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Radical Climate Policies

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ABSTRACT

In the presence of strategic complementarities stemming from peer effects in demand or from technological spill-overs, propagation and amplification mechanisms increase the effectiveness of climate policies. This suggests that climate goals can be met with smaller policy interventions. However, if there are multiple equilibria, radical and more ambitious climate policies are needed to shift the economy from a high-emissions to a low-emissions path.. Once the radical shift has taken place the transformative policies can be withdrawn. More generally, such policies can set in motion social, technological, and political tipping points. The rationale for such policies is strengthened due to key households, corporations and institutions being at the centre of networks, and thus radical climate policies should identify those agents and leverage them. Our proposals offer a complementary perspective to scholars that have emphasised insights from the literature on early warning signals to advocate sensitive intervention points to get more effective and more transformative climate policies.

Keywords: climate policy, peer effects, learning by doing, strategic complementarities, multiple equilibria, tipping points, networks.

JEL codes: Q54, Q58

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1. Introduction

Mitigating global warming by ensuring net zero emissions by the middle of this century is one of the key challenges faced by policy makers around the globe. It is crucial because global mean temperature is driven by cumulative global carbon emissions and temperature increase must be kept below 1.5 or 2 degrees Celsius. Where in the world emissions take place is irrelevant since carbon dioxide mixes rapidly throughout the atmosphere. Emissions can still take place in certain industries, but must be fully offset by negative emissions (e.g. capture of carbon dioxide from the air). The traditional policy advice of economists has been to internalize the damages caused by global warming in polluters' decision taking by imposing a global carbon tax (or competitive market for emissions permits) that is set to the social cost of carbon (SCC), i.e. the expected present discounted value of all global warming damages resulting from emitting one ton of carbon today (e.g. Nordhaus, 2008).[1,2] This advice has, except for a few countries and the EU, been ignored, and where carbon prices are in place their coverage is fragmented and incomplete. This is often due to political and societal obstacles which can and should be resolved.[3]

But more important, this policy advice misses the point that marginal, incremental policies are wholly inadequate for a successful green transition due to the wide prevalence of positive feedback effects in preferences, technology, and politics. Instead, what is needed is non-marginal, transformative change to shift the economy, technology, and society from a bad, high-emissions equilibrium to a better, low-emissions

[1] Rising carbon prices cut fossil fuel demand, boost substitution from coal to less carbon-intensive fossil fuels such as gas, stimulate R&D in renewable energies and markets for carbon capture and sequestration, and signal corporations to invest in green rather than fossil-based projects. Of course, a successful green transition also requires supplementary climate policies such as subsidies to internalize learning-by-doing benefits in emerging green industries and to correct for imperfect patent markets for green R&D, climate finance to overcome imperfect access to capital markets, and planning to meet the increasing spatial demand for solar panels, windmills, and other forms of renewable energies.

[2] In the Kyoto agreement, the focal point of international climate negotiations is to translate the cap on global cumulative emissions to caps on cumulative emissions for each country but the Paris agreement avoids this type of translation from global to national caps. The efficient policy to enforce such caps is that the carbon price is not aligned with the social cost of carbon but is determined by the marginal cost of decarbonization and grows at a rate equal to the risk-adjusted interest rate.

[3] For example, carbon leakage will make politicians hesitant in implementing climate policies unless an effective border tax adjustment scheme can be devised. Also, carbon pricing hurts the poor and may lead to Yellow Vest protests unless part of the revenue of carbon taxes is used in a visible and transparent way to compensate the poor. Uncertainty about future carbon pricing can lead to Green Paradox effects and to an increased risk of stranded financial assets. A survey of these obstacles is given in van der Ploeg (2021).

equilibrium. Marginal policies such as setting the carbon price to the SCC can at most achieve a local maximum around the terrible equilibrium we are in currently.

This more radical approach to the design of climate policies thus requires a consideration of externalities in household preferences and externalities in technology as well as the usual global warming externalities. Such externalities lead to positive feedback effects (often called strategic complementarities by economists) which can give rise to three equilibrium outcomes: a stable bad equilibrium, a stable good equilibrium, and an unstable equilibrium in the middle. The unstable equilibrium is like a tipping point, since if the policy change is not radical enough the economy will remain stuck in a (slightly improved) bad equilibrium while if it is radical enough and passes the unstable equilibrium, the economy will settle in the good equilibrium.

On the household side, this recognizes that preferences are not cast in stone but that more households will turn green when a larger fraction of households has already turned green. Gillingham and Bollinger (2021) investigate a large-scale behavioral intervention to leverage social learning and peer effects to boost adaptation of residential solar photovoltaic systems. They find that when municipalities offer group pricing and set up informational campaigns using volunteer ambassadors, installations increase. The randomized controlled trials indicate that selection into the program is important, but group pricing is not. The intervention thus led to economies of scale and lowered consumer acquisition costs. Talevi (2022) finds empirical evidence for peer effects in the adoption of solar PV in the U.K. and shows that these peer effects are stronger in the earlier years of a subsidy change. Social learning seems more important than bandwagon effects. Dechezleprêtre et al. (2022) also present evidence that information matters in whether people favor climate policies.[4] Boucher et al. (2022) find strong peer effects for adolescent activities in the U.S.[5]

[4] Dechezleprêtre et al. (2022) use new surveys with more than 40,000 respondents in twenty countries to show that support for climate policies hinges on three perceptions regarding effectiveness, inequality, and self-interest. They show experimentally that information addressing these concerns can substantially increase the support for climate policies. Explaining how policies work and who can benefit from them is critical to foster policy support, whereas simply informing people about the impacts of climate change is not effective.

[5] They estimate the linear-in-means model, where agents are linearly affected by the mean action of their peers. They find that spill-over effects strongly dominate for grade point averages, social clubs, self-esteem, and exercise, while for risky behavior, study effort, fighting, smoking, and drinking, conformism plays a stronger role. Furthermore, they find that imposing the mean action as an individual social norm is misleading and leads to incorrect policy implications.

Wolske et al. (2020) point out that various studies from different disciplines demonstrate the role of peers in shaping energy-related behaviors. They highlight that this research varies from documenting spatial peer effects in the adoption of rooftop solar panels — when an individual's behavior is influenced by the behaviors of neighbors — to showing how comparisons across neighbors can be used to reduce household electricity consumption. Also, they discuss recent research on social influence in energy behavior and how this might result in peer effects and make suggestions on how to predict when social influence will most result in peer effects.

Such peer effects have been shown to amplify the negative effects of carbon pricing on emissions. For example, Konc et al. (2021) allow for preferences with peer effects in a social network and show that the effects of carbon taxation on emissions are increased by about 30% which in turn allows a cut in the effective tax of 38%.[6] Mattauch et al. (2018) also make the case that Pigouvian policies can lead to greener preferences, towards say active travel and low-meat diets, and thus amplify the effects of carbon taxation, and also make low-carbon infrastructure investments more valuable.

On the production side, production externalities might take the form of increasing returns to scale as the cost of green products fall as the aggregate production of these products rises. This is captured by Wright's law, which shows that every doubling of total use of windmills, solar panels or batteries reduces unit costs by 20% to 40%.[7] For example, Tiang and Popp (2014) suggest that each new 60 GW wind power project in China cuts unit costs by 0.25%. Others have emphasized the need to redirect the economy from carbon-intensive to green directions of technical change (e.g. Bovenberg and Smulders, 1995, 1996; Acemoglu et al., 2012).[8] Various integrated assessment studies have investigated how to internalize such technological externalities stemming from learning-by-doing effects including the externalities associated with endogenous technical progress (e.g. de Zwaan et al., 2002; Popp, 2004; Goulder and Mathai, 2000;

[6] The precise size of the effects depends on the size of the peer effects, the distribution of initial tastes, the network topology, and the income distribution.

[7] This is often referred to as Swanson's law when applied to solar panels.

[8] Acemoglu et al. (2012) find that if clean and dirty inputs are sufficiently substitutable, sustainable growth can be ensured if *temporary* taxes and subsidies redirect technical progress towards green inputs. Their optimal policies require both carbon taxation and green R&D subsidies. Langer and Lemoine (2022) show that the efficient subsidy for residential solar energy in California increases over time due to intertemporal price discrimination, despite the tendency for the subsidy to fall over time due to taking advantage of future technological progress. This study does not discuss the possibility of multiple equilibria.

Fisher and Newel, 2008; Hübler et al., 2012).[9] Firm-level evidence supports directed technical change, so that clean innovation obtains on average 43% more patent citations than carbon-based innovations taking account of the whole history of patent citations to capture indirect knowledge spill-over effects (Dechezleprêtre et al., 2014). Evidence from a novel firm-level panel data set for 80 countries on innovation in production of carbon-intensive cars (with internal combustion engine) and clean cars (electric, hybrid or hydrogen) suggests that firms innovate more in clean and less in dirty technologies when faced with higher tax-inclusive fuel prices and that clean and dirty innovation (from aggregate spill-over effects and from the firms' innovation histories) display path dependence (Aghion et al., 2016). Hence, if carbon tax increases are high enough, clean technologies will overtake dirty technologies. In subsequent work, households care about their environmental footprint while firms pursue greener production to soften price competition and acting as complements these determine R&D, pollution, and welfare (Aghion et al., 2021). Evidence for the car industry suggests that exposure to prosocial attitudes fosters clean innovation, especially if competition is strong.

Although such studies are important and at best indicate path dependence and the importance of prosocial and environmental attitudes, they usually do not discuss that peer effects in demand and/or technological externalities can result in multiple equilibria and that carbon taxes may reduce emissions, but fail to shift the economy from a high- to a low-emissions equilibrium. Such studies also do not investigate the radical, transformative policies that are needed to move from the bad to the good equilibrium.

Our main objective is to study how such peer effects in demand and technological externalities may give rise to non-incremental change, and the rethinking of climate policy that is required in the presence of such change. Financial markets, corporations, central banks, and more and more governments have begun to realize that radical and transformative actions must be taken to get the global economy out of the high-emissions trap and arrest the process of global warming. We first give some simple micro-founded models with peer effects in demand and technological spill-over effects to illustrate how there may be a stable, high-emissions equilibrium and a stable low-emissions equilibrium with an unstable equilibrium in the middle. We use these models to discuss locally

[9] See Zeppini and van den Bergh (2020) for a recent study on the effects of learning curves, path dependence, and climate policies.

optimal policies and the need for more radical climate policies to achieve the transition between equilibria. We then review previous and related attempts to understand radical climate policies.

Section 2 sets up a simple framework in which demand and technological externalities create the possibility of multiple equilibria, and then discusses its implications for the green transition. Section 3 extends this framework to allow for micro-foundations of peer effects in consumer demand and for production externalities on the supply side. We show how this generates the possibility of lock-in to a bad equilibrium, and how a dynamic green transition may stall at some point. Section 4 uses this model to consider various tax and other policies that can be used to get out of a pollution trap and shift from a high-emissions trap to a new equilibrium with low or no emissions. Section 5 discusses how these ideas about a climate trap pan out in a political context and emphasizes the need for credibility and commitment to climate policies. Section 5 also surveys the broader literature on transformative climate policies, including a discussion of the importance of targeted policies and learning in networks for the design of radical climate policies and a discussion of the importance of expectations and strategic investments to ensure the economy gets locked into green technology. Section 6 concludes.

