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Van der Ploeg, Frederick; Venables, Anthony J.

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Article

Green transitions: complementarities, multiple equilibria, and tipping points

Frederick van der Ploeg[*] and Anthony J. Venables[**]

[*]Department of Economics, University of Oxford, UK, and University of Amsterdam, The Netherlands, e-mail: rick.vanderploeg@economics.ox.ac.uk
[**]Department of Economics, University of Oxford, UK, and Monash University, Melbourne, Australia, e-mail: tony.venables@economics.ox.ac.uk

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Abstract

With strategic complementarities stemming from peer effects in demand or technological spillovers, 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 policies are needed to shift the economy from a high-emissions to a low-emissions path. Once the radical shift has taken place these policies can be withdrawn. More generally, such policies can set in motion social, technological, and political tipping points. The paper develops an analytical framework within which policies to achieve these tipping points are studied, looking at the extended role for tax and subsidy policies, at dynamics of change, and at policy under uncertainty. Our proposals offer a complementary perspective to scholars that have emphasized insights from the literature on early warning signals to advocate sensitive intervention points to obtain 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

I. Introduction

The traditional policy advice for mitigating global warming is to internalize global warming damages by imposing a global carbon tax (or competitive market for emissions permits) equal to the social cost of carbon (SCC), i.e. the expected present discounted value of all global warming damages resulting from emitting one tonne of carbon today (e.g. Nordhaus, 2008).[1] This advice has, except for a few countries and the EU, been largely ignored, and where carbon prices are in place their coverage is fragmented and incomplete. This policy 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, green equilibrium. Aligning marginal costs and benefits,

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[1] The alternative is to have a cap on temperature or cumulative emissions (cf. the Paris agreement). The efficient carbon price to enforce such a cap is determined by the marginal cost of decarbonization.

such as setting the carbon price to the SCC, can at most achieve a local maximum around the current high-emissions equilibrium. The point is that households and firms need, collectively, to *switch* from high- to low-emissions behaviour and technology.

A more radical design of climate policies must consider these feedback effects, in addition to global warming externalities. Such feedback effects or complementarities may give rise to several equilibrium outcomes: a stable bad (dirty) equilibrium, a stable good (green) equilibrium, and an intermediate unstable equilibrium. If the policy change is not radical enough, the economy remains stuck in a (slightly improved) bad equilibrium, but if it is radical enough and jumps past the unstable equilibrium, the good equilibrium is reached.

Positive feedback effects and complementarities occur if there are positive externalities between agents. They can arise for multiple reasons, including peer effects among households (social preferences), network effects, and positive externalities between firms generating external economies of scale. Many of these features, and their implications, have long been recognized in different areas of economics, particularly industrial organization (e.g. Vives, 2005), and more recently in the analysis of redirecting the economy from carbon-intensive to green directions of technical change (e.g. Bovenberg and Smulders, 1995, 1996; Acemoglu *et al.*, 2012; Aghion *et al.*, 2014; Smulders and Zhou, 2024).[2] We do not offer a new theoretical analysis, but apply these ideas to make a case for 'big-push' green transition policies.

We put forward a simple yet rigorous family of micro-founded models to make clear the key externalities and complementarities that may be present, draw out their implications for the multiplicity of equilibria, and examine some of the policy issues that arise in the transition from a dirty to a clean equilibrium. The basic model can be exposited on supply and demand diagrams, and we push the analysis further looking at tax and subsidy policies, at dynamics, and at policy under uncertainty.

Section II sets up our benchmark model and discusses the key externalities, those that create complementarities, as well as those that inflict climate damage. It demonstrates how these may give rise to multiple equilibria, looking at both peer effects and technological spillovers, and outlines the issues that arise in moving from a high-emissions equilibrium to a low-emissions equilibrium. Section III analyses tax and subsidy policies, looking at the relationship between Pigovian policies (securing local efficiency around a particular equilibrium) and the tax/subsidy rates that are needed for a 'big push'. While complementarities reduce the tax/subsidy rates required to achieve a given level of emissions in the former case (around a particular equilibrium), they increase the rates required for the transformational shift between equilibria.

Section IV analyses dynamic issues in a context where investment decisions drive changes in the stocks of clean and dirty assets. The simplest case—with myopic behaviour—may have multiple steady states, and the possibility that transition to the clean equilibrium starts, then stalls. Adding forward-looking behaviour creates the possibility of multiple rational expectations paths, along which self-fulfilling expectations guide investment. Some of these lead to successful transition, others do not. A key question remains how to shape expectations and thus change the chance of following a path to the green transition.

Section V allows for uncertainty about the likelihood that a tax or subsidy policy secures the shift between equilibria. The cost of securing transition with a targeted high probability increases sharply the greater the uncertainty. Policy designed to maximize expected welfare requires higher tax/subsidy rates the greater is uncertainty, up to some point beyond which further uncertainty causes policy to drop close to zero.

Together, these sections offer insights about the policies needed to secure transformative change in a series of economic environments. Section VI relates this to the existing literature, and to a broader view of transformative change paying attention to social norms, expectations and lock-in, networks, sensitive intervention points, and political economy. Section VII concludes.

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[2] Langer and Lemoine (2022) analyse the design of dynamic subsidies to spur adaptation of residential solar panels, but do not focus on multiple equilibria or on transition policies.

II. Complementarities and transformational change

The central idea is easily seen through a simple example. Suppose there are two individuals and two possible actions, X and Y, that each could take. These actions are complementary in the sense that the value to each of performing X is greater if the other also performs X, and similarly for action Y. Then, depending on the payoffs associated with actions X and Y, there may be an equilibrium in which both choose X, and another one in which both choose Y. Let both individuals be better off with the pair of choices {X, X} than with {Y, Y}. However, if they have chosen {Y, Y}, there is no incentive for either of them to change their action, as each prefers {Y, Y} to either {X, Y} or {Y, X}. Coordinated action would allow them to agree to move to (X, X), but coordination failure leaves them stuck in the worse equilibrium {Y, Y}. In the climate context there are many agents, not just two, so coordination problems are acute, and the policy challenge is to find ways of inducing the change in behaviour that induces a switch to the better equilibrium. Policy needs to push behaviour beyond the tipping point at which a virtuous circle is triggered moving the system towards the better equilibrium. It is important to note that policies that achieve this 'transformational' change may be temporary, since once society has shifted to the better equilibrium individuals do not have an incentive to move back.[3]

If an individual buys more of something, its price goes up, making the product *less* desirable for others, not more. So, when are important complementarities likely to occur? The first is when there are positive reciprocal externalities between the actions of different firms or individuals. These include knowledge spillovers and peer effects, as is developed further in this paper. The second is where interactions go through markets, but these markets are imperfect such that the individual undertaking the action does not receive all the benefit.[4] Variety and network effects fall in this category. If an individual joins a network, or a firm introduces a new variety of good, this expands the choice set for others, a benefit not fully captured by the supplier.

