Working Paper 27/2013

Optimal environmental policy with network effects: Is lock-in in dirty technologies possible?

Mads Greaker and Kristoffer Midttømme
Statistics Norway and University of Oslo

The CREE Centre acknowledges financial support from The Research Council of Norway, University of Oslo and user partners.
ISBN: 978-82-7988-168-1
ISSN: 1892-9680
http://cree.uio.no

Optimal environmental policy with network effects: Is lock-in in dirty technologies possible?

Mads Greaker and Kristoffer Midttømme
Statistics Norway and University of Oslo

Memo 15/2013
(This version June 2013)

Abstract

Network externalities could be present for many low or zero emission technologies. One obvious example is alternative fuel cars, whose use value depends on the network of service stations.

The literature has only briefly looked at environmentally beneficial technologies. Yet, the general literature on network effects is mixed on whether governments need to intervene in order to correct for network externalities.

In this paper we study implications of network effects on environmental policy in a discrete time dynamic game. Firms sell a durable good. One type of durable is causing pollution when being used, while the other type is "clean". Consumers' utility increase in the number of other users of the same type of durable, which gives rise to the network effect.

We find that the optimal tax depends on the size of the clean network. If starting from a situation in which the dirty network dominates, the optimal tax may exceed the marginal environmental damage, thereby charging consumers for more than just their own emissions. Applying a Pigovian tax may, on the contrary, fail to introduce a socially beneficial clean network.

JEL-Classification: Q55, Q58, H23
Keywords: Network effects, lock-in, enviromnetal taxes

1 Introduction

The solution to an environmental problem often involves replacing an old dirty technology with a new clean technology. According to Barrett (1999) technological innovation was crucial for the success of the Montreal protocol protecting the ozone layer. When it comes to climate change, the technology options are not as evident. The question then arises; will a carbon tax implemented in the industrialized countries induce technological change such that in due time new carbon free technologies will overtake the markets?

According to several authors the answer could be no: The market entry of carbon free technologies is prevented by *lock-in* in fossil based technologies, and a carbon tax equal to the social cost of carbon may not lead to the necessary technological shift. Acemoglu et al. (2012), Chakravorty et al. (2011) and Greaker and Heggedal (2010) all argue that this may be the case for carbon free technologies.

Many mechanisms may lead to lock-in like situations. Acemoglu et al. (2012) describe a process of market driven directed research in which dirty technologies steadily improve and clean technologies are not developed further. Chakravorty et al. (2011) find that fossil fuel resource owners have an incentive to slow learning in the alternative emission free technology by increasing their own extraction. In this paper we will focus on *network externalities* as a potential source for technological lock-in.

Positive network externalities arise if one agent's adoption of a good (a) benefits other adopters of the good and (b) increases others' incentive to adopt it (Farrell and Klemperer (2007)). The literature so far has failed to agree on whether the market outcome will be efficient when network effects are present. Liebowitz and Margolis (1994), for instance, argue that in order for there to be inefficiencies, benefits of an unrealized outcome must exceed the costs, and this can be exploited by private agents with profit motives. Hence, they argue, inefficient outcomes due to network effects will rarely be observed.

In principle the argument of Liebowitz and Margolis should hold even if we have an environmental externality as long as the dirty technology faces a tax corresponding to the social cost of emissions. Yet, it is not obvious that there are such private agents who can exploit coordination failures; the market structure could vary from case to case. Define a *technology sponsor* to be a monopolist supplier of a network good. We investigate the case where both the green and dirty technology are sponsored, the case where only the clean technology is sponsored, and the case where non of the technologies are.

In this paper we pose the following research questions: I) Should environmental policy be adjusted when there are network effects?, II) Does the need for adjustment depend on the existence of sponsors? and III) May a failure to internalize the network externality lead to lock-in? First, we find that optimal environmental policies should take into account the network externality by making policy contingent on the size of the clean network. This holds for all the configurations of sponsors, and may be effectuated by setting an emission tax that departs from the Pigovian tax.

Finally, to answer the third question, we simulate a numerical version of the model. Our point of departure is the competition between fossil based and zero emission cars. Surprisingly, when only the zero emission technology has a sponsor, the market might be dominated by the inferior fossil based technology even if this technology is subject to a Pigovian tax. In this case the government can improve social welfare by subjecting the dirty technology to an emission tax far in excess of the social cost of emissions.