2. Bad and Good Equilibrium Outcomes in the Energy Transition

To illustrate the idea of multiple equilibria in the simplest of possible manners, we take as example the problem of choosing an electric vehicle (EV) or petrol/diesel (ICE) vehicle, say green or brown for short. The more people choose to use electric vehicles, the larger the demand and production of these vehicles, and consequently the cheaper the electrical vehicles will become. Furthermore, with a larger proportion of drivers changing to electric vehicles, there will be more demand for charging locations and thus the supply of these locations will increase. An economy may get stuck in a brown (high-emissions) equilibrium in which these complementary benefits of green demand and production are not achieved Conversely, if society were able to leave the brown equilibrium and shift towards the green equilibrium, all are happy to stay in the green equilibrium once they are there. Both the brown and the green outcomes are Nash equilibria, in the sense that no individual wants to change the decisions they have made.

Many other examples are possible. For example, the introduction of heat pumps into people's homes depends on the actions of others as the more houses are taken off gas by using a heat pump, the more experience we get with installing and using them and the cheaper they get. We will illustrate these points in more formal detail in sections 3 and 4. Before we do that, we first illustrate these ideas using a simple coordination game to better understand the green transition as put forward and discussed by Nyborg (2020) and Nyborg et al. (2006, 2016) as this highlights the features discussed above.

Assume that individuals each purchase a vehicle and vehicles come in two varieties, one (type-x) is green, e.g. an EV, and the other (type-y) is brown, an ICE vehicle. Consumers choose which to buy, and the net utility derived from a vehicle of type-x is $U_x(q_x)$ and from a type-y is $U_y(q_y)$. These utilities depend, respectively, on q_x, the proportion of the population purchasing type-x, and q_y, the proportion buying type-y, where $q_x + q_y = 1$. What is the form of this dependence? The assumption of much standard economics is that net utility diminishes as more people choose the same good. The standard rationale is that higher demand bids up the price of the good and of the inputs used to produce it, so the net benefit from choosing the good is reduced. This case is shown in figure 1a, which has the proportion of the population choosing type-x on the horizontal, and the utility that a consumer derives from choosing each type on the vertical axis. The more is purchased of each type, the lower is utility. Equilibrium is where individuals are indifferent between choosing x or y, i.e. where the two curves intersect.

What if the utility of choosing type-x, $U_x(q_x)$, is increasing rather than decreasing in q_x (and similarly, $U_y(q_y)$ increasing in q_y)? There are several reasons to believe this could be the case. One is increasing returns, so that as more of a type gets produced its production costs and price fall, rather than increase. A second is that peoples' tastes may be (positively) influenced by the choices of others, a social herding or peer effect. A third is that there are network effects – such as the installation of more charging points – so that as there are more users of type-x so the costs of owning type-x fall. This case is shown in figure 1b. There are three equilibria. One is on the left-axis, where everyone purchases brown goods of type-y, so $q_y = 1$ and $q_x = 0$. This is a rational outcome, since $U_y\big(q_y = 1\big) > U_x(q_x = 0)$. A second equilibrium is on the right axis with everyone purchasing green, so $q_x = 1$. And a third equilibrium is at the intersection of the curves, a point we label q^*. This equilibrium is unstable, because a small increase in purchases of either of the two goods increases the relative value of consuming this good.

Figure 1a: Diminishing utility

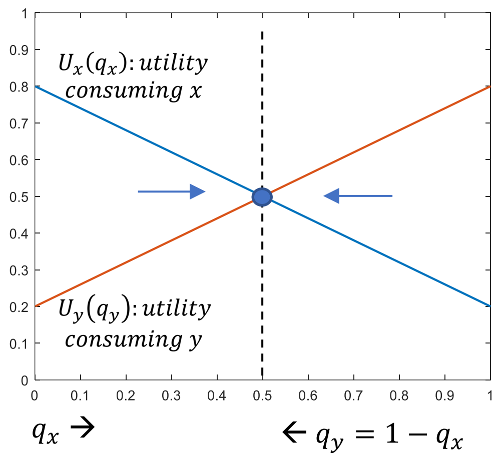
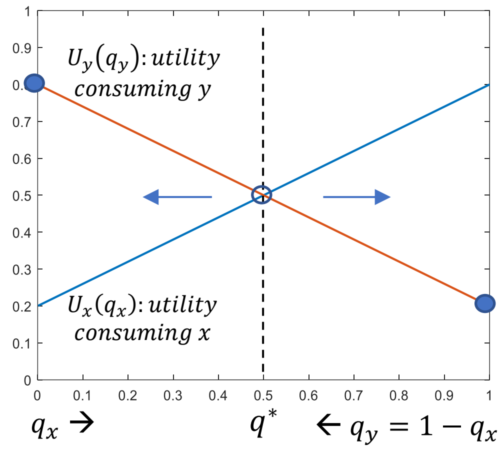


Figure 1b: increasing utility



Diminishing utility implies a unique equilibrium, but increasing utility gives two equilibria that are stable, and one that is unstable.

The unstable equilibrium will never be observed, but which of the two stable ones might the economy be in? Starting out from the high-emissions equilibrium, $q_x = 0$, marginal policies such as pricing carbon at a level equal to the SCC might lead some people to choose type x goods instead of type y, and thus q will become slightly higher than zero but below $q_x = q^*$. But there will be an immediate tendency to force the economy back to the high-emissions equilibrium on the left axis. Only policies that are radical enough to push the fraction of people consuming green above the critical point q^* will lead to the zero-emissions equilibrium characterised by $q_x = 1$ on the right axis. In this sense, the critical point q^* is like a tipping point.

Hence, marginal policies such as setting the price of carbon to the SCC are not much use here. More radical policies are needed to shift society from the carbon-intensive towards the green equilibrium. It is important to note that such ***big-push policies*** may be ***temporary***, since once society has shifted to the green equilibrium it is a stable outcome. We will now investigate these issues in a richer framework with more detailed economic foundations. This framework also yields better understanding of the type of policies that might shift the economy from a high-emissions to a low-emissions equilibrium.

3. Multiple Equilibria: Environmental, Social and Production Externalities

We develop a model that captures the essentials of how positive feedback effects resulting from peer effects and production externalities can lead to multiple equilibrium outcomes, how these can be interpreted and their implications for policy. At the core of the model are three types of decision makers. Households, who choose between a clean, green option (good x) and a polluting, carbon-intensive option (good y). Firms which produce these goods and price them at unit cost. And a government that sets a range of possible taxes and subsidies.

Central to our analysis are three distinct externalities associated with non-market interactions relevant for the green transition. The first one is the ***global warming externality*** due to emission of greenhouse gases. Emissions are created by the carbon-intensive good y, and the resulting impact on global warming affects utility negatively.[10]

The second one relates to ***social externalities***. They stem from social preferences, under which the preferences of any individual depend directly on the behavior of others (cf. Mattauch et al., 2018). One example of this is that as more people make green choices, so more people develop a taste for green and follow suit. This type of positive feedback effect thus allows for changing preferences due to various kinds of social pressures. However, it might alternatively be that individuals choose to become less green if already many others are acting in a green way (using the selfish reasoning "why clean up if others are cleaning up?") in which case there is a negative feedback effect. Economists refer to positive feedback effects as strategic complementarities and to negative feedback effects as strategic substitutes. Positive feedback effects can lead to multiple equilibria, but negative feedback effects give rise to a unique equilibrium. Our interest is in the former.

The third one relates to ***technological externalities***. These may stem from external economies of scale in production in which, while each firm perceives constant marginal and average cost, unit costs decrease with the total volume of each good produced by the industry as a whole. A justification for this might be learning-by-doing effects in the production of green goods or in the production of renewable energies. For example, Swanson's law suggests that for every doubling of solar capacity installed, the cost of a

[10] An alternative is to let global warming affect aggregate production negatively as is done in the extensive literature on the integrated assessment of the economy and the climate (e.g., Nordhaus, 2008). It is straightforward to also allow for this, but we abstract from it for ease of exposition.

solar panel drops by around 20%. More generally, Wright's law indicates that for every doubling of renewable energy use whether it is solar panels, windmills, or batteries, cost per unit of renewable energy drops by 20% to 40%. If these technological externalities are not fully internalized by the firms that create them (through, e.g. a patent system), there is a case for government subsidizing renewable energy use.[11]

Starting with households, we focus on the consumption decisions made on one activity – such as motoring -- which can be undertaken in different ways. How do prices and preferences shape both the total amount spent on the activity and choices within the activity, between good x and good y (e.g. between a green EV or brown ICE vehicle)? The amount spent on these goods depends on the price index for the activity ('motoring') as a whole, P, and the price elasticity of demand for the activity is ϵ. Other income is spent on goods in the rest of the economy (the 'outside good') which we assume to have fixed prices and to be non-polluting. Within the activity, choices between x and y depend on their prices, p_x and p_y, and on preference parameters, a_x and a_y. The price sensitivity of these choices (and hence the price elasticity of demand) depends on whether they are close substitutes, and is measured by σ, the elasticity of substitution, and we make the usual assumptions that $\sigma > 1$ and $\sigma > \epsilon$. Substitution between green and brown vehicles is thus easier than between vehicles and other commodities. We use the standard CES formulation for this, so that households' demand for each good is

$$(1) \qquad x = a_x p_x^{-\sigma} P^{\sigma-\epsilon} \quad \text{and} \quad y = a_y p_y^{-\sigma} P^{\sigma-\epsilon}.$$

In this expression P is the price index for the activity as a whole ('motoring'), and depends on prices and preferences taking the form

$$(2) \qquad P = \left(a_x p_x^{1-\sigma} + a_y p_y^{1-\sigma}\right)^{1/(1-\sigma)}.$$

Demand for each good thus declines in its own price but increases in the price of the other good, this entering via the price index.[12] The Appendix details the derivation of this from consumer preferences and budget constraints.

Production uses the outside good, an aggregate, including labor. Firms face constant returns to scale, operate under perfect competition, and set their producer price equal to

[11] Although patents create their own problems if they impede the dissemination and adoption of new technologies.

[12] There are no income effects in these demand equations as we assume preferences between the sector under study and the outside good are quasi-linear. The price index can be interpreted as an indirect sub-utility function. Total expenditure on the activity (motoring) is $P^{1-\epsilon}$.

unit cost, c_x and c_y for goods x and y respectively. Output of each good faces an ad valorem tax factor, t_x and t_y, so that the prices faced by consumers are

$$(3) \qquad p_x = t_x c_x \text{ and } p_y = t_y c_y.$$

For example, a tax of 20% on the green goods implies $t_x = 1.2$. Tax revenue collected on the consumption of using these goods is rebated to each household as lump-sums.