We put forward a benchmark model with three distinct externalities relevant for the green transition. The first are *social externalities*. They stem from social preferences, where preferences of any individual depend on the behaviour 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 case is similar to that of network externalities, where joining a network is more attractive the more members it has. The second are *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. For example, a positive externality arises if there are learning effects in the production of green goods and some knowledge spills over to benefit other firms. Finally, there is the *global warming externality* from the adverse effects of carbon emissions.[5]

We incorporate these externalities in a model that contains 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.

For household behaviour we focus on one activity which can be undertaken in different ways. For example, motoring can be undertaken in a green EV (good X) or a brown ICE vehicle (good Y). The amount spent on these goods depends on the price index P for the activity ('motoring') as a whole, with price elasticity of demand ϵ.[6] 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 price elasticity of demand) depends on whether they are close substitutes and is measured by σ, the elasticity of substitution. We make the usual assumptions that $\sigma > 1$ and $\sigma > \epsilon$, so substitution between green and brown vehicles is easier than between vehicles and other commodities. The standard constant elasticity of substitution (CES) formulation for this

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[3] Transformational change can be defined as occurring when an input to a system (e.g. a policy) causes a change which is not reversed if the input is removed.

[4] Sometimes referred to as pecuniary rather than technological externalities.

[5] Utility loss could occur directly or via a negative effect on productivity, as in integrated assessment models of the economy and climate (e.g. Nordhaus, 2008).

[6] Other income is spent on other goods (the 'outside good') which we assume to have fixed prices and to be non-polluting. So, there are no income effects in demand for green or brown goods.

gives households' demands for each good, x, y, as

$$x = a_X p_X^{-\sigma} P^{\sigma-\epsilon} \text{ and } y = a_Y p_Y^{-\sigma} P^{\sigma-\epsilon}. \tag{1}$$

In this expression P is the price index for the activity ('motoring') which takes the form

$$P = \left(a_X p_X^{1-\sigma} + a_Y p_Y^{1-\sigma}\right)^{1/(1-\sigma)}. \tag{2}$$

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.[7] Appendix 1 details the derivation of this.

On the supply side, firms face constant returns to scale, operate under perfect competition, and set prices to unit cost, c_X and c_Y, for goods X and Y, respectively. Each good faces an *ad valorem* tax factor, t_X and t_Y , so that the prices faced by consumers are

$$p_X = t_X c_X \text{ and } p_Y = t_Y c_Y. \tag{3}$$

For example, a tax of 20 per cent 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 (1–3) determine prices, the price index, and quantities of these goods produced and consumed. These, together with consumption of the outside good and welfare loss arising from climate damage, determine household utility. This specification implies that households purchase both goods X and Y, albeit in different quantities. This is the simplest way to set out the model, but it can be interpreted as a discrete choice model in which heterogeneous households choose either X or Y.[8]

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 household choices equal the aggregate quantities, $x = X$ and $y = Y$. We use square brackets to highlight these non-market interactions.

Social externalities stemming from peer effects are modelled with preference parameters that depend on *aggregate* output and consumption of each good, measured by the share of the population consuming each good. Thus, the preference parameter for good X is $a_X = a[\Pi_X]$, where $\Pi_X \equiv X/(X+Y)$ is the share of green goods and $a[.]$ is a weakly increasing function. Preferences for Y are symmetric, so $a_Y = a[1-\Pi_Y]$.

Technological externalities arise from economies of scale and learning effects which are generated by the total output of each good (but are external to individual firms), so take the form $c_X[X]$, and $c_Y[Y]$, both decreasing functions in the presence of scale economies.

The *global warming externality* depends on 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, with damage function $K_Y[Y]$, positive and increasing in Y.

(i) Equilibrium with social externalities

We start by ignoring technological externalities and studying equilibrium with social externalities (peer effects). At equilibrium the share of good X in total sales, Π_X, must be consistent with household demands as given in equation (1), and now including the social externalities. Hence, given prices p_X and p_Y, we can solve Π_X from

$$\Pi_X \equiv \frac{X}{X+Y} = \frac{a_X[\Pi_X](p_X)^{1-\sigma}}{a[\Pi_X](p_X)^{1-\sigma} + a[1-\Pi_X](p_Y)^{1-\sigma}}. \tag{4}$$

Multiple equilibria occur if there are several distinct solutions. To illustrate, Figure 1 shows an intuitive plot depicting supply and demand.[9] Hold the price of good Y at its equilibrium value, $p_Y = t_Y c_Y$, vary Π_Y, and ask what values of price p_X solve equation (4). These values of p_X trace

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[7] 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. Total expenditure on motoring is $P^{1-\epsilon}$.

[8] This is discussed further in van der Ploeg and Venables (2022).

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

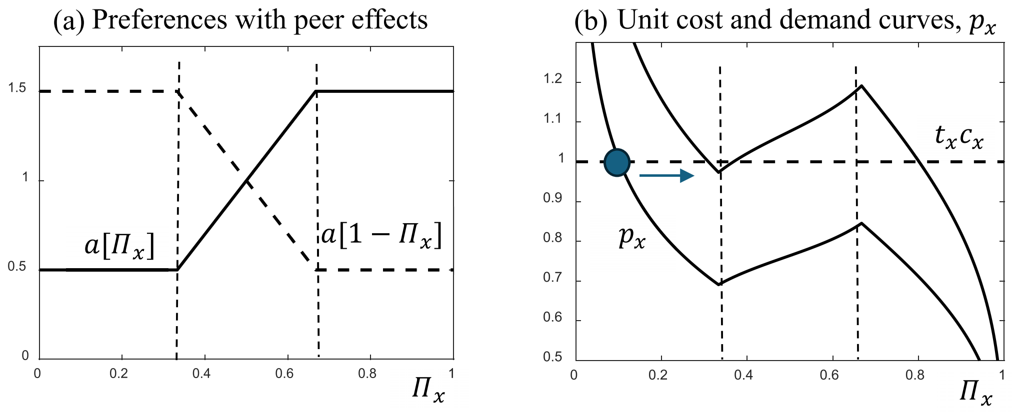

Figure 1: (a) Preferences with peer effects. (b) Unit cost and demand curves, p_x.

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

an inverse demand curve, or the willingness to pay for good X, as a function of relative supply of the good measured by Π_X. The supply curve for good X is horizontal at $t_X c_X$, and an equilibrium occurs at intersections of demand and supply.