In our opinion network externalities could be present for many clean technologies. The literature distinguishes between *direct* and *indirect* network externalities. In the former case there is a direct benefit to existing consumers when a new consumer is recruited to the network, while in the latter case the benefit to existing consumers from a new consumer comes from increased supply of some complementary product Farrell and Klemperer (2007).

Direct network externalities are for instance likely to be present in the competition between advanced virtual meeting equipment and air travel. *Indirect* network externalities might be the case for both zero emission cars, and for carbon capture at powerplants and industries. Carbon capture requires the complementary pipeline transport service in which there are economies of scale. Thus, the more plants that adopt carbon capture, the lower the per-plant cost of carbon transportation to storage sites.

With respect to the car market, Nicholas and Ogden (2009) report from a survey, demonstrating a strong relationship between the willingness to pay for a hydrogen car and the availability of hydrogen filling stations. The same type of interdependency could also be the case for electric cars and the network of fast charging stations.

Possible indirect network externalities in the car market is also briefly explored in the environmental economics literature. Greaker and Heggedal (2010) builds an explicit model of the relationship between the market share of hydrogen cars and the density of hydrogen filling stations, and show that this could lead to multiple equilibria. In some equilibria fossil based cars dominate the market, although these equilibria are welfare inferior. However, unlike this paper, they do not include a potential sponsor in their analysis, and they only look at a static game.

Indirect network externalities in the transport market is also treated by Sartzetakis and Tsigaris (2005). Sartzetakis and Tsigaris (2005) do not model the network externality explicitly, but their game is dynamic as consumers arrive sequentially. However, prices follow exogenously given rules, and the government do not set taxes optimally. They therefore do not investigate optimal policy with technology sponsors.

This paper will extend the analysis in Cabral (2011) who studies a model with two sponsored networks competing in prices. Each period one consumer makes an adoption decision given the prices. His utility from the good depends on it's network size for each period he's alive. We introduce pollution from one of the networks, while the other network is clean. Moreover, we introduce a government who sets emission taxes to maximize social welfare.

In Cabral (2011) the two network technologies are equally good, while in our model the clean technology is superior from a social point of view, although identical in the eyes of the consumers. Further, the focus in Cabral is to characterize competition in a network industry, while we question whether the market achieves the correct mix between the networks, or whether the market is locked in to the inferior dirty technology. Lock-in has been a topic in the general literature on network externalities, which we will shortly review in the next subsection.

1.1 Literature on network externalities and lock-in

There is a body of literature looking at the lock-in phenomenon from a more general point of view. Farrell and Saloner (1985) also analyze a general model with network externalities. Firms choose whether to switch from an old to a new technology. The decisions of the firms are modeled as a multi stage game in which one firm starts and the other firms follow sequentially. Farrell and Saloner explore different versions of this game in which firms have either complete or incomplete information about other firms' pay-off functions. They define *excess inertia* to be a situation in which firms do not adopt a welfare dominant technology. This corresponds to how the literature defines a lock-in situation. In the Farrell and Saloner model, excess inertia cannot happen if firms have complete information.

In another paper Farrell and Saloner (1986) develop their ideas further, and introduce an installed base of users of the old technology. Due to the installed base, users of the old technology will adopt the new technology at a slow pace, depending on how fast the installed base depreciates. Early adopters of the new technology must then bear the cost of a small network while waiting for more consumers to adopt the new technology. This effect can lead to *excess inertia* even with complete information.

In our model early adopters of the clean durable must also bear the cost of a small network while waiting for more consumers to adopt the clean good. However, in our model the clean technology sponsor may speed up this process by offering the clean good at a low price. Katz and Shapiro (1986) introduced the concept of technology sponsors. With a sponsor they imply a private agent that has monopoly rights to a technology, and can claim a part of the future monopoly rents from this technology. They find that having a sponsor is crucial for the market development of a new technology. In particular, opposed to one of our results, they find that if the superior technology has a sponsor, it will dominate the market.