Given preference parameters, costs, and tax rates, equations (1), (2) and (3) determine prices, the price index, and quantities demanded of these goods. These, together with consumption of the outside good and welfare loss arising from climate damage, determine household utility levels. It may be noted that this specification seems to imply that households generally purchase both goods x and y, albeit in different quantities. This is the simplest way to set out the model, but we will show below that it can be interpreted as a discrete choice model, where each household chooses either x or y.

The final, and critical, aspect of the model is to add the three externalities that we discussed above. These depend on the aggregate quantities of each good produced, and we distinguish aggregate quantities from individual choices by denoting aggregate output of each good X and Y. We assume a unit measure of consumers, so that at equilibrium the equality of demand and supply for the two goods requires that $x = X$ and $y = Y$.

We highlight these non-market interactions in what follows by using square brackets to illustrate the key relationships between variables that create these externalities. The first is the ***global warming externality***, which is a function of the total output of each of the goods. We assume that good x is perfectly clean, so there is damage only from production of good y, and we write the damage function as $K_Y[Y]$, positive and increasing in Y. The second are ***social externalities*** under which household preferences depend on the behavior of other households. Social preferences stemming from peer effects are modeled by assuming that demand parameters are a function of aggregate output and consumption of each good. In general, these preferences depend on quantities of both goods as, for example, preferences may be influenced by the share of the population consuming each good. We express these relationships as $a_x[X, Y]$ and $a_Y[Y, X]$, and assume particular functional forms for these relationships in what follows. The third are technological externalities arising from economies of scale and learning effects which are external to the firm but internal to the type of good produced. They are captured by $c_x[X]$, and $c_y[Y]$. This is our general setting, and particular externalities will be switched on and off in the various contexts we develop below.[13] Each of these functions is exogenous, and they shape the endogenous equilibrium values of prices, outputs, emissions, and utility.

A. EQUILIBRIUM WITH DEMAND COMPLEMENTARITIES

We consider first the case where social norms create demand complementarities in household choices so that preferences for the x- and y-goods depend on total volume sold. We first have to specify the form that these relationships, the functions, $a_x[X,Y]$ and $a_Y[Y,X]$, take. We assume this is

$$(4) \qquad a_x[X,Y] = a[\Pi_x], \;\; a_y[Y,X] = a[1-\Pi_x], \;\; \text{with} \;\; \Pi_x \equiv X/(X+Y).$$

This embodies several assumptions. The first is preferences depend on the share of each good in total output, Π_x, rather than on the absolute levels. This gives a focus on switching behavior, so a shift in preferences towards x is associated with a shift against y. The output levels have been entered in physical units, a plausible assumption for the motor vehicle context, although in other contexts units might need to be made comparable, e.g. by being expressed in value terms. We also assume that preferences are symmetric, i.e. there is a common function $a[.]$, with arguments for each good Π_x, $1-\Pi_x$. We construct an example of this in Figure 2a, with Π_x on the horizontal axis and preferences $a[\Pi_x], a[1-\Pi_x]$ on the vertical. The steep central segment indicates that preferences shift sharply towards good x as households observe the share of this good increasing in the central range, $\Pi_x \in [0.33, 0.67]$. Outside this range, there are no peer effects (i.e. a assumed to be constant).[14] There may also be global warming damages, but technological externalities are switched off, so that we take c_x, and c_y to be constants, not dependent on output levels X or Y.

[13] Notice that we assume technological externalities are within type, i.e. technological improvement in EVs does not benefit ICE vehicles, or vice-versa. But in social preferences, shifting preferences towards EVs (increasing a_x) is likely to be associated with shifting preferences away from ICE (reducing a_y).

[14] The piece-wise linear form helps with interpretation of later figures, making clear intervals in which peer (and later technological spill-over) effects are, and are not, operating. An alternative is to have random preferences with, for example, an extreme value distribution function and to aggregate so that one gets a sigmoidal shape for the function $a_x[X]$. We use such a shape in sub-section 3.C.

Equilibrium requires that, at the prices $p_x = t_x c_x$, $p_y = t_y c_y$, the share of good x in total sales, Π_x, is consistent with individual choice probabilities as given in equations (1), i.e. $\Pi_x = x/(x+y)$. It follows that equilibrium values of Π_x must satisfy

$$(5) \qquad \Pi_x = \frac{a[\Pi_x](t_x c_x)^{1-\sigma}}{a[\Pi_x](t_x c_x)^{1-\sigma} + a[1-\Pi_x]\left(t_y c_y\right)^{1-\sigma}}.$$

The values of Π_x that solve this equation are not immediately apparent but can be illustrated in an intuitive supply and demand context as follows.[15] Hold the price of good y at its equilibrium value, $t_y c_y$, vary Π_x, and ask what values of price, $\tilde{p}_x$, solve

$$(6) \qquad \Pi_x = \frac{a_x[\Pi_x](\tilde{p}_x)^{1-\sigma}}{a[\Pi_x](\tilde{p}_x)^{1-\sigma} + a[1-\Pi_x]\left(t_y c_y\right)^{1-\sigma}}.$$

These values $\tilde{p}_x$ trace an inverse demand curve, or the willingness to pay for good *x*, as a function of relative supply of the good, as measured by Π_x. This is illustrated as the blue line in figure 2b, and equilibrium is where this willingness to pay equals the supply price, the horizontal line $t_x c_x$.

Figure 2a: Preferences with peer effects

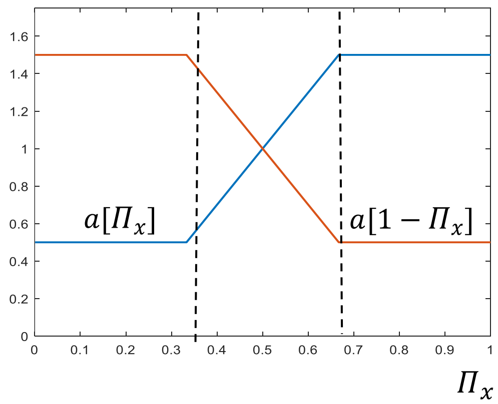
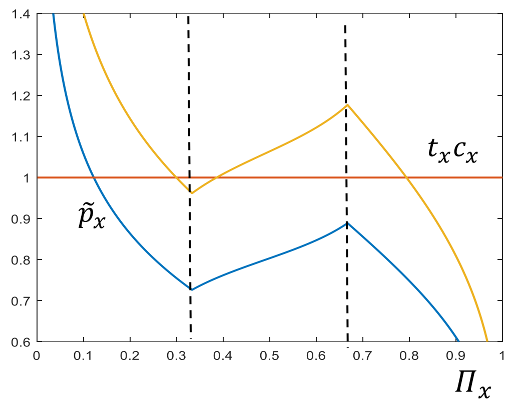


Figure 2b: Unit cost and demand curves, $\tilde{p}_x$



Peer effects in preferences can cause the demand curve to slope upwards, creating the possibility of multiple equilibria.

At levels of Π_x where $a[\Pi_x]$, $a[1-\Pi_x]$ are constant, $\tilde{p}_x$ is the usual downward sloping inverse demand curve. But in the region where peer effects are operating this demand curve may become upwards sloping, as indicated. Essentially, the peer effects associated with higher levels of consumption of Π_x shift preferences toward good *x*, and if the effect is sufficiently strong ($a[\Pi_x]$ sufficiently steep), then willingness to pay $\tilde{p}_x$ increases.

[15] See Vives (2005) for a technical discussion of equilibria in games with complementarities.

This is the demand side, and the supply side is firms selling at price equal to constant unit cost and tax, $t_x c_x$. Equilibrium is where the two relationships intersect, so the blue inverse demand curve gives an equilibrium at a low level of *X* output, and consequently also a high level of *Y* output and pollution. The blue demand curve thus supports a single equilibrium outcome with a low level of *X* output and high level of *Y* and hence pollution.

If instead, demand takes the form indicated by the yellow inverse demand curve in Figure 2b then there are three distinct equilibria. When the quantity of good *x* produced and consumed is large, so too is $a[\Pi_x]$. This will support the equilibrium with high production and consumption of the green good, *x*. At this point consumption and production of the carbon-based good, *y*, is low, and so too are emissions. The converse holds at the equilibrium with lower *x*-output, giving the high-emissions equilibrium. As in Figure 1b, the middle equilibrium in Figure 2b is unstable under a dynamic adjustment process in which firms expand output if price exceeds unit cost, and contract it otherwise.

This illustrates the three possible equilibria. Suppose that the economy starts out at the high-emissions equilibrium indicated by the unique intersection of the blue inverse demand curve and supply curve, horizontal at $t_x c_x$. What can policy do to get to an outcome with lower aggregate emissions and global warming damages? If the polluting good is subject to tax t_y, increasing the value of t_y shifts expenditure towards good *x*, thereby raising the inverse demand curve for *x* towards and above that illustrated by the yellow line. Starting at the lower equilibrium, *x* output increases steadily with t_y until it reaches the tipping point at which this equilibrium disappears (as does the unstable middle equilibrium). The dynamic adjustment process then sets off movement towards the green high *x* equilibrium. Tax policy has marginal effects in each of the stable equilibria, except at the critical value where a small increase in the tax rate has a non-marginal effect, causing a discontinuous change in the relative scale of consumption and production of each good. We will return to a more formal analysis of tax rates and associated utility levels, in section 4, but we first discuss a different interpretation of our model and various extensions of this basic model to highlight how pervasive the possibility of multiple equilibria and tipping points are.

B. DISCRETE CHOICE INTERPRETATION[16]

The model above has identical households, all of whom consume some good x and some of good y, in proportions that depend on prices and preferences. The same model can be given a more attractive interpretation from an empirical point of view as a discrete choice model. Each household chooses to purchase either good x or y, but not both. Some peoples' preferences are intrinsically biased to x, and others towards y, and this heterogeneity means that, in the aggregate, both goods are consumed, the proportions depending on costs and the distribution of heterogeneous preferences across the population. Formally, each household has a fixed expenditure ($\epsilon = 1$) on either good x or good y, and we set this at unity. The quantity each purchases is therefore either $1/p_x$ units of x or $1/p_y$ units of y, yielding utility for household h, $A_x(h)a[\Pi_x]^{1/s}/p_x$, or $A_y(h)a[1-\Pi_x]^{1/s}/p_y$. The peer effect preference parameters, $a[\Pi_x]$, $a[1-\Pi_x]$, are as before, and $A_x(h)$and $A_y(h)$ are household h specific preference parameters that are Frechet distributed across households the distribution having shape parameter s.[17] The Frechet assumption gives discrete choice function with functional form such that the proportion of households that purchase good x is $a[\Pi_x](p_x/P)^{-s}$, where $P = \left[a[\Pi_x]p_x^{-s} + a[1-\Pi_x]p_y^{-s}\right]^{-1/s}$. This is clearly analogous to the previous case and it gives rise to multiple equilibria, as before. However, it is important to note that the shape parameter s has quite different interpretation from the exponent $1-\sigma$ in the previous example High s means that there is little variation in preferences across the population. This makes demand curves highly price elastic because people are relatively more willing to switch their choice between the carbon-based and renewables-based goods.