Figure 1a specifies a functional form for the social externalities, with Π_X on the horizontal axis and preferences $a[\Pi_X]$ and $a[1-\Pi_X]$ on the vertical. Preferences shift sharply towards good X in the steep central segment ($\Pi_X \in [1/3,\ 2/3]$) as households observe the share of this good increasing and peer effects kick in. Outside this range, there are no peer effects (i.e. a is constant).[10] Figure 1b gives supply and demand curves, with relative quantities, Π_X, on the horizontal axis. The supply curve is the horizontal line $t_x c_x$, and the demand curve, the willingness to pay, p_x, is traced out by varying Π_X in equation (4).

At levels of Π_X where $a[\Pi_X]$ and $a[1-\Pi_X]$ are constant, p_X is the usual downward-sloping inverse demand curve indicating that demand for X decreases with price. But in the region where peer effects operate, this demand curve slopes upwards. The peer effects associated with higher levels of consumption of X, i.e. higher Π_X, shift preferences towards X and, if the effect is sufficiently strong (i.e. $a[\Pi_X]$ sufficiently steep), then p_X, willingness to pay, increases.

Equilibrium is where the willingness to pay is such that $p_X = t_X c_X$. This gives a single equilibrium, as marked, at a low level of X output and hence a high level of Y and pollution. If the economy starts at this point, what policy can lower aggregate emissions and global warming damages? Taxing the polluting good (i.e. increasing t_Y) switches expenditure towards good X, so raising the p_X curve. Equilibrium X output increases steadily with this shift, as illustrated by the arrow. At some point two other equilibria become possible, as shown by the higher demand curve on the figure. This has three intersections with supply, the middle one is unstable and the two outer ones (where demand intersects supply from above) are stable. Since the low X equilibrium remains stable, it remains the likely outcome until the point at which the demand curve shifts somewhat higher. The low X equilibrium disappears, and the system jumps to the (single and stable) high X equilibrium. Thus, an emissions tax has marginal effects except at a critical value at which it induces a discontinuous change in the level of consumption and production of each good. Once the emissions tax has moved the system past this tipping point, it can be reduced somewhat, since the high X (green) equilibrium remains stable.

(ii) External economies of scale in production

Similar analysis applies if the X sector exhibits increasing returns, driven by external economies of scale or learning-by-doing effects that are not fully internalized in any single firm's

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[10] The piecewise linear form for the function $a_X[\ \Pi_X]$ helps with interpretation of later figures, making clear intervals in which peer (and later technological spill-over) effects are, and are not, operating.

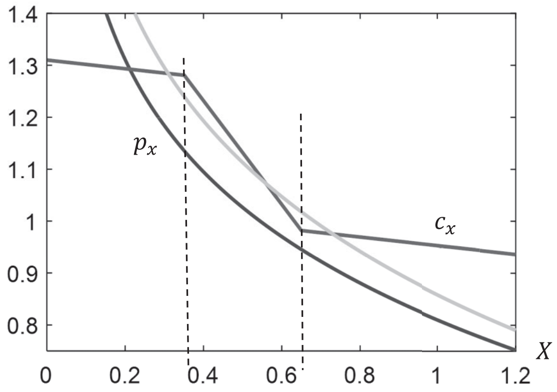

Figure 2: Unit costs with increasing returns to scale.

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

decisions. Underlying micro-foundations may be knowledge spillovers between firms or input–output links in which suppliers pass some net benefits to users. Formally, unit cost decreases with total production of X, so, $c'_X[X] \leq 0$. We assume that this cost effect is present only in the X sector, and depends only on the aggregate level of output X. There are no such externalities in Y as the technology is mature and any such spill-over advantages have already been reaped.

The story is illustrated in Figure 2. The horizontal axis gives output of the green sector X. The supply curve, i.e. unit cost $c_X[X]$, is in this example piecewise linear, decreasing everywhere, but with a steep central range where learning by doing and technical spillovers are strong. The curved lines are inverse demand curves (now ignoring peer effects), giving the price at which households purchase quantity X. The lower demand curve supports a single equilibrium while the upper one supports three.

If the economy is at the unique equilibrium indicated by the intersection of the lower inverse demand curve and the unit cost schedule, then a subsidy on X or a tax on Y shifts the demand curve upwards. This increases production of X because of the direct subsidy effect together with an amplification caused by the downwards slope of the cost curve; we discuss this amplification effect further in section III. Shifting further, there are two additional equilibria (as illustrated, one unstable, one stable), and still further there is just one green equilibrium with high X output and low Y output. As with peer effects, a tipping point is passed. Such a climate policy is transformative in the sense that it does not just induce a marginal drop in emissions, but also manages to shift the equilibrium from the bad to the good one, ensuring a substantial drop in emissions.

Finally, technical innovation may be in part cost reduction, and in part the development of new products—e.g. the range of EVs is increasing. While this is driven by technology, its effect is analogous to an increase in a_X, as in section II(i), as more product varieties affect preferences and induce consumers to switch expenditure to X-goods.

III. Optimal pollution tax and green subsidy policies

How should taxes and subsidies be optimally set in the presence of climate, social, and technological externalities, i.e. with good Y polluting, good X clean, and operating with peer effects and external economies of scale?

Standard marginal analysis looks at the effects of policy changes around a particular (stable) equilibrium. The polluting Y sector should then be subject to Pigouvian tax, at a rate equal to the marginal social damage inflicted by the climate externality. Increasing returns and diminishing marginal cost mean that the X sector should be subsidized such that the consumer price is brought

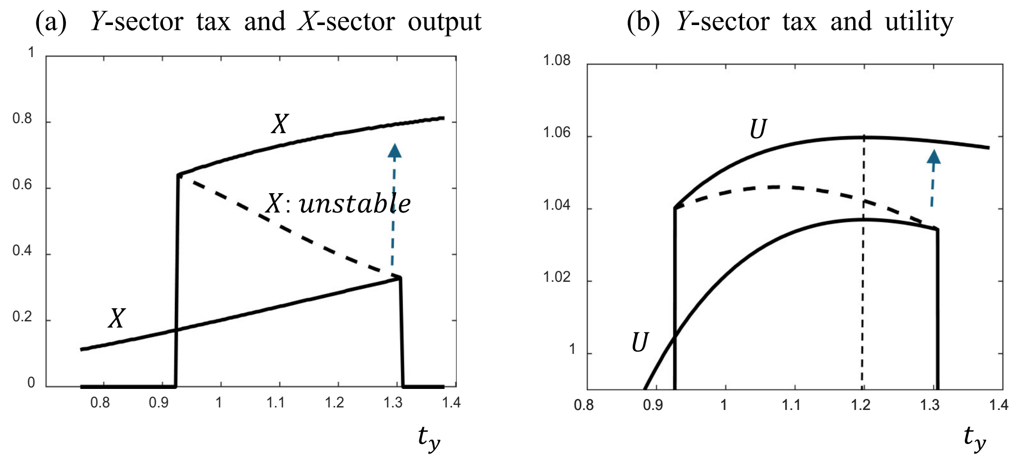

Figure 3: (a) *Y*-sector tax and *X*-sector output. (b) *Y*-sector tax and utility.