In Katz and Shapiro (1986) the two technologies only differ with respect to their network sizes, while in our model the technologies differ with respect to both network size and product characteristics. Since products are differentiated, firms may start to price high focusing only on the most eager customers when their network has reached a critical size. Thus, in our model an inferior technology my dominate the market even if only the superior technology has a sponsor.

Ochs and Park (2010) extend the analysis in Farrell and Saloner (1986), and find that as long as the timing of entry is endogenous (so that the most eager consumers move first) and entry decisions are irreversible (so that no network ever declines in size), then as the discount factor tends to one, any coordination problem found by Farrell and Saloner (1986) vanishes, and the equilibrium is efficient as the population grows large. On the other hand, in Ochs and Park (2010) none of the technologies have sponsors that can act stratigically. Moreover, durables wear out, and hence, consumers must choose network over again. Both these features are included in our model.

The paper proceeds as follows: In Section 2 we lay out the model, while in Section 3 we derive the main results. In Section 4 we simulate the model numerically, and in Section 5 we conclude.

2 Model primitives

Following the original model of Cabral, we will have discrete timing with two competing networks and a fixed number N of consumers. The networks will be indexed by $k = c$ for clean and d for dirty. For each network there is an access price the consumer has to pay to join the network. These prices are set by the firms, and can be thought of as prices for some durable goods that grant the consumer access to the network in question. Denote these prices p_c and p_d, respectively.

The government will set two different taxes, one tax t on the purchase of the dirty durable, and one tax τ on the use of the dirty good. We will study markov-perfect equilibria (MPEs). The setup will be time homogeneous, hence we suppress all time subscripts. The only payoff relevant variables will be the network sizes, denoted n_c and n_d. We assume that the market is fully covered, so that all consumers own a good. Since the total number of consumers is fixed at N, we only need to keep the clean network size n_c as a state variable.

2.1 The consumers

At the beginning of each period, there are $N-1$ consumers present in the market. One consumer arrives, and is confronted with the prices and taxes. Subject to these, he has to choose which network he wants to enter. After he makes his choice, there is an intermediate stage, the aftermarket stage, in which the durable goods are being put to use. At this stage all consumers each enjoy some aftermarket benefits $\lambda(n_k)$, common to all consumers and weakly increasing in the network size n_k.[1] At the end of the period, with uniform probability, one random consumer is chosen to exit the market.

Due to this random exit, an entering consumer neither knows for how many periods he will enjoy the aftermarket benefits nor how large the network

---

[1] For instance, the function $\lambda(n_k)$ can be seen as the reduced form of the explicit network model in Greaker and Heggedal (2010).

is going to be in the future. We therefore introduce the function $u_k(n_k)$ which is the expected present value (EPV) of entering network k at size n_k. That is, it is the expected discounted sum of the aftermarket benefits $\lambda(n_k)$ over all the future periods the consumer expects to be in the market.

In addition to the aftermarket benefits that are common to all consumers, each consumer draws two idiosyncratic, private utility components at birth. The components, $\{\zeta_c, \zeta_d\} \in \mathbb{R}^2$, determine the technology-specific utility he enjoys from joining either of the networks. The total net benefit B_k is then given by:

$$B_k = \begin{cases} \zeta_c + u_c(n_c + 1) - p_c(n_c), & \text{if clean network} \\ \zeta_d + u_d(n_d + 1) - p_d(n_d) - t(n_d), & \text{if dirty network.} \end{cases}$$

We assume that the values of ζ_k are sufficiently high such that the consumer always chooses one of the networks. Since the market is then completely covered, we can restrict our attention to the distribution of the difference between the two utility parameters $\xi_c \equiv \zeta_c - \zeta_d$. As we assume that the ζ_k are *i.i.d*, ξ_c has expected value equal to zero.