C. DYNAMICS AND STALLED TRANSITION

All of these changes take place through time, and minor reformulation of the model gives a dynamic analysis that captures the possibility of a stalled transition between multiple long-run equilibria. The reformulation involves, in general, reinterpreting all three externalities – global warming, social, and technological – as functions of the accumulated

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[16] The discrete-choice formulation can also be cast in a dynamic framework to obtain an evolutionary explanation of the consumer market leading to dynamics of fashions and fads (Mercure, 2018).

[17] For a full treatment of the discrete choice model and application to international trade, see Eaton and Kortum (2002). The Fréchet distribution is also often used in other parts of economics where agents make choices between discrete alternatives.

stock of past output and consumption rather than of the current flow. To illustrate this, suppose that, as in the previous section, households make discrete choices and there are peer effects in demand for goods *x* and *y* good. Pollution externalities are present in the background, while externalities in production remain switched off (c_x, and c_y are constants). Peer effects depend on the accumulated stock rather than the flow of output, i.e. on past purchases of *x* and *y* goods, perhaps as habits become formed or learning by doing takes place. The variables *X* and *Y* now denote the stock of accumulated output in each product, and are driven by the differential equations

$$(7)\quad \dot{X} = \delta\{a[\Pi_x](t_x c_x)^{1-\sigma} P^{\sigma-1} - X\}, \qquad \dot{Y} = \delta\left\{a[1-\Pi_x]\left(t_y c_y\right)^{1-\sigma} P^{\sigma-1} - Y\right\},$$

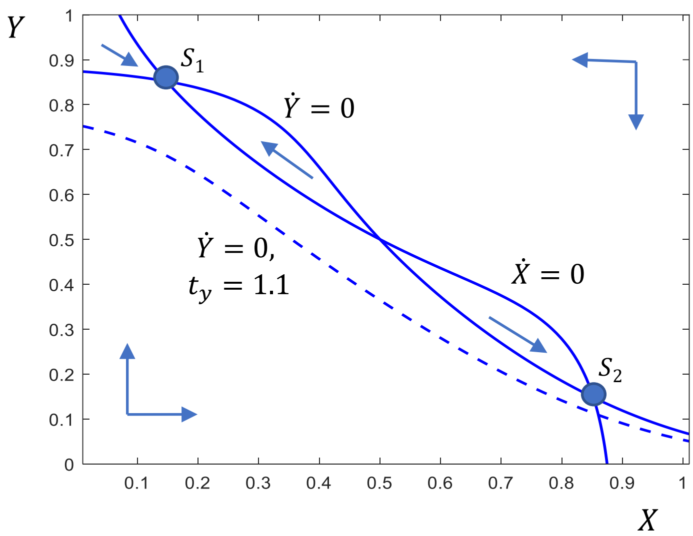
with $P = \left(a[\Pi_x](t_x c_x)^{1-\sigma} + a[1-\Pi_x]\left(t_y c_y\right)^{1-\sigma}\right)^{1/(1-\sigma)}$ and $\Pi_x = X/(X+Y)$. $\dot{X}$ and $\dot{Y}$ denote changes in these stocks per unit time (a dot over a variable denotes the time derivative). The first term on the right hand side of each of these differential equations is the flow of current consumption and production. Proportion δ of the population purchase a product (i.e. a motor vehicle) each period, and fraction $a[\Pi_x](t_x c_x)^{1-\sigma} P^{\sigma-1}$ of these are type *x*, as in the previous section. At the same time proportion δ of the existing stock of *x* goods depreciate (i.e. δX are scrapped), so the net change in the stock of *x* goods is purchases minus depreciation, $\dot{X}$, and similarly for $\dot{Y}$, as given in the second equation.

Figure 3 illustrates the dynamics of equations (7). The two solid lines are loci of (*X*, *Y*) along which $\dot{X} = 0$ and $\dot{Y} = 0$. At low values of *X*, *Y*, stocks are increasing (as depreciation is low), while at high values, above and to the left of $\dot{X} = 0$ and $\dot{Y} = 0$, stocks are falling. The curvature of the loci is shaped by peer effects in demand, $a[\Pi_x]$ and $a[1-\Pi_x]$. The figure is constructed with the function $a[.]$ taken to be sigmoidal, the cumulative density function of a normal distribution with mean 0.5 and variance 0.33 so that on support $\Pi_x \in [0,1]$ the range is $a(\Pi_x) \in [0.07, 0.93]$.

There are three stationary points shown in the figure, of which two are stable, and the middle one unstable. Stationary point S_1 has a high stock of the brown good, *Y*, and continuing high output of good *y* replacing depreciating stock. Conversely, stationary point S_2 has a high stock and output of the green good *x*. The question is, if the economy starts from high emissions with a high value of *Y*, can it make the green transition from S_1 to S_2? Starting from *X* = 0 and *Y* > 0 the answer is no. A transition may start, with rising production and stock of good *x*, but gets stalled as the system moves to point S_1. At this point $a[\Pi_x]$ is low, so demand for and production of good x is no greater than depreciation of the existing stock X.

Policy can resolve this problem by shifting one or both of the stationary loci. The dashed line illustrates the Y stationary when the polluting good y is subject to a tax, $t_y = 1.1$. This reduces demand and output of good y shifting the Y stationary downwards so, for example, point S_1 is now above the stationary, meaning that $\dot{Y} < 0$ at this point. There is a single stationary point, at the intersection just below S_2, which is globally stable and to which the economy converges to a low-emissions equilibrium.

Figure 3: Stalled transition: dynamics of X and Y



Starting from a low stock of X transition stalls at point S_1, where production of x is no greater than depreciation of the existing stock.

In policy terms, there are two considerations. First, for the case where there is a single stationary value, optimal control techniques can be used to give an optimal path from any starting point to the green equilibrium at S_2, trading off the cost of distorting current consumer prices away from marginal cost against the benefit of faster transition thereby cutting global warming damages.[18] Second, for the case where stalling may occur, the primary task of policy is 'non-marginal' in the sense that it must prevent the economy stalling at the stationary point S_1 with high emissions. The challenge is then to ensure that

[18] Although local and global policy has been studied in dynamic ecological systems with tipping points (e.g. Polasky et al., 2011; Hinlopen et al., 2013; Wagener, 2020), a similar analysis has not been conducted yet for policy in models with tipping points stemming from peer effects and/or technological externalities.

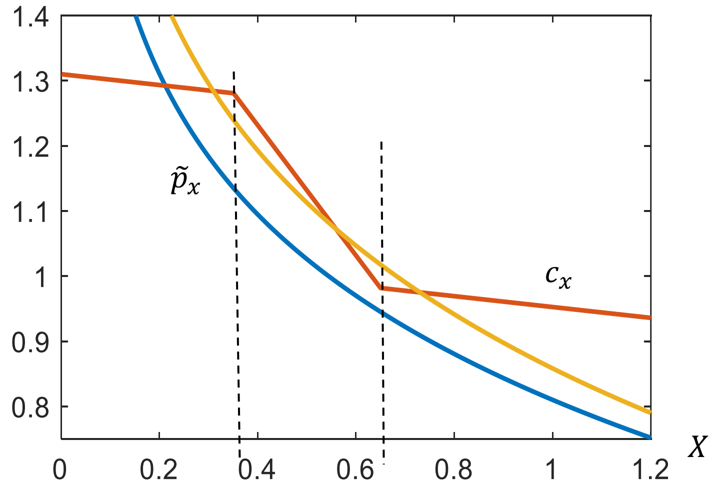
the economy moves from the low-X stationary point, with low green consumption to the high-X equilibrium with a high share of green products in the mix.

D. EXTERNAL ECONOMIES OF SCALE IN PRODUCTION

We now turn attention to economies of scale in production. Switching off peer effects in demand (i.e. making the demand parameters a_x and a_y constant), we look at the case in which unit cost in the clean sector decreases with total output, $c_x'[X] \leq 0$. This is due to external economies of scale or learning-by-doing effects in the production of the clean good, which are not internalized by any of the price-taking firms in the sector. We assume that this depends on the aggregate level of output of X, not the share of X in total output; thus, c_x is not directly affected by the level of y-production, and vice versa. Underlying micro-foundations of this relationship come from there being multiple firms involved in production of good x, including those producing intermediate goods at different stages of the production process or generating technical knowledge. The pecuniary and technological externalities so created are not internalized in any single firm's decisions, so production by the green sector as a whole exhibits increasing returns. We assume that there are no such production externalities in production of the dirty good as the technology is mature and any and such spill-over advantages have already been reaped.

The analysis is analogous to that above, and the story is drawn out in Figure 4. The horizontal axis gives output of the green sector X. The supply curve is the red line, i.e. unit cost $c_x[X]$, assumed in this example to be piecewise linear, decreasing everywhere, but with a steep central range. The blue and yellow lines are inverse demand curves, giving the price at which households purchase quantity X. The blue line supports one equilibrium while the yellow line supports three equilibria, as in the previous example shown in Figure 2.

Figure 4: Unit costs with increasing returns to scale



External economies of scale in production of good x cause the unit cost curve to slope down, creating the possibility of multiple equilibria.

Suppose that the economy is at a unique equilibrium indicated by the intersection of the blue inverse demand curve and the red unit cost schedule. This corresponds to an outcome with low output of the green good, *x*, and thus high output of the brown good *y*, and high emissions. Starting from this situation, consider the introduction of a subsidy to the green good or a tax on the carbon-based good, which raises the inverse demand curve from the blue curve to the yellow line. This increases production of green goods because of the direct subsidy effect and, in Figure 4, it is further increased due to an amplification caused by the downwards slope of the cost curve; we discuss this amplification effect further in section 4A. Along the yellow demand curve there are now two further equilibria (one unstable, one stable), although the upper intersection remains an equilibrium.

However, if the subsidy for the clean good or the tax on the polluting good is further increased, the yellow line shifts up further until there is only one instead of three equilibria. This equilibrium is stable and corresponds to a high value of renewable-based goods *X* and low levels of emissions and global warming. It has thus become worthwhile for individual price-taking firms to expand production of the green goods fast; unit cost is less than price, and this continues until the high-*x*-output equilibrium is reached at the higher output and lower cost intersection of the demand and unit cost curves in Figure 4. Such a climate policy is radical in the sense that it does not just induce a marginal drop in emissions, but manages to shift the equilibrium from the bad to the good one, thus ensuring a substantial drop in emissions.

Finally, we note two further points. First, just as a dynamic version of peer effects can be developed (section C above), so too for these technological externalities, with the same risks of stalling emerging. Second, technical innovation may be in part cost reduction, and in part the development of new products – at its simplest, the range of electric vehicles is increasing. While this is driven by technology, its effect is exactly analogous to an increase in a_x, as more varieties of product affect preferences, and have the effect of inducing consumers to switch expenditure to green x-goods.

4. Tax and Subsidy Policies

How should the presence of social and technological externalities change environmental tax and subsidy policies? We address this question first using standard marginal analysis, i.e. looking at the effects of policy changes around a particular (stable) equilibrium. We then argue that this is only part of the story as policy is also needed to move through tipping points – although the practical quantification and design of policy in the presence of multiple equilibria and tipping points remains highly uncertain.