Note: Utility maximization requires a pollution tax high enough to flip from the high emission to the clean equilibrium. In this example this exceeds the Pigouvian rate of 1.2.

down to the marginal cost of production. If the peer effects are pure expenditure switching (i.e. without any direct effect on utility) there is no case for further tax/subsidy policy on good X.

Peer effects do however affect the quantitative impact of tax and subsidy policies. Tax and subsidy instruments initiate quantity changes that are amplified as peer effects cut in causing 'copy-cat' behaviour. Hence, if the objective is to hit a quantity target (e.g. a target for production of good Y and thus for emissions), peer effects curb the tax rate required (cf. Mattauch *et al.*, 2018; Konc *et al.*, 2021). If the objective is welfare maximization (rather than a particular quantity target), the tax on Y remains the Pigouvian social marginal cost. 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.[11]

Our central message is that these locally optimal tax rates are not optimal as they ignore the potential to tip from a dirty to a green equilibrium. We demonstrate this with an example using demand complementarities as in Figure 1 (see Appendix 2) and sector Y pollution damages implying a Pigouvian tax rate of 20 per cent, i.e. $t_Y = 1.2$. Figure 3a traces out equilibrium values of X as a function of the tax rate t_Y, given on the horizontal axis, (*ad valorem* rate $t_Y - 1$) 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 per cent ($t_Y = 1.4$). The lines on Figure 3a give equilibrium levels of X-output. In the interval $t_Y = [0.2, 1.31]$, three equilibria exist, the middle one of which (the dashed line) is unstable.

Figure 3b gives the corresponding level of utility, U, (net of global warming damages), again as a function of t_Y. Utility is locally maximized at the Pigouvian tax rate of 20 per cent, i.e. $t_y = 1.2$, as illustrated by the local utility maxima for each of the stable equilibria. However, utility is higher in the green high X-output equilibrium. Starting with a low value of t_y in the high-pollution equilibrium, Figure 3b illustrates how increasing the pollution tax t_y has modest effects on utility until it reaches the critical level (t_y =1.31) at which point switching further expenditure to the green good X triggers complementarities large enough to cause the equilibrium to flip, thus raising utility from the lower to the upper utility curve as illustrated by the dashed arrow. Once the flip has occurred—and all behaviour has adjusted to the new equilibrium—it is efficient to reduce the pollution tax back to the Pigouvian level (local utility maximum) as illustrated in Figure 3. The transformative policy is thus to have a temporary big push, i.e. a temporary increase in the pollution tax over and above the Pigouvian pollution tax.

Figures 4a and 4b take the same example but vary the tax/subsidy rate on the clean good, t_x, while holding the tax on the polluting good at its Pigouvian level, $t_y = 1.2$. Local utility maxima

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[11] These properties are worked out in full in van der Ploeg and Venables (2022).

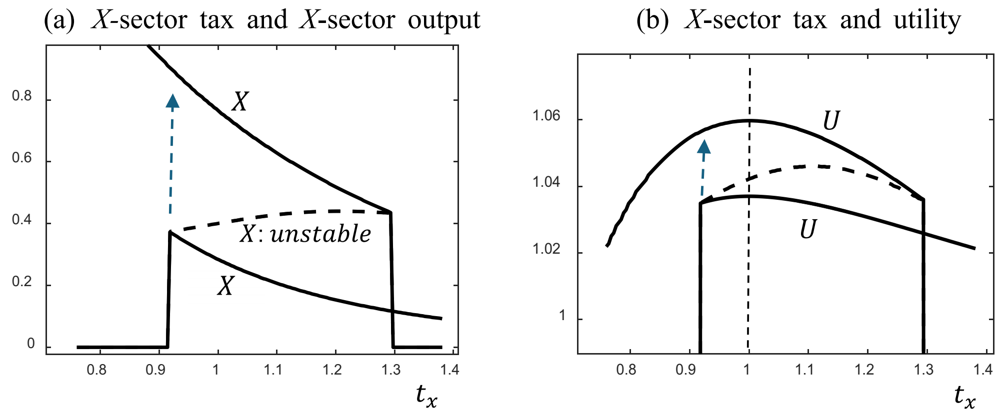

Figure 4: (a) *X*-sector tax and *X*-sector output. (b) *X*-sector tax and utility.

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

are achieved at $t_x = 1$ (vertical dashed line on Figure 4b), so that there is no role for subsidizing the clean good if a Pigouvian tax on the polluting good is in place. But at this point there are multiple equilibria, and the economy may be in the high-emissions equilibrium. To move out of this equilibrium requires that the clean good is subsidized (on top of the Pigouvian tax on good y) by setting $t_x \leq 0.91$ (vertical dashed arrow). Once the economy has fully adjusted to the clean equilibrium the subsidy can be removed to achieve the global maximum (corresponding to the maximum of the upper line).

Summing up, complementarities from peer effects in demand and from technological spillovers amplify the effects of carbon taxes and green subsidies on emissions, which suggests that lower carbon taxes are needed to achieve a given cut in emissions. However, moving a tax or subsidy towards its optimal value is more valuable, precisely because it brings about larger effects. Furthermore, if complementarities are sufficiently strong, there are two stable equilibria with, respectively, low and high emissions, and a third equilibrium in the middle which is unstable. A key role for policy is to bring about the switch between equilibria, and this requires a big-push policy (e.g. a temporarily higher pollution tax or green subsidy). The outstanding questions are how large must complementarities be to give the multiple equilibria configurations illustrated in this section, and how policy-makers can know where these points are. We now turn to placing these ideas in more complex economic environments (dynamics in section IV, uncertainty in section V), and a wider social and political context (section VI).

IV. Dynamics: stalled versus successful green transitions

Here we give a dynamic analysis that captures the possibility of a *stalled transition* between multiple long-run equilibria. The reformulation involves reinterpreting all three externalities—global warming, peer effects, and technological—as functions of the accumulated stock of past output and consumption, rather than of the current flow.

