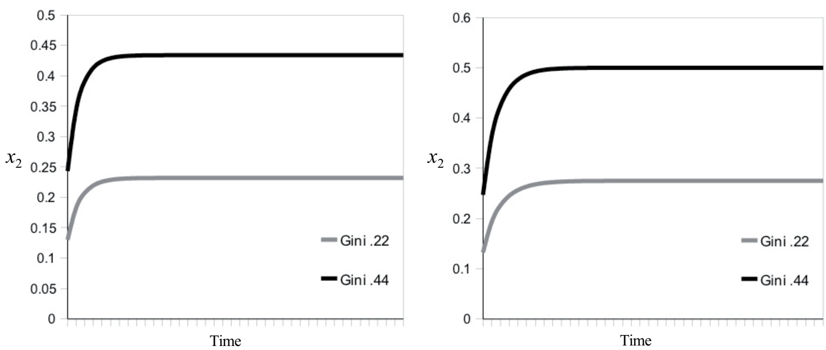


Figure 5. Dynamics of of consumption of the green good (lower mean income)



3.2. The effect of a carbon tax

To examine the effect of a carbon tax, we use a slightly different approach and extract randomly 100 couples of populations of 1000 consumers. Each couple of populations is a random sample from two lognormal distributions having the same mean but two different variances that correspond to the lower and upper bounds of the Gini coefficient in OECD countries, respectively .22 and .44. For every couple we analyze the effect of a 5% carbon tax on the diffusion of the new good. We run the model for four cases: with and without the tax for each of the two population. As we already discussed in the previous section, the dynamics of the system depends on the income distances between agents. In each population, these distances vary although they are all randomly extracted from the same stochastic process. The 100 replications allow to make the results independent from the income distances of the specific population. First, we consider a benchmark case setting the parameter c at an intermediate level (the same as in the left panel of Figure 4), then we will move to the more general case, by varying c in its relevant range.[17]

Table. Final Levels of X_2

		no tax	tax	% change
Population1	mean	844.8	993.4	17.75
(Gini=0.22)	std. dev.	[1.9]	[1.5]	[1.6]
Population2	mean	760.4	839.1	10.31
(Gini=0.44)	std. dev.	[1.8]	[1.5]	[1.8]

Source: Simulated values for 100 couples of populations of 1000 consumers.

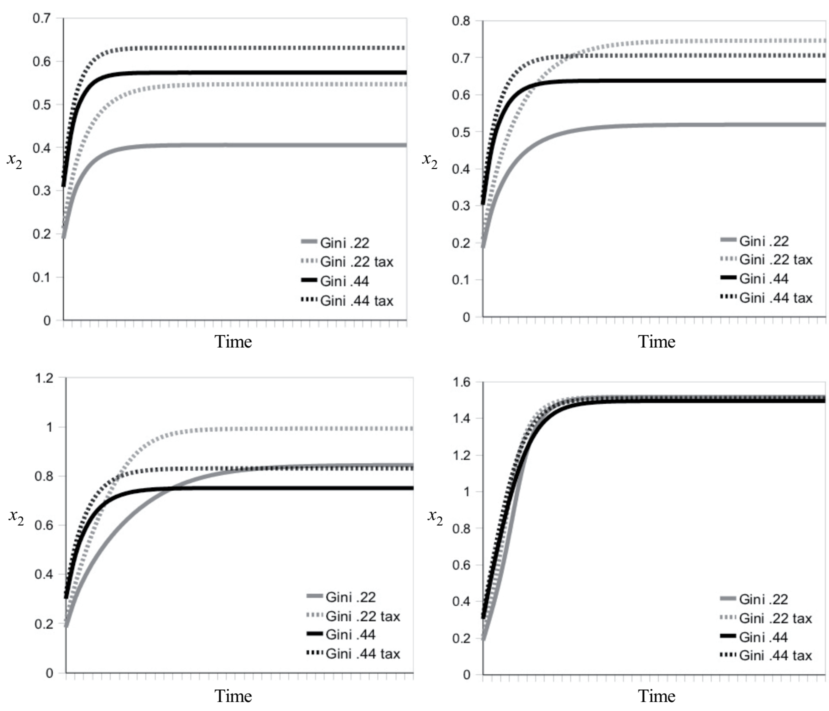
The first two columns in Figure 1 show the average final demand levels of of the new good in the four cases. The third column shows the average relative increase of the final demand level involved by taxation. The result states the higher effectiveness of the tax for the more equal population. In particular, the average improvement is 17.75 for the equal population with respect to an average of improvement of 10.31 for the unequal one. The difference in the effect of the tax is highly statistically

17. The parameters for the benchmark case are: c = 0.2, $p^1 = 1$, the initial level of the price gap is $\delta p = 2$ and the mean income is $\mu = 2$.

significant since standard deviations are very low. Comparing column 1 and 2, it is evident that the tax amplifies the positive effect of lowering inequality on the diffusion of the green good.