A. TAX AND SUBSIDY POLICY: MARGINAL CHANGE

Previous sections have referred to tax and subsidy policy being used to shift demand curves, but without specifying the precise magnitude of such effects, or assessing their impact on welfare. The starting points for making this fuller assessment are the demand curves, equation (2). Any change in equilibrium output must lie on these demand curves so, it follows that changes in total outputs X and Y must satisfy

$$\hat{X} = \hat{a}_x - \sigma\hat{p}_x + (\sigma - \epsilon)\left[\mu\hat{p}_x + (1-\mu)\hat{p}_y\right], \quad (8)$$

$$\hat{Y} = \hat{a}_y - \sigma\hat{p}_y + (\sigma - \epsilon)\left[\mu\hat{p}_x + (1-\mu)\hat{p}_y\right],$$

derived by totally differentiating equations (2). Here ^ denotes proportional change, and μ is the share of spending that goes on good x. The first two terms on the right-hand side of each of these equations are the effect of changes in preference and price holding the price index, P, constant, and the last two are changes transmitted through the price index. Changes in prices enter the index, weighted by expenditure shares, and so too may changes in preference, $\hat{a}_X, \hat{a}_y$. However, we assume that changes in preferences are, in the neighborhood of the equilibrium, pure switching effects, i.e. switch expenditure between the two goods without having any effect on the price index, so these terms do not enter equations (8) (any increase $\hat{a}_X$ is cancelled out by decrease $\hat{a}_y$, see appendix).

We continue to suppose that y production has constant returns to scale but may be subject to taxation, so $\hat{p}_y = \hat{t}_y$. The green good, x, has both technological and social externalities, and is also subject to policy change $\hat{t}_x$. Its price change therefore includes both a tax effect and a scale effect $\hat{p}_x = \hat{t}_x + \gamma_x \hat{X}$, where $\gamma_x \equiv X c_x'[X]/c_x[X]$ is the elasticity of unit costs with respect to output, negative if there are increasing returns. For simplicity we suppose that peer effects for each good are a function only of own output, so $a_x[X]$, $a_y[Y]$ and hence $\hat{a}_x = \alpha_x \hat{X}$, $\hat{a}_y = \alpha_y \hat{Y}$ where α_x, α_y are elasticities of preference with respect to output, e.g. $\alpha_x \equiv X a_x'[X]/a_x[X]$.[19] It follows from (8) and these assumptions that the effect of policy on output are given by,

$$(9) \qquad \hat{X} = \frac{-\sigma \hat{t}_x + (\sigma - \epsilon)\big[\mu \hat{t}_x + (1-\mu)\hat{t}_y\big]}{1 - \alpha_x + \gamma_x[\sigma - (\sigma - \epsilon)\mu]},$$

$$\hat{Y} = \frac{-\sigma \hat{t}_y + (\sigma - \epsilon)\big[\mu \hat{t}_x + (1-\mu)\hat{t}_y\big]}{1 - \alpha_y}.$$

The numerators of these expressions are intuitive, and say that demand for each good is decreasing in its own tax rate and increasing in the tax rate the other good (providing $\sigma > \epsilon$). The denominators point to the amplification effect (as in Konc et al. 2021). Any given change in the tax or subsidy on either good has a larger absolute effect on quantity if there are positive peer effects, $\alpha_x > 0$, or technological externalities creating increasing returns to scale, $\gamma_x < 0$. Both effects are present for good x, and only the former for good y. To hit a quantity target (on good x or good y and hence emissions) a smaller policy instrument is therefore needed (smaller subsidy to x or tax on y, as in Mattauch et al. 2018).

We now proceed to the welfare effects of policy change. Under-pinning the models outlined above is household utility, given by

[19] This is in contrast to the shares approach used previously, $a_x = a[X/(X+Y)]$; it simplifies algebra greatly. Pure switching then implies that, in the neighbourhood of the equilibrium $\mu \hat{a}_y + (1-\mu)\hat{a}_y = \mu \alpha_x \hat{X} + (1-\mu)\alpha_y \hat{Y} = 0$.

$$(10) \qquad U = P^{1-\epsilon}/(\epsilon - 1) + M + T - K_y[Y] .$$

In this expression P is the sector price index (equation 2), and $P^{1-\epsilon}/(\epsilon - 1)$ is the indirect utility function incorporating privately optimal choice of goods x and y. M is exogenous household income, T is tax revenue that is returned to households in a lump sum manner, $T = c_x X(t_x - 1) + c_y Y(t_y - 1)$, and the pollution damage functions is $K_y[Y]$. Locally optimal tax/ subsidy policy can be found by totally differentiating (10) to get an expression for the change in utility, dU, when taxes change. The change has direct effects, and causes changes in endogenous variables, in particular levels of output of each good. Some of these changes net out so the final expression for the change in utility can be derived as (see appendix)

$$(11) \qquad dU = c_x X(t_x - 1 - \gamma_x)\hat{X} + c_y Y\big(t_y - 1 - K_y'/c_y\big)\hat{Y}.$$

The terms on the right-side of the equation say that changes in output levels $\hat{X}, \hat{Y}$ change utility according to the wedge between price and marginal cost, the latter including the externalities associated with increasing returns in x production, and pollution costs generated by y output. Peer effects and increasing returns influence the magnitude of changes output, $\hat{X}, \hat{Y}$ but, in the pure switching case, have no direct effect on P nor therefore utility.

The first-order condition for local welfare maximization is $dU = 0$. If both tax instruments, t_x and t_y are under the control of the policy maker then, from (11) locally optimal tax/ subsidy rates simply line up consumer prices with full social marginal costs.

$$(12) \qquad t_x - 1 = \gamma_x, \quad \text{and} \quad t_y - 1 = K_y'/c_y.$$

As expected, these are Pigouvian, depending on technological and pollution externalities, implying a subsidy on good x to internalize increasing returns to scale, $\gamma_x < 0$, and a tax on good y, equal to the marginal cost of emissions.

Pulling this together, there are three points. First, the amplification effect means that the presence of peer effects and/or increasing returns to scale require smaller policy instruments to hit a particular target level of output and emissions (equation 9). Second, the (locally) optimal first best tax or subsidy policy is unchanged by the presence of peer effects, if these are purely expenditure switching. And third, a unit change in a policy instrument towards its first-best Pigouvian value brings greater utility benefit in the presence of peer effects and technological externalities. As is apparent from equations (9) and (11), a given change in policy instruments brings a larger output response and thence a greater benefit, as the economy moves towards the (locally) optimal point. A corollary of this is that the utility cost of having instruments away from their (locally) optimal values is larger in the presence of these complementarities.

It is possible that only one tax instrument can be used, in which case this instrument must take account of multiple markets failures and policy is second-best optimal. For example, suppose that policy is restricted to the polluting good, i.e. good x is untaxed (or subsidized), so $t_x = 1$. From equation (11), the second-best optimal tax on good y is then

$$(13) \qquad t_y - 1 = \frac{K_y'}{c_y} + \gamma_x \frac{c_x}{c_y}\frac{dX}{dY} > \frac{K_y'}{c_y} > 0.$$

Both terms on the right-hand side of the expression are positive if x production is subject to increasing returns ($\gamma_x < 0$), since $dX/dY < 0$.[20] Alternatively, it may be that political constraints rule out carbon taxes, but permit renewable energy subsidies. With t_y constrained to unity, second best policy on good x is a subsidy

$$(14) \qquad t_x - 1 = \gamma_x + \frac{K_y'}{c_y}\frac{dY}{dX} < \gamma_x < 0.$$

In each of these cases second-best optimal policy takes larger absolute value than the first-best Pigouvian pollution tax or subsidy.

B. TAX POLICY AND TIPPING POINTS

The central theme of this paper is that the local, or marginal tax rates derived above may not be optimal as they ignore the potential to tip the economy from a dirty equilibrium to a cleaner one. We demonstrate this possibility with an example, based on demand complementarities as in Figure 2 (see appendix) . Recall that good y is the polluting good and increases in t_y shift the demand for good x upwards. Figure 5a traces out these equilibrium values of X as a function of the tax rate t_y (horizontal axis where the ad valorem rate is $t_y - 1$, and t_x is constrained at unity). The range of t_y illustrated is from a subsidy ($t_y < 1$) through to a tax of 40 percent. The lines on Figure 5a give equilibrium

[20] dX/dY can be found from the ratio of equations (9), given a change $\hat{t}_y$.

levels of x-output and, as is apparent, in the interval t_y = [0.92, 1.31], three equilibria exist, the middle one of which (the red line) is unstable.

Figure 5b gives the corresponding level of utility, again as a function t_y, constructed for the case in which each unit of y-output causes marginal pollution damages, assumed for illustrative purposes to be $K'_y/c_y = 0.2$. The Pigouvian tax rate is therefore 20%, i.e. $t_y =$ 1.2, as illustrated by the local utility maxima for each of the stable equilibria.[21] However, utility is higher in the high x-output (clean) equilibrium than the low x-output (dirty) equilibrium, and reaching this point through taxation of the polluting good requires t_y =1.31, above the Pigouvian rate. Starting with a low value of t_y in the high-pollution equilibrium, Figure 5b illustrates how increasing t_y has modest effects on utility until it reaches the critical level (t_y =1.31) at which point switching further expenditure to good x triggers complementarities large enough to cause the equilibrium to flip, raising utility as illustrated by the dashed arrow. Once the flip has occurred – and all behavior has adjusted to the new equilibrium – it is efficient to reduce the rate of tax back to the Pigouvian level, as illustrated in the figure.

Figure 5a: *Y*-sector tax & *X*-sector output.

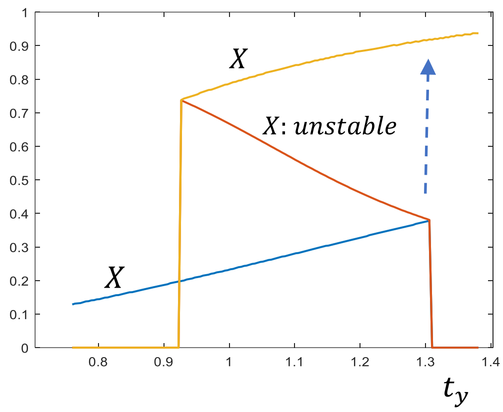
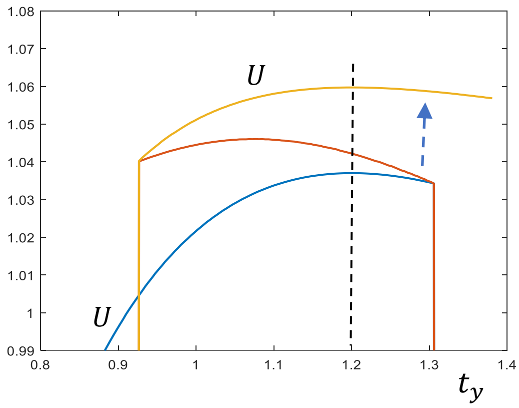


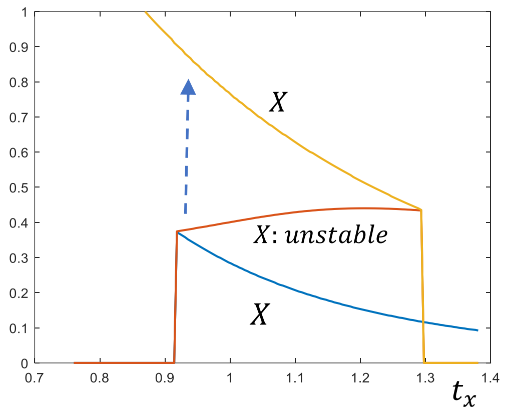
Figure 5b: *Y*-sector tax & utility.