The consumer who is indifferent between the two networks will have: $B_c = B_d$, or $\xi_c = x(n_c)$ where the latter is given by:

$$x(n_c) = p_c(n_c) - p_d(n_d) - t(n_d) - u_c(n_c + 1) + u_d(n_d + 1). \tag{1}$$

That is, $x(n_c)$ indicates the position along the real line of the consumer who is indifferent between the two goods when the clean network has size n_c, and prices and taxes are as given. Now, assuming that ξ_c is normally distributed with cdf $\Phi(\cdot)$ and density $\phi(\cdot)$, we derive the probability that a newborn consumer chooses the clean network:

$$\begin{aligned} q_c(n_c) &= Pr\left[\xi_c \geq x(n_c)\right] = 1 - Pr\left[\xi_c < x(n_c)\right] \\ &= 1 - \Phi\left[x(n_c)\right], \end{aligned} \tag{2}$$

and the probability of choosing the polluting network is:

$$\begin{aligned} q_d(n_d) &= Pr\left[\xi_c < x(n_c)\right] \\ &= \Phi\left[x(n_c)\right]. \end{aligned} \tag{3}$$

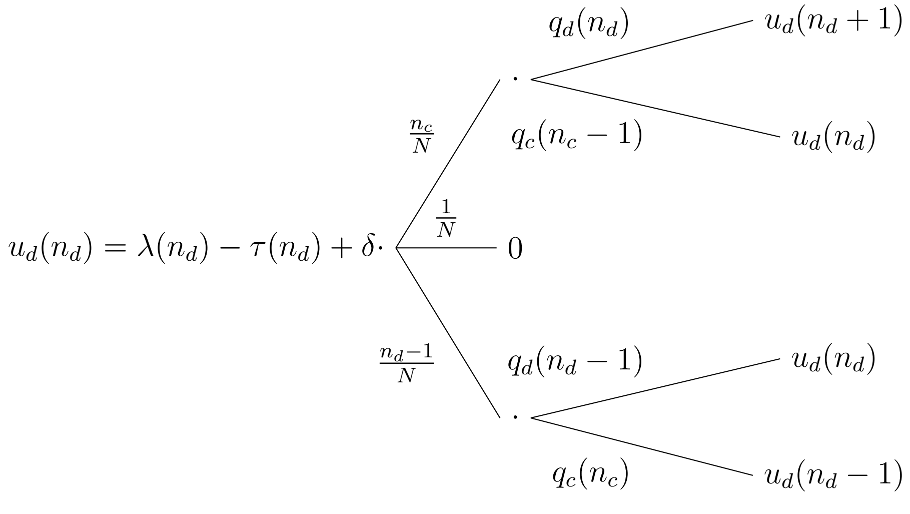
The taxes levied on the dirty network introduces asymmetries, such that $q_c(a) \neq q_d(a)$ in equilibrium, but the probabilities are related through $q_c(a) + q_d(N-1-a) \equiv 1$. From these expressions, we can see that the probability that firm k makes the next sale is, ceteris paribus, continuously and monotonically decreasing in p_k.

Given a sequence of taxes and prices, we now have the law of motion for the network shares. Given that every consumer has the same probability of being chosen to leave the market, the EPV of future network benefits does not depend on how long a consumer has been present. We can therefore define $u_k(n_k)$ recursively in the following way (first for the dirty network):

$$\begin{aligned} u_d(n_d) = {} & \lambda(n_d) - \tau(n_d) + \frac{1}{N} \cdot 0 + \delta \frac{n_c}{N} q_d(n_d) u(n_d + 1) \\ & + \delta \left[\frac{n_c}{N} q_c(n_c - 1) + \frac{n_d - 1}{N} q_d(n_d - 1) \right] u_d(n_d) + \delta \frac{n_d - 1}{N} q_c(n_c) u(n_d - 1) \end{aligned} \tag{4}$$

Each period you enjoy the aftermarket benefit as a function of the market share, and consumers in the dirty network also pay a tax $\tau(\cdot)$ every period for the use of their good. At the end of each period, there is a probability $1/N$ that you are the one who dies, after which you get zero by assumption. If you are not chosen to exit, there are three possibilities: your network increases, decreases or remains at the same size. There is only one possible way your network can increase in size: with a probability of n_c/N someone in the clean network exits, and with probability $q_d(n_d)$ the arriving consumer opts for the dirty network, and the network size increases one step. There are two events that may reproduce the current state the next period; that is when one of the networks experience exit and the arriving consumer chooses to join that same network. And finally your network may decrease by one step if someone other than you dies, and the next consumer chooses the clean network. See Figure 1 for a visualization of (4).