Households make discrete choices and there are peer effects in demand for goods X and Y. Pollution externalities are present while learning by doing and externalities in production are switched off (i.e. c_X and c_Y are constants). X and Y now denote the stock of accumulated output in each product, and are driven by the differential equations

$$\dot{X} = \delta \left\{ a\left[\Pi_X\right] \left(t_X c_X\right)^{1-\sigma} P^{\sigma-1} - X \right\}, \quad \dot{Y} = \delta \left\{ a\left[1-\Pi_Y\right] \left(t_Y c_Y\right)^{1-\sigma} P^{\sigma-1} - Y \right\}, \tag{5}$$

with $P = \left(a[\Pi_X](t_X c_X)^{1-\sigma} + a[1-\Pi_X](t_Y c_Y)^{1-\sigma}\right)^{1/(1-\sigma)}$ and $\Pi_x = X/(X+Y)$, as before. $\dot{X}$ and $\dot{Y}$ denote changes in these stocks per unit of time. 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

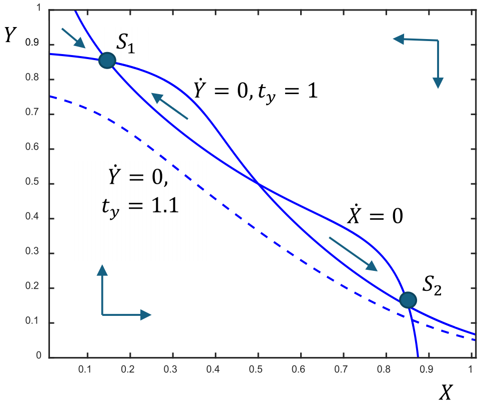

Figure 5: Stalled transition: dynamics of *X* and *Y*.

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

the population purchases a product each period, and fraction $a[\Pi_X](t_X c_X)^{1-\sigma} P^{\sigma-1}$ of these are type X, as in section II. At the same time, proportion δ of the existing stock of X goods depreciates, i.e. δX of the stock of motor vehicles is scrapped, so the change in the stock of X goods, $\dot{X}$, is purchases minus depreciation, similarly for $\dot{Y}$.

Figure 5 illustrates the dynamics of equations (5). 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 right 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 a sigmoidal (not piecewise linear) $a[.]$ (see Appendix 2).

There are three stationary points, of which two are stable, and the middle one is unstable. Stationary point S_1 has a relatively high stock of the polluting good, Y, and with continuing high output replacing depreciating stock. Conversely, stationary point S_2 has a relatively high stock and output of the green good X.

(i) Stalled transitions with myopic households

If the economy starts with a high value of Y and of emissions, can it make the green transition from the dirty stationary point S_1 to the clean one S_2? Unless the initial value of X is also very large, the answer is no. The dynamics illustrated by the arrows indicate that the system moves to the stationary point S_1.[12] Starting from a stock of Y to the left of the middle stationary point, a low initial X, the answer is no. It is possible that a transition starts (X increases) but it gets stalled as the system moves to point S_1. At this point $a[\Pi_X]$ is low, so demand for and production of the clean 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 if the polluting good Y is subject to a tax, $t_Y = 1.1$. This reduces demand and output of the polluting good Y, shifting the Y stationary downwards. There is a single stationary point, at the intersection just below S_2, which is globally stable and to which the economy converges to the clean equilibrium. This indicates that the primary task of policy is 'non-marginal' in the sense that it must prevent the economy stalling at the dirty stationary point S_1.

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[12] If the sectors are symmetric (except in emissions) the dividing line between basins of attraction is the 45° line through the origin.

(ii) Forward-looking behaviour and expectations

We have assumed that households are myopic—choices are based on current prices and peer effects. Here we suppose that households are forward looking, and take decisions based on expectations about the future value of purchasing green good X relative to dirty goods Y, these varying as stocks of each type and associated peer effects change (van der Ploeg and Venables, 2025). This gives two state variables: the relative stock of green goods, Π_X, and the expected present value of benefits derived from purchasing X relative to Y, denoted V. There are costs of switching from one type to the other and these vary in the population, this giving a slow transition path. This setting can be analysed in the 'history versus expectations' framework of Krugman (1991), in which there may be multiple rational expectations paths, along which there are self-fulfilling expectations.[13]

Thus, for a given initial share Π_X, there are one or more values of V, the relative valuation, which if held by the population generates a path of Π_X and V along which expectations are self-fulfilling. If the initial stock of green products Π_X is very low, the only path is downwards, i.e. towards the dirty equilibrium. Conversely, if initial Π_X is sufficiently high, the only rational expectations path is full transition towards the green equilibrium. For a range of initial intermediate values of Π_X, there are multiple rational expectations paths, at least one downwards towards the dirty equilibrium, and one upwards to the green equilibrium. The edge of this range is analogous to the switch points seen in sections II and III, and is associated with a discontinuous change in the set of equilibrium outcomes.

The analysis highlights several points. The first is the need to reach an initial share of green stocks Π_X to trigger the process of transition; one way to achieve this is by generous initial subsidies to kickstart the process among those households with the lowest switching costs. The second and more difficult point is how to set expectations to get on an expectational equilibrium path. The analysis shows the existence of such a path, but it depends on beliefs of households about the future path of Π_X. It seems clear that policy is required to set expectations about the path indeed leading to the green equilibrium, which must be credible. If this is the case, the policy does not need to be mandated quantity measures. Given credible information about a green transition path, decentralized forward-looking household behaviour could—in theory—achieve it.

V. Uncertainty about tipping points

So far, the point at which the system switches on a path towards a green equilibrium is known, or expected, with certainty, and policy instruments can be fine-tuned to reach that point. In practice this point is highly uncertain, so the question becomes: how should policy be set in the presence of this uncertainty?

To address the question, we draw two elements from the preceding analysis. First, if policy instruments differ from the Pigouvian values, optimal for a given equilibrium, there is a cost to this distortion—an 'excess burden'. Second, switching from the dirty to the green equilibrium brings a discontinuous gain in utility; see Figures 3 and 4. If the policy that achieves this switch is known only up to some probability distribution, policy faces a trade-off between the benefit of increasing the probability of reaching the tipping point and setting in motion the transition to the green equilibrium, and the short-run cost of distorting the economy away from the Pigouvian optimum.

In our model with peer effects but without technological externalities, the Pigouvian value of our policy instruments are a pollution tax t_Y set equal to the social cost of carbon, and zero subsidy (or tax) to X production, which we now denote $s_p = 1$. We now consider introducing an *ad valorem* subsidy s to consumption of the green good X and let the short-run cost of distorting policy away from its Pigouvian optimum, s_p, be $C(s) = c(s - s_p)^2$. In this 'excess burden' the constant c depends on the price elasticities of demand and supply. The benefit of this green subsidy is the probability of making the switch to the green equilibrium and achieving a positive utility

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[13] See Fukao and Benabou (1993) for a comment on Krugman (1991), and Smulders and Zhou (2024) for an application to directed technical change and the green transition. For these issues in a macroeconomic growth with a convex–concave production function context, see Skiba (1978).