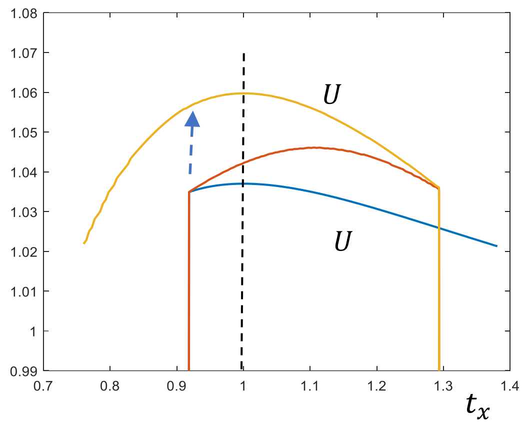


Utility maximisation requires a tax high enough to flip from the dirty equilibrium (blue line) to the clean equilibrium (yellow). In this example the tax exceeds the Pigouvian rate.

[21] There are no peer effects externalities at either of these equilibria, since at these points $a'_x[X] = 0$.

Figure 6a: X-sector tax & X-sector output. **Figure 6b: X-sector tax & utility.**





Dirty output is subject to the Pigouvian tax, but it takes a subsidy to the clean good to flip the economy from the dirty equilibrium to the clean equilibrium.

Figures 6a and 6b take the same example, but vary the tax rate on the clean good, t_x, while holding that on the polluting good at its Pigouvian level, $t_y = 1.2$. Local utility maxima are achieved at $t_x = 1$ (vertical dashed line on figure 6b), suggesting that there is no role for tax/ or subsidization of the clean good. But at this point there are multiple equilibria, and the economy may be in the dirty equilibrium. To move out of this equilibrium requires that the clean good is subsidized (in addition to having the Pigovian tax on good y), by setting $t_x \leq 0.91$ (vertical dashed arrow). Once the economy has made the full adjustment to the clean equilibrium the subsidy can be removed to achieve the global maximum.

C. IMPLICATIONS

It helps to summarize the main insights we have obtained from our analysis. First, complementarities from positive peer effects in demand and from positive technological spill-over effects in production create an amplification of the effects of carbon taxes and green subsidies on emissions, thus suggesting that lower carbon taxes can achieve the same quantitative effect on emissions (cf. Mattauch et al., 2018; Konc et al., 2021). At the same time, moving a tax or subsidy towards its optimal value is more valuable, precisely because it brings about larger effects. Second, if complementarities are positive and strong enough, there are two stable equilibria with, respectively, low and high emissions and a third equilibrium in the middle which is unstable. An important role for policy is to bring about the switch between equilibria – or to prevent a transition from stalling –

and this may well require a higher tax rate (or, in general more activist policy) than is suggested by usual prescription on the price of carbon.

The outstanding questions are how large must complementarities be to give the multiple equilibria configurations illustrated in this section, and how can policy makers know when to try to bring about a tipping point or prevent a technological transition from stalling. While these uncertainties are enormous it is essential to recognize that – in the presence of substantial complementarities – optimal policy is likely to go well beyond the Pigouvian policies so often advocated. We place these ideas in a wider context in the following section.

5. Transformative Climate Policies: A Broader View

Climate tipping points and regime shifts have long been analyzed in the complex, adaptive systems used by climate science (and biology) literature. Multiple potential tipping points are identified such as melting of the Greenland and the West Antarctic Ice Sheet and the East Antarctic Wilkes Basin, slow-down or reversal of the circulation in the Atlantic Ocean, the loss of Arctic Sea ice, thawing of the permafrost, and deterioration of the boreal forests (e.g. Lenton et al., 2019). Some of these irreversible shifts take hundreds of years before they have their full effects while others take only a few decades. Climate tipping points can arise from bifurcation in a nonlinear system (not unlike our analysis in section 3) but are also often modeled either via a probability of a climate catastrophe that rises with global warming or via a threshold for cumulative emissions or temperature beyond which the climate system tips. The latter has led to temperature targets of 1.5 or 2 degrees Celsius relative to the preindustrial level.

Economists have argued that policy makers should internalize the externality resulting from the adverse effects of global warming on aggregate production by setting the carbon price equal to the SCC (e.g. Nordhaus, 2008) and that this should include estimates of the cost of possible climate catastrophes and be set to minimize the risk of passing an irreversible threshold (e.g. Lemoine and Traeger, 2014; van der Ploeg and de Zeeuw, 2018; Cai and Lontzek, 2019). The precautionary principle also calls for a vigorous climate policy. If policy makers also internalize the risk of cascading climate tipping points, they would price carbon much more highly (Lemoine and Traeger, 2016; Cai et al., 2016). The increased risk of (cascading) climate tipping points implies that we are in a state of planetary emergency with both the expected damage and the urgency, i.e. reaction time to achieve net zero emissions (thirty years at best) divided by the intervention time left to prevent tipping (shrunk to almost zero), of the situation being acute (Lenton et al., 2019). The Intergovernmental Panel on Climate Change (IPCC) has also warned that the stability and resilience of our planet is at risk unless quick and vigorous action is taken to move to an economy with net zero emissions.

The argument of this paper is that tipping points occur not only in climate science and biology, but also in economic and social behavior, creating a further set of arguments for radical and aggressive policy. The preceding sections of the paper provide a simple, yet micro-founded and integrated way of thinking about these tipping points and their policy implications. Our arguments build on large economics literatures on social norms, networks, and political economy, which we discuss in the remainder of this section.

We have argued in sections 2-4 that due to strategic complementarities stemming from complementarities in demand (peer effects) and supply (increasing returns to scale, learning by doing), radical climate policies are needed to shift the economy from one high-emissions equilibrium to another low-emissions equilibrium. So, the challenge is not only to prevent climate tipping points occurring, but also to set in motion social and technological tipping points that can lead to quick and sudden transition towards a net-zero economy. Social and technological tipping points can thus be put to good use, although it must be realized that the required time scales are much shorter than those involved in climate tipping.

One can also set in motion political tipping points. For example, if some municipalities are successful in switching dwellings from gas to heat pumps and solar panels, other municipalities may follow according to the premise "seeing is believing". A similar mechanism is at play between countries. The example set by Scandinavian countries to make progress on the green transition encourages other countries to the same. One way of setting in motion a political tipping point is a climate club, where a group of countries pushes ahead as a free-trade zone with ambitious green policies but countries outside the group who do not have a serious climate policy have to pay a tariff to trade with the group. Nordhaus (2015) suggests that a modest tariff of 2 to 5% that rises with the carbon price, could lead over time to a large and stable coalition of countries with high levels of abatement. In an early contribution Heal and Kunreuther (2011) show that international climate negotiations can be modeled as a non-cooperative game with increasing differences, since these have multiple equilibria and a subset of agents who by changing from the inefficient to the efficient equilibrium can induce all others to do the same. This so-called tipping set is a small group of countries that by adopting climate mitigation measures can make it in the interests of all other countries to do likewise.

A. SOCIAL NORMS

The literature on social norms includes use of stochastic evolutionary game theory to analyze punctuated equilibria and rapid change in social norms (e.g. Weibull, 1995; Young, 2015). If people respond to incentives and are influenced by norms for good conduct from earlier generations, strategic complementarities between values and current behavior emerge with values evolving over time but where there is path dependence and adverse initial conditions can lead to an outcome where legal enforcement remains weak and individual values discourage cooperation (Tabellini, 2008). More specifically, self-enforcing social norms can be sustained by a desire to coordinate, fear of being sanctioned, signaling membership of a group, or following the lead of others. Examples of rapid shifts in social norms can be found in norms for dueling or for foot binding (in China), and contraceptive use (e.g. Young, 2015). Interestingly, such norms often involve without top-down intervention but through a process of trial and error, experimentation, and adaptation, and depend on social, cultural, and historical contexts.

The insights from this literature can also be applied to understand potential rapid switches in environmental attitudes. For example, Besley and Persson (2021) suggest that scientists care about how and where they deploy their skills and that this can cut the cost of green innovation if scientists have green values. Innovation determines the relative growth rates of green and carbon-based goods. The combined effect of the dynamics of directed technical change with cultural dynamics among consumers further strengthens the influence of science which can now speed up the green transition and even change the direction of a society's path. Another example is the study by Schlüter et al. (2016) which shows analytically that in the specific context of common-pool resources (e.g. fish, water, or forests) that under certain social and biophysical conditions (e.g. resource scarcity, resource variability, and spatial connectivity), self-organized cooperation can evolve. Community members then follow a social norm of socially optimal extraction of a common resource, enforced by social sanctioning.

B. EXPECTATIONS AND CARBON LOCK-IN

We have emphasized the importance of bad and good equilibrium outcomes and unstable tipping points when there are peer effects or learning by doing and increasing returns to scale in production. Expectations about future developments are typically important in this context, particularly in the transition between equilibria. For example, Bretschger and Schaefer (2017) use a dynamic model in which the revenue product of capital is non-monotonic in the capital stock, to study the effect of history and expectations for macroeconomic performance. They identify conditions so that pure expectations determine which of the multiple steady-state outcomes will prevail. Energy policy (taxes and subsidies) can then be used to shift the region where expectations matter and can determine whether a low-emissions equilibrium will be selected. Expectations and momentum effects lower policy costs and raise political acceptance and are thus important for the energy transition.

Similarly, van der Meijden and Smulders (2017) highlight the interaction between directed technical change and resource capacity to show that expectations about future energy use can affect the transition from fossil fuel to renewable energies. Technical change that leads to less use of fossil fuel curbs incentives to implement renewable energies, and the anticipation of a green transition reduces incentives to invest in carbon-based technologies. Expectations determine whether a stable no-emissions equilibrium with a transition to renewables or a stable high-emissions equilibrium without renewables and high fossil-fuel efficiency occurs.

Acemoglu et al. (2012) show how market size and initial conditions determine whether the direction of technical change is clean or dirty, and thus directed technical change exhibits path dependency. Smulders and Zhou (2020) show using a model with directed technical change that multiple equilibria arise naturally when innovators are forward-looking. Whether an equilibrium with green innovation or one with carbon-based innovation is attained depends on initial conditions as well as the degree of substitutability between carbon-based and green goods, so market size and policies are not the only deciding factors anymore in determining the direction of technical progress.[22] Both a transition to a green economy and a transition to an economy that is locked in carbon-based technologies can thus be self-fulfilling prophecies.