Figure 1 “Expected utility of entering the dirty network”



For a consumer present in the clean network, we get the following value:

$$\begin{aligned} u_c(n_c) = {} & \lambda(n_c) + \frac{1}{N} \cdot 0 + \delta \frac{n_d}{N} q_c(n_c) u(n_c + 1) + \\ & \delta \left[\frac{n_d}{N} q_d(n_d - 1) + \frac{n_c - 1}{N} q_c(n_c - 1) \right] u_c(n_c) + \delta \frac{n_c - 1}{N} q_d(n_d) u(n_c - 1) \end{aligned} \tag{5}$$

Note that there is no use tax $\tau(\cdot)$ in (5).

To gain some intuition on these expressions, we can consider the case with a constant use tax and zero network benefits e.g. $\lambda(\cdot) = 0$. Equation (4) then collapses to $u_d = -\tau(1 - \delta\frac{N-1}{N})^{-1}$, i.e. the expected net present value of the future outlays on the use tax, while (5) collapses to 0. Note that the discount factor is augmented with the factor $\frac{N-1}{N}$, that is the probability that the consumer will stay alive. Further, with constant access prices, the marginal consumer is given by: $x_c = p_c - p_d - t - \tau(1 - \delta\frac{N-1}{N})^{-1}$. Hence, only consumers with $\zeta_c - \zeta_d < p_c - p_d - t - \tau(1 - \delta\frac{N-1}{N})^{-1}$ will choose the dirty network.

2.2 Firms

Firms derive revenue equal to the entry price p_k every time a new consumer enters their technology.[2] Costs are normalized to zero, and hence revenue is equal to profits. Remember that the utility a consumer gets from a technology depends on the number of consumers already using the technology. Hence, expected revenue for a given p_k will depend positively on the size of the network.

The value functions of the firms are evaluated before the firms set the price and the arriving consumer makes his choice. The total number of consumers who *currently* are in the market is therefore $N-1$. For a network of technology $k = c, d$ we have:

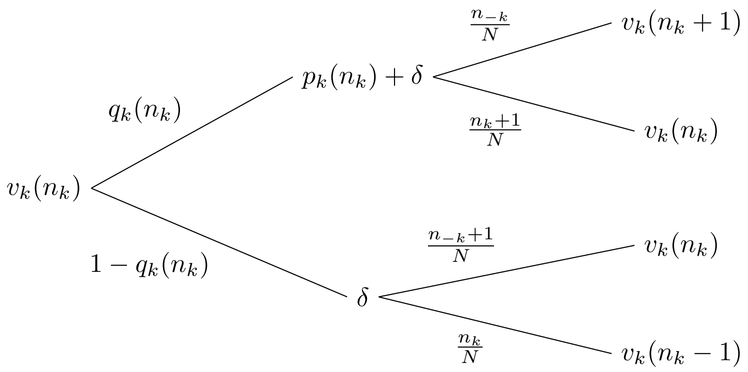
$$\begin{aligned} v_k(n_k) = q_k(n_k) & \left(p_k(n_k) + \delta \frac{n_{-k}}{N} v_k(n_k+1) + \delta \frac{n_k+1}{N} v_k(n_k) \right) \\ & + (1 - q_k(n_k)) \left(\delta \frac{n_{-k}+1}{N} v_k(n_k) + \delta \frac{n_k}{N} v_k(n_k-1) \right) \end{aligned} \tag{6}$$

where $n_k + n_{-k} = N - 1 \Rightarrow n_{-k} = N - 1 - n_k$. The first line above is the event that the newborn consumer chooses network k when it's size is n_k. In that case network k sells a unit at value $p_k(n_k)$ and it's network size increases to $n_k + 1$. In the next period there are two possibilities; either the other network has experienced exit (with probability n_{-k}/N), or someone in network k has exited (with probability $(n_k+1)/N$). The network size at the beginning of the next period is updated accordingly. The second line is the event that the arriving consumer chooses the other network. In that case there is a higher probability that the other network experiences an exit, and vice versa. It is visualized in Figure 2.

Figure 2 "Expected firm value"

---

[2] In Cabral (2011) firms also enjoy aftermarket benefits depending on the size of their networks. For simplicity, we disregard these here. This can for instance be the case if the complimentary services are supplied from a sector separate from the two technology owners.