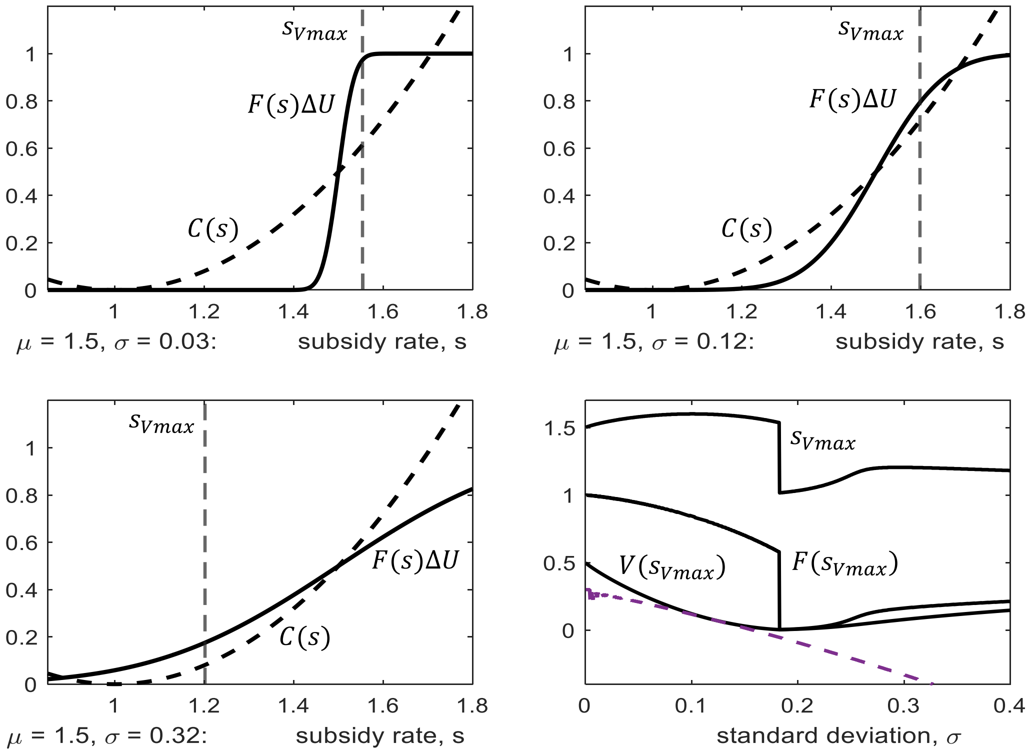

Figure 6: Policy under uncertainty.

increment ΔU, where the probability of the switch increases in the subsidy, s. The expected payoff to the subsidy s is thus

$$V(s) = F(s)\,\Delta U - c\big(s - s_p\big)^2, \tag{6}$$

where $F(s)$ is a cumulative distribution function (cdf), giving the probability of achieving the switch with subsidy rate s.[14] Policy-makers thus have a one-shot chance to achieve a long-lasting gain. The short-run cost $c(s - s_p)^2$ is the distortion cost during some fixed and finite period in which policy is active. The switch may or may not occur at the end of this period, and $F(s)\Delta U$ is the expected present value of a long-lasting flow thereafter.

The terms $F(s)\Delta U$and $C(s)$ are illustrated as functions of subsidy rate s on the first three panels of Figure 6, each panel constructed with a different level of uncertainty. The vertical, dashed line is the quadratic cost function, minimized at $s = s_p = 1$. The solid line is the expected benefit, $F(s)\Delta U$ (scaled with ΔU normalized at unity). For any unimodal distribution this has the sigmoid shape illustrated, and the panels of Figure 6 are drawn with $F(s)(\mu, \sigma)$. The vertical distance between these lines is the expected net benefit (or cost) of the green policy, $V(s)$. The experiment is to vary the standard deviation, σ, of the distribution, holding the mean μ constant—a mean-preserving increase in risk. In the figure $s_p = 1$, $\mu = 1.5$, and panels of the figure are for different values of σ.

(i) Uncertainty and policy to maximize expected utility

Without uncertainty, the probability mass is concentrated at μ, and setting the subsidy at this level delivers the switch, as in the deterministic case. The first panel is for low σ, and the subsidy rate that maximizes the expected payoff $V(s)$ is given by the vertical line at $s_{Vmax} = 1.55$, a rate somewhat above $\mu = 1.5$. Thus, an increase in uncertainty around a given mean raises the optimal

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[14] We use the standard terminology of uncertainty, although a better word would be risk.

subsidy rate for green goods. The reason is that at μ the benefit curve is steeper than the cost curve, so it is worthwhile increasing the distortion to purchase a higher probability of switching from dirty to green.

The second panel (top right) has more uncertainty, this flattening the cdf and further increasing the optimal policy to $s_{Vmax} = 1.6$. The third panel has still larger σ, this flattening the cdf further and changing the direction of the intersection between the benefit and cost curves. The optimal policy is now discretely different, remaining positive ($s_{Vmax} > s_p$), but at a much lower value, $s_{Vmax} = 1.2$.

The reason for this behaviour is that $V(s)$ is not generally concave in s, so at intermediate values of σ there are two local maxima. Underpinning this is that the second derivative of $F(s)$ has sign changes for any distribution with an interior mode. Thus, a distribution with a single interior mode has $\partial^2 F/\partial s^2$ switch from positive to negative as s increases, this changing $V(s)$ from convex to concave if $\Delta U \partial^2 F/\partial s^2 > 2c$.

The way in which a policy that maximizes expected utility varies with uncertainty is summarized in the bottom right panel of Figure 6, which has σ on the horizontal axis. The top line is the optimal value of policy, s_{Vmax}, and the bottom solid line the associated maximized value of expected utility $V(s_{Vmax})$. The middle line gives the probability that the optimal policy achieves switching. The discontinuity in policy is apparent. Low levels of uncertainty about a successful green transition are associated with a higher subsidy rate, while beyond the discontinuity expected utility is maximized by a low subsidy and low (although positive) probability of achieving the switch. The discontinuity is not completely general but arises due to one (or more) points of inflexion in a cdf.[15] It occurs even though the mean is held constant as σ varies, and the decision-taker is risk neutral.

(ii) Insights

Several messages emerge if the location of the unstable equilibrium is uncertain. First, to achieve a high probability of a switch to the green equilibrium a green subsidy higher than its Pigouvian level is warranted.