Harstad (2020) highlights the consequences of policy makers with time-inconsistent preferences either due to fear of losing power or due to hyperbolic discounting. He then shows that optimal green investment subsidies are larger for technologies that are strategic complements to future investments, that are further upstream in the supply chain, or that are characterized by a longer maturity. Also, one might tax investments in carbon-based technologies if these substitute for future investments. Effectively, politicians want to influence the policy choices of their successors. By investing in green technologies, they can motivate subsequent politicians to act sustainably. Also, time inconsistency and strategic investments are especially important for long-term policies associated with externalities.

C. AMPLIFICATION VIA NETWORKS

Economies are complicated networks of trade and communications between firms and households. Ballister et al. (2006) give a formal analysis of who is the key player in a network. Leister et al. (2022) analyze a coordination game among agents in a network in an uncertain environment, where agents decide whether to adopt say new technology that yield increasing value in the actions of neighboring agents. For this purpose, they partition the network into communities in which agents have the same propensity to adopt. Social connectedness captures both the number of links each agent has within her community and the number of links she has with members of other communities who have a higher propensity to adopt. It determines the propensity to adopt for each agent. They show that contagion is localized within these communities such that a shock to an agent affects all other members of its community but not those outside.

Exploiting the specific structure of networks is important for effective targeting of climate policies.[23] Also, networks may lead to unintended effects of sectoral policies. For example, King et al. (2019) show that a sector-specific carbon tax can increase aggregate emissions, as resources get reallocated to more polluting sectors. But carbon tax reforms

[22] There is a third interior equilibrium in the model of Smulders and Zhou (2020) which is unstable.

[23] The study by Lee et al. (2021) finds that the key player in a network of juvenile delinquents is not always the most active delinquent. Compared to a policy that removes the most active delinquent from the network, a policy targeted at the key player leads to a much higher delinquency reduction.

that target sectors based on their position in the production network can achiever bigger emission cuts than reforms that target sectors that are only based on their direct emissions. A study by Greaker and Midttømme (2016) analyses a model where the utility of both green and dirty goods increases in their respective market share due to network effects. They find that a constant tax that only internalizes the environmental damages caused by the dirty good may lead to excess inertia. Konc et al. (2021) allow for social preferences due to the influence of peers in a social network. They show that this leads to amplification of the effects of environmental policy and that the size of these effects depends on the typology of the network, but do not analyze the possibility of multiple equilibrium outcomes in networks.

Future research could be concerned with how multiple equilibria emerge naturally in network and how learning and targeted climate policy may steer the economy in the most effective way towards the good, low-emissions equilibrium.

D. SENSITIVE INTERVENTION POINTS

Given the disappointing progress in international climate negotiations, there has been an increasing interest in so-called sensitive intervention points to unleash radical climate policies and not to rely only the climate stabilization wedge (e.g. Farmer et al., 2019). The idea is that a relatively small change can trigger a larger change that becomes irreversible. Here feedback effects act as amplifiers (cf. section 2-4). It is thus important to investigate how to exploit such sensitive intervention points and amplification mechanisms in social, technological, and political systems to achieve a rapid green transition. The search should thus be for policies in which an intervention kicks or shifts the system so that the initial change is amplified by feedback effects that deliver an outsized impact.

Lenton (2020) defines tipping points as small perturbations causing a qualitative change in the future state or trajectory of a system and explains that these can be explained by bifurcation theory. He argues that triggering positive tipping points towards sustainability in coupled social, ecological, and technological systems is important, and that tipping points occur naturally in continuous-time dynamic systems and networks. He highlights the causal interactions that can occur between tipping events across different types and scales of system — including the conditions required to trigger tipping cascades, the potential for early warning signals of tipping points, and how they could inform deliberate tipping of positive change.

It is fair to say that despite the various suggestions for such interventions that have been made, detailed empirical evidence for the outsized impacts they might trigger is missing. For example, Otto et al. (2020) have employed online expert elicitation, a workshop, and literature survey to evaluate the potential of socio-economic tipping point interventions that can activate contagious processes of rapidly spreading technologies, behaviors, social norms, and structural reorganizations. Examples of tipping triggers they highlight are removing fossil-fuel subsidies and incentivizing decentralized energy generation, building carbon-neutral cities, divesting from carbon-based assets, revealing moral implications of fossil fuels, climate education and engagement, and disclosing information of greenhouse gas emissions.

Van Ginkel et al. (2020) offer a tipping point typology and, also, study socio-economic tipping points which they define as an abrupt change of a socio-economic system induced by climate change, into a new, fundamentally different state. Through stakeholder consultation, they identify 22 candidate socio-economic tipping points with policy relevance for Europe and analyze three of these (collapse of winter sports tourism, abandonment of farmland, and migration induced by rising sea levels) in more detail. They point out that it is hard to isolate the role of climate drivers from other drivers due to complex interplays with socio-economic factors, and sometimes the rate of change rather than the magnitude of change causes a tipping point. They also suggest that the clearest socio-economic tipping points are found at the local level, much less so at the national or continental level. Moore et al. (2022) also study potential nonlinearities and feedback effects that might lead to social, political, or technological tipping points. They suggest that public perceptions of climate change, future costs and effectiveness of mitigation technologies, and the responsiveness of political institutions affect emissions pathways and global warming.

Tabara et al. (2022) attempt to clarify the notions of leverage points, sensitive interventions, social tipping points, transformational tipping points, and positive tipping points. They propose methods based on processes of social construction and time dynamics that may help to identify and support emergence of social-ecological tipping points such as rapid decarbonization. They argue that three key moments need to be considered: (i) building of transformative conditions and capacities for systemic change; (ii) a tipping event or intervention that shifts the system towards a different trajectory or systems' configuration; and (iii) structural effects derived from such transformation.[24] Their insights are derived from the examination of the implementation of household renewable energy systems at the regional level in two rural areas of Indonesia and Bangladesh.

Chapin III et al. (2022) draw on empirical studies to argue that earth stewardship for a sustainable and equitable future can be leveraged with social tipping points by interactively changing either policy incentives or social norms and exploiting complementarities across policy areas, based on values, system design, and agency. They also argue that it is crucial to align actions to be synergistic, persistent, and scalable.

Although these five last studies offer laudable policy suggestions and insights, it is not clear from an empirical point of view *why* and *if* these would get one out of a climate trap and move the economy from a bad to a good equilibrium. These policies may lower emissions around the high-emissions equilibrium, but it is not clear whether they will shift the economy to a radically different low-emissions equilibrium. More sound empirical evidence is urgently needed in this area.

E. SUSTAINABILITY SCIENCE APPROACHES

Sustainability science has been concerned with the question of transformational change, which clearly relates to the idea of radical climate policies. For example, Abson et al. (2017) drawing on ideas by Donella Meadows, argue that sustainability interventions often target highly tangible, but weak, leverage points. There is thus an urgent need to focus on less obvious but potentially far more powerful areas of intervention. They suggest a research agenda inspired by systems thinking that focuses on transformational 'sustainability interventions', centered on three realms of leverage: reconnecting people to nature, restructuring institutions and rethinking how knowledge is created and used in pursuit of sustainability. They suggest that the notion of leverage points has the potential to lead to genuinely transformational sustainability science. The study by

[24] They also argue that the discovery and enactment of positive social-economic tipping points require the consideration of multiple ontological, epistemological, and normative questions that affect how researchers and change agents define, approach, and assess their systems of reference.

Blythe et al. (2018) suggests that new ways of theorizing and supporting transformations are emerging which open exciting spaces to (re)imagine and (re)structure radically different futures, but they also note how these academic concepts can be translated into an assemblage of normative policies and practices, and how this process might shape social, political, and environmental change. They thus identify five latent risks for a successful and efficient transformational change: shifting the burden of the response to the most vulnerable in society; transformational discourse may be used to justify business as usual; insufficient attention to social differentiation; resistance to change; and insufficient treatment of power and politics. These risks point to the need to consider the political and social obstacles to the transition towards a net-zero economy but do not necessarily give new insight into social, political, or technological tipping points.

Efferson et al. (2020) suggest that, if an intervention convinces enough people to abandon the tradition, this can spill over and induce others to follow. A key objective is thus to activate such positive social spill-over effects to amplify the effects of an intervention.[25] Even if conformity pervades decision making, spill-over effects can vary from irrelevant to indispensable. Individual heterogeneity can severely limit spill-over effects, so that a sound understanding of heterogeneity in a population is essential. Although interventions often target samples of the population biased towards ending the harmful tradition, targeting a representative sample is a more robust way to achieve spill-over effects. Finally, they suggest that, if the harmful tradition contributes to group identity, the success of spill-over effects can depend critically on disrupting the link between identity and tradition.

Radical climate policies are meant to be a form of transformational change, so it would be good for economists to engage with scholars in the field of sustainability science.

F. POLITICAL ECONOMY APPROACHES

Environmental policy is set by politicians who have their own preferences and incentives, and policy design needs to recognize the biases that this will induce. This requires studying the joint dynamics of environmental values, politics, and environmental policy. Besley and Persson (2019) do exactly that and identify a range of complementarities

[25] Motivated by the example of female genital cutting, they develop empirically informed analytical and simulation models to examine this idea.

between value adaptation and choice of policies. They distinguish two types of citizens: materialists and environmentalists. Their model of electoral competition has two political parties seeking office by attempting to get the votes of those citizens who are willing to switch allegiance. Political parties thus determine their environmental policies to cultivate the interests of the average swing voter. They show that with a basic evolutionary process these policies and expectations of these policies can drive society towards either environmentalism or materialism.

They thus explain how the shares of environmentalists and materialists in society can coevolve with taxes on emissions to protect society against damages caused by environmental degradation. Even though politicians internalize welfare of those currently alive and pick utilitarian optimal policies, the dynamic equilibrium paths of policies and evolving values do not necessarily converge to the steady state with the highest level of long-run welfare and environmental policies may shrink rather than grow over time. This study indicates that the failure of the democratic political system to achieve an outcome with a growing number of environmentalists is to a certain degree the result of an inability to commit to future policy choices. Current political majorities affect future values as well as current outcomes. If it easier to commit to future institutions than to future policies, this suggests the importance of far-sighted institutions that are independent of short-term political vagaries such as an independent central bank for emission permits (e.g. Helm et al., 2003).

Besley and Persson (2020) recognize that curbing greenhouse emissions requires radical changes in consumption patterns and the structure of production and study the interdependent roles of changing environmental values, changing technologies, and the politics of environmental policy, in creating sustainable societal change. They use a model of the joint dynamics of green values and technology, where the model of values and environmental taxation is based on their earlier paper (Besley and Persson, 2019) and the model of technical is based on theories of directed green or carbon-intensive technical change (cf. Acemoglu et al., 2012). This allows one to investigate the dynamics of technologies, values, and political decisions. They point out that the inability to commit combined with the prevalence of strategic complementarities (positive feedback effects) can generate a climate trap, where society stays stuck in carbon-intensive lifestyles and technologies (cf. section 3.C). They show that lobbying by corporations, private politics, motivated scientists, and endogenous subsidies for green innovation make it hard to get out of such climate traps. Attention should be focused on incentive-compatible policies since governments cannot tie the hands of their successor.