As mentioned, we consider three different market configurations, all compatible with (6): I) both technologies are sponsored, II) only the clean technology is sponsored, while the dirty technology is supplied by several firms, and III) both technologies are supplied by more firms.[3]

2.3 The government

Environmental damages from the polluting network accrues according to $d * n_d$, where d is a parameter and n_d is the number of consumers present in the polluting network today. This is a reasonable representation of environmental costs as long as a) the emissions from the network in question is only a part of the total emissions, and b) the use intensity is exogenous to the agents once they have joined the dirty network.

We equip the government with two instruments: a purchase tax $t(n_d)$ levied at the time of purchase, and a flow tax $\tau(n_d)$ levied each period on all consumers present in the polluting network and thus affecting the the expected present value of entering network d.

In addition to the environmental damage function, the public welfare function is assumed to be utilitarian, it is the unweighted sum of profits and consumer utility. We are thus lead to the following value function evaluated before the consumer chooses a network:

---

[3] The first configuration corresponds to the set up used by Cabral. In the transport market application the durables could be either a fossil fuel car or a hydrogen (electric) car which both provide a tranportation service that depends on the density of refueling stations. Further, the inventor owning the patent on the premium fuelcell (rechargeable battery) can through her pricing of the patent set the access price for the clean network. For the dirty network, we can either assume that current car companies act as a cartel using their pricing to keep consumers in the dirty technology, or we may have that only the green network has a sponsor.

$$
\begin{aligned}
g(n_c) = \; & \\
& q_c(n_c) \cdot \Big\{ \mathbb{E}\left[\zeta_c | \xi_c > x(n_c)\right] + (n_c+1)\lambda(n_c+1) - p_c(n_c) \\
& + n_d\left[\lambda(n_d) - \tau(n_d)\right] - d n_d + \tau(n_d) n_d + p_c(n_c) \\
& + \delta_G \left[\frac{n_c+1}{N} g(n_c) + \frac{n_d}{N} g(n_c+1)\right] \Big\} \\
& + (1 - q_c(n_c)) \cdot \Big\{ \mathbb{E}\left[\zeta_d | \xi_c < x(n_c)\right] + (n_d+1)\left[\lambda(n_d+1) - \tau(n_d+1)\right] \\
& - p_d(n_d) - t(n_d) + n_c \lambda(n_c) - d(n_d+1) + \tau(n_d+1)(n_d+1) \\
& + p_d(n_d) + t(n_d) + \delta_G \left[\frac{n_c}{N} g(n_c-1) + \frac{n_d+1}{N} g(n_c)\right] \Big\}
\end{aligned}
\tag{7}
$$

The welfare measure is the expected value of two scenarios. First the case that the newborn consumer chooses the clean network. This happens with probability q_c. The value is then the expected idiosyncratic utility of the consumer, conditional on him choosing clean. Then we subtract the price he pays, we add the government tax revenue from the use of the dirty good and the consumers' network benefits, net of any flow tax paid. Further, we add the price revenue the clean network made from selling. Finally we add the expected continuation value, conditional on the clean network having been chosen today. Then the same exercise is repeated in the event the dirty network is chosen. The only difference is that we now also have to take into account the purchase tax $t(n_d)$ levied on the consumer.

3 Solving the model

The timing of the game in every period is as follows: First, the government sets taxes. Second, firms observe the current taxes, and then they compete in prices. Finally, the consumer makes his choice, knowing the prices and the current taxes. As we do not find it reasonable that the government can commit to future tax rates, we will only allow a stagewise leadership. Thus we are searching for a stochastic stagewise Stackelberg equilibrium.

What does this mean in practice? Our interpretation is that both the government and the firms announce a markovian rule that specifies the optimal response in every state. If both the industry and the current government believe the rules will be followed in all future periods, then it is optimal for the current government to follow it, too. This holds true in all periods, so the announced markovian strategies will indeed be followed.

To implement the equilibrium, we solve a set of dynamic programming problems by backwards induction. The consumer's choice problem is already solved by (4) and (5), which for given prices and taxes constitute a system of $2 * N$ equations with $2 * N$ unknowns e.g. $u_c(1) \ldots u_c(N)$ and $u_d(1) \ldots u_d(N)$. We also have everything we need to solve the firms' problems for given taxes. Lastly we solve the government's problem, taking into account the response