Second, while a small amount of uncertainty raises the welfare-maximizing green subsidy, a lot of uncertainty may substantially reduce it. It is worth going all in if uncertainty is sufficiently low. Conversely, one should do (almost) nothing at high levels of uncertainty.

Third, it raises the question of whether expected utility maximization is the right way to think about this. Achieving the switch may be the fundamental objective of policy, in which case it is perhaps more interesting to ask: how does the value or cost of achieving the switch with at least a given target probability vary with the degree of uncertainty? For the example of Figure 6, the answer is given by the dashed line in the bottom right panel of the figure. This gives the value/cost of achieving the switch with an 80 per cent probability. With low uncertainty the expected utility-maximizing policy gives higher than 80 per cent probability, but with high uncertainty the 80 per cent target gives lower benefit or a net cost; the curve is concave, indicating costs increasing at increasing rate with high uncertainty.

Finally, this points to the importance of measures to decrease uncertainty. One is the use of quantitative rather than price measures. In all cases we have studied, the tipping points are driven by quantities—quantities of products of each type consumed or produced—so uncertainty is reduced by acting directly on these quantities, rather than intermediating the effect through prices and market responses to prices.

VI. Transformative climate policies: a broader view

We have outlined the case for using policy as a tool for transformative change, given the presence of the many interlocking complementarities that arise in moving to net zero. These complementarities can impede change or—if recognized and acted on by policy—accelerate it. Our modelling

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[15] Mean-preserving spreads of a uniform distribution rotate $F(s)$ clockwise around the point (1.5, 0.5) and, by inspection of the figures, this would reduce s_{Vmax} monotonically to zero.

is highly stylized, designed to focus on key mechanisms and results. We now link some of our themes to wider literatures on complementarities, on transformational change, and on climate.

(i) Peer effects

Peer effects are a central part of a wider literature on social norms.[16] The analysis of social norms uses evolutionary game theory to analyse punctuated equilibria and rapid change in social norms (e.g. Weibull, 1995; Young, 2015), and help to understand rapid switches in environmental attitudes.[17] Such norms often evolve without top-down intervention but through a process of trial and error, experimentation, and adaptation, and depend on social, cultural, and historical contexts. Scientists also care about how and where they deploy their skills; this can cut the cost of green innovation if scientists have green values (Besley and Persson, 2021). The combined effect of directed technical change and cultural dynamics among consumers further strengthens the influence of science and speeds up the green transition. Under certain social and biophysical conditions (e.g. resource scarcity, resource variability, and spatial connectivity), self-organized cooperation can evolve in common-pool resources (e.g. fisheries or forests) where community members follow a social norm of socially optimal extraction enforced by social sanctioning (Schlüter *et al*., 2016). If an intervention convinces enough people to abandon the tradition, this can induce others to follow. Activating such positive social spillovers amplifies the effects of an intervention (Efferson *et al*., 2020). A similar mechanism is at play between countries. The example set by Scandinavian countries to make progress on the green transition might encourage other countries to the same.

(ii) Technological spillovers

The massive literature on non-appropriability, directed technical change, and learning curves gives insights into technological spillovers. For example, market size and initial conditions determine whether the direction of technical change is clean or dirty, and whether there is path dependency (Acemoglu *et al*., 2012). With directed technical change, multiple equilibria arise if innovators are forward-looking (Smulders and Zhou, 2024).[18] Whether an equilibrium with green innovation or one with carbon-based innovation emerges depends on initial conditions as well as the degree of substitutability between carbon-based and green goods. Both a green transition and a stalled transition to a dirty outcome can thus be self-fulfilling prophecies.

New green technologies follow steep learning curves. Wright's law indicates that every doubling of total use of windmills, solar panels, or batteries cuts unit costs by 20 per cent to 40 per cent.[19] These benefits are passed to consumers (via lower prices), and to other firms as technical knowledge diffuses (e.g. Goulder and Mathai, 2000; Zwaan *et al*., 2002; Popp, 2004; Fisher and Newel, 2008; Hübler *et al*., 2012).[20] This externality creates the positive feedback effects that can also lead to multiple equilibria. Dugoua and Dumas (2024) use data on patents, supply-chain relationships, and national policies to highlight the role of cross-sectoral spillovers and technological complementarities. These give a rationale for coordination between firms and global industrial policies to make the transition to EVs.

(iii) Politics

A further source of tipping points, not addressed in our analysis, can arise via politics. Besley and Persson (2019) distinguish materialist and environmentalist citizens, and study two political

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[16] Barnes *et al*. (2022) and Talevi (2022) document positive peer effects in the diffusion of solar panels in Las Vegas and the UK, respectively. Wolske *et al*. (2020) point out the role of peer effects in shaping energy-related behaviours. Gillingham and Bollinger (2021) investigate a large-scale behavioural intervention to leverage social learning and peer effects to boost adaptation of solar PV, finding that coordinated group activity increases installations.

[17] Examples of rapid shifts in social norms are norms for duelling, foot binding in China, and contraceptive use (e.g. Young 2015) and green transitions (e.g. Nyborg *et al*., 2006, 2016).

[18] See Dechezleprêtre *et al*. (2014), Aghion *et al*. (2016), Bretschger and Schaefer (2017), Meijden and Smulders (2017), and Jin *et al*. (2024). Prosocial attitudes of households foster clean innovation, especially if competition is strong (Aghion *et al*. 2023).

[19] This is known as Swanson's law when applied to solar panels. Way *et al*. (2021) use probabilistic forecasts of the costs of solar, wind, and batteries to obtain experience curves. Tiang and Popp (2014) suggest that each new 60 GW wind power project in China cuts unit costs by 0.25 per cent.

[20] See Zeppini and van den Bergh (2020) for learning curves, path dependence, and climate policies.

parties seeking office by attempting to get the votes of those citizens who are willing to switch allegiance. Political parties thus set environmental policies to cultivate the interests of the average swing voter. Using an evolutionary process, these policies and expectations of policies can drive society towards either environmentalism or materialism. The failure of the political system to set policies to achieve a growing number of environmentalists results from an inability to commit to future policy choices.[21] If it is easier to commit to future institutions than to future policies, far-sighted institutions that are independent of short-term political vagaries such as an independent central bank for emission permits are called for (e.g. Helm *et al*., 2003). Besley and Persson (2023) show that lobbying makes it hard to get out of such climate traps where society gets stuck in dirty lifestyles and technologies. Attention should be focused on incentive-compatible policies since governments cannot tie the hands of their successor.