There is not much empirical work yet on the political economy of green transition with multiple equilibria.[26] In future work, the evolution of values may be accelerated by the emergence of green grass root movements (e.g., "Extinction Rebellion" and the school strike movement started by Greta Thunberg) and green political parties as well as by the faster evolution of environmental values and lifestyle changes due to changes in the education system. The challenge is to examine how fast and unprecedented changes in social values, technology, politics, and institutions, fueled by the cascading of these changes, can lead to quick transition to the carbon-free economy.

6. Conclusions

To keep temperature below 1.5 degrees Celsius above preindustrial levels requires significant carbon pricing and substantial, continued cuts in greenhouse gas emissions. In the presence of strategic complementarities stemming from peer effects in demand or from technological spill-overs and network effects, propagation and amplification effects increase the effectiveness of climate policies. This suggests the need for *less* ambitious climate policies. However, if there are multiple equilibria, radical and *more* ambitious climate policies are needed to shift the economy from a high-emissions to a low-emissions economy. Once the radical shift has taken place these transformative policies can be withdrawn. The transformative nature of these policies arises from their ability to set in motion social, technological, and political tipping points. The rationale for such policies is strengthened if policies target and leverage key households, corporations, and institutions at the centre of networks. Our proposals complement suggestions to identify sensitive intervention points to get more effective and more transformative climate policies

[26] De Groote et al. (2020) analyze the political impact of solar panel subsidization in Belgium, where subsidies were much bigger than their social benefit and were partly financed by new taxes on adopters and electricity surcharges on all consumers. As a result, votes for government parties in municipalities with high adoption rates fell. Punishment mainly came from non-adopters, who changed their vote towards anti-establishment parties.

Marginal policies such as setting the carbon price equal to the SCC are thus unlikely be sufficient, given the wide-spread presence of strategic complementarities in demand and supply of renewable energies varying from peer effects in demand for green products to learning by doing and returns to scale in the production of renewables. Substantially higher carbon prices than the SCC may be needed to move the economy from the high-emissions trap to a low-emissions equilibrium. Networks can amplify the effects of climate policies, thus requiring lower carbon prices, but networks also lead to multiple equilibria in which case non-incremental climate policies are thus needed. Crucial is to leverage the green transition by implementing policies that lead to ubiquitous change to green preferences, redirect technical change towards green innovations, and thus lead to a regime shift with much lower emissions.

The newspaper the Guardian rightly summarises the results of the 2021 Glasgow COP26 summit by "*After so many squandered years of denial, distraction and delay, it's too late for incremental change. By mobilising just 25% of the people we can flip social attitudes towards the climate*" (Monbiot, 2021). The challenge is thus to harness the power of domino dynamics (nonlinear change, proliferation from one part of the system to another, cascading tipping points) so that cause and effect are no longer proportionate. Policy makers should thus aim to activate tipping points and tipping cascades, which requires radical, non-incremental, systems-wide policies (Sharpe and Lenton, 2021).

Since there is so much political resistance to pricing carbon, one must consider other climate policies (e.g. subsidies, rebating carbon tax revenues to lower-income groups, or feebates) to complement policies designed to induce tipping from a high- to a low-emissions equilibrium by exploiting strategies complementarities in green demand and supply. One may also take account of how regulatory regimes affect the number of people displaying moral or climate-conscious behaviour. For example, Herwig and Schmidt (2022) show that a carbon tax complements voluntary efforts to cut emissions while a cap-and-trade scheme discourage such efforts and shift the burden of adjustments to poor consumers and has adverse incentive effects.

To set in motion a cascade of tipping points requires in-depth consideration of the process of societal and technological change. The latest report of the Intergovernmental Panel on Climate Change (IPCC, 2022, section T.S. 6.5) therefore stresses different pillars of policy for each stage of the transition to a green economy. The first policy pillar highlights strategic investments in green R&D, demand-pull infrastructure, and industrial development, and is concerned with *emergence* of niches of new technologies (some of which will fail) and the gradual disappearance of incumbent technologies. The second pillar stresses market policies such as prices, taxes, market structures, and planning and regulation, and is concerned with *breakthrough and diffusion*. The third pillar deals with norms and behaviours (e.g. standards, engagement, or dissemination), and corresponds to the *maturation* of new green technologies. The reconfiguration or redirection of technologies in the second pillar is the one where radical (non-incremental) climate policies are most needed, and where barriers and enabling conditions across social, technological, political, and institutional dimensions must be dealt with. The second pillar is thus crucial as it is where the various social, technological, political, and institutional tipping points must be activated.

The political economy of these changes poses numerous challenges. First, governments are prone to pick winners by supporting some renewable technologies over others. But that often results in failure when governments are captured by lobbies. The danger is therefore that the policy tipping narrative is used to pick the wrong 'winners'. Second, once businesses and households have fully converted to green technologies and ways of living it makes sense to lower the ambitious climate policies that have been used to tip the economy from the high-emissions to the net-zero equilibrium. It is thus important that governments bring down renewable energy subsidies and other policies that are no longer needed once the economy has tipped to the net-zero emissions equilibrium even when there is pressure to keep those subsidies in place. It is important to announce horizon clauses in advance to avoid these issues. At the same time, a balance must be struck since it may take time to build before societies get fully stuck in the new cleaner equilibrium. Third, different sectors need different prices or different complementary subsidies for them to tip to the new equilibrium networks. The tipping measures need thus be specific to technologies and sectors. For example, it may be optimal to invest more and price carbon less in sectors that are difficult to carbonise (cf. Vogt-Schilb et al., 2018). Finally, scaling up arguments have often been used to argue for a big push in development economics. Unfortunately, this has not always been a success. It is therefore important to learning from the older big push experience in shaping a new policy tipping narrative.

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Appendix

Micro-economic foundation:

Household decision problem: Households choose their consumption of two goods which are substitutes, one green good x, and the other brown good y. They also consume an 'outside' good, z, which is an aggregate of the rest of the economy, is non-polluting, and used as the numeraire. Utility is quasi-linear and given by $U = u(x,y)^{1-\frac{1}{\epsilon}}/(1-1/\epsilon) + z - K_Y[Y]$, where $K_Y[Y]$ is the pollution costs associated with aggregate output Y. Each household takes the aggregate quantities X and Y as constant, and in equilibrium $X = x$ and $Y = y$, since the number of households is normalized to unity. The CES sub-utility function is $u(x,y) = \left(a_x^{\frac{1}{\sigma}} x^{1-\frac{1}{\sigma}} + a_y^{\frac{1}{\sigma}} y^{1-\frac{1}{\sigma}}\right)^{\sigma/(\sigma-1)}$, where $\sigma > 1$ denotes the elasticity of substitution between the two goods. Households choose x, y, z to maximize utility subject to their budget constraint. The budget constraint of the representative household is $z = M + T - (p_x x + p_y y)$, where M denotes exogenous income of households and $T = p_x x(t_x - 1)/t_x + p_y y(t_y - 1)/t_y$ is lump-sum redistribution of any tax revenue (subsidy cost) incurred. Choosing x and y to maximize utility subject to the budget constraint gives $x = a_x p_x^{-\sigma} P^{\sigma-\epsilon}$ and $x = a_y p_y^{-\sigma} P^{\sigma-\epsilon}$ with $P \equiv \left(a_x p_x^{1-\sigma} + a_y p_y^{1-\sigma}\right)^{1/(1-\sigma)}$ as given in equations (1) and (2). Substituting these optimally chosen quantities into the utility function gives indirect utility function, $U = P^{1-\epsilon}/(\epsilon - 1) + M + T - K_Y[Y]$. The price index P can be interpreted as an indirect sub-utility function, and by Shephard's lemma total expenditure on x and y together is $P^{1-\epsilon}$, and Shephard's lemma also gives the demand functions for each variety, equations (1).

Switching effects and the price index: The total derivative of the price index is

$$\hat{P} = \mu\hat{p}_x + (1-\mu)\hat{p}_y + \{\mu\hat{a}_x + (1-\mu)\hat{a}_y\}/(1-\sigma)$$

where $\mu \equiv p_x X/(p_x X + p_y Y)$, and ^ denotes proportional change, so $\hat{p}_x \equiv dp_x/p_x$. We assume that peer effects are (in the neighborhood of the equilibrium) pure 'switching effects' so have no impact on total expenditure on goods x and y together. This requires that they have no effect on the price index, i.e. that $\mu\hat{a}_x + (1-\mu)\hat{a}_y = 0$.

Derivation of the marginal effects on utility: Total differentiation of utility, letting taxes, prices, and output levels change gives

$$dU = -Xdp_x + c_x X dt_x + (t_x - 1)(c_x + Xc_x')dX \;\; - Ydp_y + c_y Y dt_y + \{(t_y - 1)c_y - K_y'\}dY.$$

In this expression ʻ denotes a derivative, peer effects and the x sector technological externality $c_x[X]$ are present, and output levels are evaluated at equilibrium values, $x = X, y = Y$. Peer effects influence the magnitudes of changes in X and Y but we maintain the assumption that they are pure switching effects, not changing P or U directly. Transfer payments can be cancelled out of this expression since, differentiating equations (3) (including the technological externality $c_x[X]$), $dp_x = c_x dt_x + t_x c_x' dX$ and $dp_y = c_y dt_y$.

Utility change can therefore be expressed as $dU = (c_x t_x - c_x - X c_x')dX + \left(c_y t_y - c_y - K_y'\right)dY$, and hence equation (11).

Parameters used in simulations:

Elasticities: $\sigma = 4$, $\epsilon = 1.5$.

Costs and taxes: Base values $c_x = 1, c_y = 1, t_x = 1, t_y = 1$.

Social preferences, $a[\Pi_x]$.

Fig 2a, 2b: $a[\Pi_x], a[1 - \Pi_x]$ as illustrated, with range [0.5, 1.5] and positive gradient on $\Pi_x \in [0.333, 0.667]$.

Fig 2b: Inverse demand curve drawn with varying values of t_y.

Fig 3: $a[\Pi_x], a[1 - \Pi_x]$ equal to cumulative density function of a normal distribution with mean 0.5 and variance 0.33, so that on support $\Pi_x \in [0,1]$ the range is $a(\Pi_x) \in [0.07, 0.93]$. Dashed stationary drawn with $t_y = 1.1$.

Technological externality, $c_x[X]$.

Fig 4: $c_x[X]$ has intercept 1.31. Gradient -0.8 on interval $X \in [0.333, 0.667]$, and -0.1 elsewhere. Inverse demand curve drawn with varying values of t_y.

Taxes and subsidies, Figs 5 and 6

$c_y = 1$, $K'_y[Y]/c_y = 0.2$, $c_x = 1.1$.

$a[\Pi_x], a[1 - \Pi_x]$ with range [0.5, 1.5] and positive gradient on $\Pi_x \in [0.4, 0.6]$.

It appears that break points on fig. 5 occur at values of t_y equal to break point values of t_x on fig. 6. These values are not equal and their approximate similarity is merely a consequence of the symmetry built into the structure of the example and not a general property.