The final robustness exercise consists in exploring the effect of the tax for different learning parameters. For the sake of simplicity, we consider two populations, characterized respectively by a Gini equal to .22 and .44 respectively, for which we plot the dynamics of the demand of the new good for different levels of the parameter c ($c_1 < c_2 < c_3 < c_4$[18]). This simple graphical analysis of specific cases allows to draw some insights on the joint role of the parameters of the model. Results are shown in Figure 6, where the third panel is the benchmark in Figure 4.

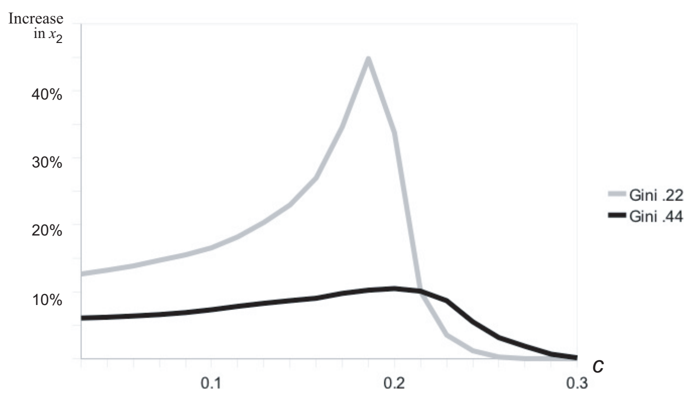
Figure 6. The effect of a tax for different learning parameters



18. We set: $c_1 = 0.16$; $c_2 = 0.18$, $c_3 = 0.20$ and $c_4 = 0.28$.

The positive effect of lowering inequality documented in the previous section is confirmed, except for high levels of the learning parameter (south-east panel of Figure 6). Similarly to Cantono and Silverberg (2010), a very effective technological learning renders useless both the carbon tax and an income redistribution. Panel north-west in the same figure confirms that the unequal society outperforms the equal one for low levels of the learning parameter. However, the tax is more effective in the equal society also in this scenario. The north-east and south-west panels stress the continuity of our main argument: the tax can be very effective when a lower inequality favours the formation of a second wave of demand for the green good, while it is relatively ineffective when inequality is too high. Interestingly, too, the tax allows the more equal system to outperform the less equal one also for relatively low learning parameters (see north-east panel in Figure 7). This important result reinforces our result (see also PV 2011) that environmental policy turns out being significantly more effective in more equal societies.

Figure 7. Tax effectiveness (average relative increase in the diffusion of the new good due to taxation) and learning parameters



To conclude, as a robustness analysis, we take the previous 100 couples of random populations and run the dynamics of the system for 20 consecutive values of c in its relevant range (0, 0.3). As in the table in Figure 1, for each value of c we obtain the average relative increase in the final level of the X_2 due to the tax for the two inequality cases. Figure 7 shows the result of this exercise.

Previous conclusions are strongly confirmed: tax effectiveness is almost everywhere higher for the equal case; the relation is reverted only for higher values of c, that is, when the effectiveness of the tax tends to zero as technological change allows by itself for a wide diffusion of the new good. Furthermore, the tax has a stronger impact for intermediate values of the learning parameter, especially in the equal case.

4. Conclusion

This paper generalizes to the case of realistic distributions of heterogeneous agents our previous theoretical and empirical findings on the reversion of the effect of inequality on the diffusion of green goods (PV 2011). In correspondence to low levels of income per capita, high inequality maximizes the positive effect of early adopters and positively affects diffusion. In turn, the reverse occurs for high levels of income per capita as pioneer consumers can effectively trigger middle class consumption, provided the income distance is sufficiently low.

The second and main result of the paper is to provide a rationale for the heterogeneity in the effect of environmental policies on green technologies (e.g. Vona *et al.* 2012). First, notice that the policy is regressive as it increases the income required to buy the basic good and hence reduces residual income that poor households can devote to the green good. For middle—and low—income households, the tax can bring a negative wealth effect that may overcome the standard substitution effect and, under certain conditions, it leads to the paradoxical result of a reduction in the overall diffusion of the green good.

In the dynamic setting, environmental taxes are generally more effective when, given the level of income, technological externalities from pioneer consumers suffice in inducing less wealthier households to buy the green good, and thus when inequality is lower. The tax can benefit also the middle and low classes only if this negative income effect in the short-term is more than offset by an effective increase in the consumption of the green good in the long-term. Another interesting result, similar to the one of Cantono and Silverberg (2010), is that the tax appears to be significantly more effective when learning is neither too slow nor too fast. When learning is too slow, green consumption remains anyway in a niche. When learning is too fast, the transition does not depend on the level of inequality. Instead, relatively unequal societies with a larger pioneer consumer effect transit fast to the new steady state characterized by fully green consumption.

Finally, as a methodological contribution, our analytically tractable model can represent a useful benchmark for numerical simulations and extensions accounting also for local interactions. Two extensions appear particularly promising. First, in the spirit of ABMs, one could explicitly set local consumers' network to examine how the distribution of income across space shapes consumers' habits and technological development. Second, one could model the green good as an impure public good to investigate how agents' implicit cooperation in the provision of that good is affected by different level of income inequality and different expected gains from new technology.

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