Political tipping points can also happen at the local level (e.g. municipalities learning from each other in switching dwellings from coal or gas to heat pumps) or international level. An example of the latter occurs when a group of countries pushes ahead with a free-trade zone with ambitious green policies, while countries outside the 'climate club' that price carbon insufficiently must pay a tariff to trade with the group. Nordhaus (2015) shows that this can lead to a growing coalition of countries with ambitious climate policies. Similarly, Heal and Kunreuther (2011) show that international climate negotiations can be modelled as a non-cooperative game with multiple equilibria and a relatively small subset of countries who by changing from the inefficient to the efficient equilibrium can induce all others to do the same. Another example is the border tax proposed by the European Union. Countries outside may then choose to levy their own carbon tax rather than pay a border tax to the European Union, which can lead to a domino effect.

(iv) The devil is in the detail

All these interactions take place within complex economic, social, and political networks, and policy design needs to be based on understanding the relationships between these parts. For example, key players play an important role in the complicated networks of trade and communications between firms and households (Ballester *et al*., 2006).[22] Exploiting the specific structure of networks is important for effective targeting of climate policies.[23] Networks may lead to unintended effects of sectoral policies. For example, a sector-specific carbon tax can increase aggregate emissions, as resources get reallocated to more polluting sectors, but carbon tax reforms 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 (King *et al*., 2019).

Interventions that kick or shift the system can amplify the initial change by feedback effects that deliver an outsized, irreversible impact (cf. Farmer *et al*., 2019; Sharpe and Lenton, 2021). Lenton (2020) highlights the causal interactions that can occur between tipping events across different types and scales of system—including tipping cascades and the use of early warning signals of tipping points, and how they could inform deliberate tipping of positive change. Sustainability science also discusses leverage points, sensitive interventions, social tipping, transformational tipping, and positive tipping, and processes of social construction and time dynamics to support emergence of social-ecological tipping points (e.g. Tabara *et al*., 2022; Chapin III *et al*., 2022). Climate science has also tried to identify social tipping points (e.g. Otto *et al*., 2020; Ginkel *et al*., 2020; Moore *et al*., 2022), but it is fair to say that to date no or little empirical evidence exists for strategic complementarities that are strong enough for small interventions to generate outsized impacts. This is a matter for further research.

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[21] Harstad (2020) shows that with time-inconsistent policy-makers, optimal green subsidies are larger for technologies that are strategic complements to future investments, further upstream in the supply chain, and with longer maturity. Current politicians thus motivate future politicians to act sustainably.

[22] Leister *et al*. (2022) study a network where agents decide whether to adopt a new technology that yields increasing value in the actions of neighbouring agents. They show that contagion is localized within rather than across communities.

[23] For example, Lee *et al*. (2021) find 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.

VII. Conclusion

With strategic complementarities stemming from peer effects in demand or technological spillovers and network effects, propagation and amplification effects boost effectiveness of climate policies. This suggests the need for *less* ambitious climate policies. However, if these effects are strong enough, there are multiple equilibria, *more* ambitious policies are needed to shift from a dirty to a green economy. Once the shift has taken place these 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. Substantially higher carbon prices than the SCC or green subsidies may be needed to move towards the green equilibrium. Crucial is to leverage the green transition by implementing policies that lead to ubiquitous change to green preferences and technologies.

To quote a journalist after the 2021 Glasgow COP26 summit: ‘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). This radical approach to climate policies (including rebating carbon tax revenues to lower-income groups, or feebates) may overcome political resistance to pricing carbon. The regulatory regime also matters for the number of people displaying moral or climate-conscious behaviour; e.g. a carbon tax boosts voluntary efforts to cut emissions while a cap-and-trade scheme discourages such efforts (Herwig and Schmidt, 2022).

To set in motion a cascade of tipping points requires in-depth consideration of the process of societal and technological change. 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, and corresponds to the *maturation* of new green technologies. The reconfiguration or redirection of technologies in the second pillar is the one where radical policies are most needed, and barriers across social, technological, political, and institutional dimensions must be dealt with. The second pillar is crucial as it is where the various social, technological, political, and institutional tipping points must be activated.

We conclude with a warning about the political risks. 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. Second, once businesses and households have fully converted to green technologies and ways of living, they are locked in and it makes sense to lower the ambitious climate policies that have been used to tip the economy to the green equilibrium. Clearly, politicians will encounter resistance and thus it helps to announce horizon clauses in advance to avoid these issues. Third, different sectors need different prices or subsidies for them to tip, hence the tipping measures must 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 carbonize (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 learn from this in shaping new policy tipping measures.

Appendix 1: Micro-economic foundation

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 is 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. The CES sub-utility function is $u(x, y) = (a_x^{\frac{1}{\sigma}} x^{1-\frac{1}{\sigma}} + a_y^{\frac{1}{\sigma}} y^{1-\frac{1}{\sigma}})^{\sigma/(\sigma-1)}$ where $\sigma > 1$ denotes the elasticity of substitution between goods. Households choose x, y, z to maximize utility subject to their budget constraint, $z = M + T - (p_x x + p_y y)$, where M denotes exogenous income 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). Choosing x and y to maximize utility subject to the budget constraint gives $x = a_x p_x^{-\sigma} P^{\sigma-\epsilon}$ and $y = a_y p_y^{-\sigma} P^{\sigma-\epsilon}$ with $P \equiv (a_x p_x^{1-\sigma} + a_y p_y^{1-\sigma})^{1/(1-\sigma)}$ 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. Shephard's lemma gives total expenditure on x and y together as $P^{1-\epsilon}$, and gives the demand functions for each variety, equations (1).

Switching effects and the price index: Peer effects are pure expenditure switching effects if they have no direct effect on P. This requires $\mu \hat{a}_x + (1 - \mu)\hat{a}_y = 0$ where ^ denotes proportionate change and $\mu \equiv p_x X/(p_x X + p_y Y)$,

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

$$dU = -X dp_x + c_x X dt_x + (t_x - 1)\left(c_x + X c_x'\right) dX \; - Y dp_y + c_y Y dt_y + \left\{\left(t_y - 1\right) c_y - K_y'\right\} dY,$$

where $'$ denotes a derivative.

Appendix 2: Quantification and parameters used in simulations

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

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

Figures 1a and 1b: $a[\Pi_x]$, $a[1 - \Pi_x]$ as illustrated, with range [0.5, 1.5] and positive gradient on $\Pi_x \in$ [0.33,0.67].

Figure 1b: Inverse demand curve drawn with varying values of t_y.

Figure 2: $c_x[X]$ has intercept 1.31. Gradient –0.8 on interval $X \in$ [0.33,0.67], and –0.1 elsewhere. Inverse demand curve drawn with varying values of t_y.

Figures 3 and 4: Taxes and subsidies,

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

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

Figure 5: $a[\Pi_x]$, $a[1 - \Pi_x]$ 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 $t_y = 1.1$.

Figure 6: Parameters described in text.

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