Towards system dynamics of carbon taxation on the demand side

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Introduction

Pricing carbon is a widely acknowledged measure to do something about the climate crisis. Price signals alone will not save us of course. In many regions around the world renewable energies are already economically feasible options, particularly so for electricity production, yet political forces lock in the fossil fuelled status quo [1]. It is important not to develop a "carbon-tax/price signal fetish" [2] when the impacts are limited. Taxing the demand side however is still an unsolved but critical problem knowing that over-consumption is a major driver of ecological devastation [3]. A carbon tax is just one special case of ecologically motivated redistributive mechanisms, all of which definitely deserve further attention.

Related to any carbon price scheme are generic questions of coverage, acceptance and justice. *Really* effective is a carbon price only if it is universal (sectoral coverage) and global (geographical coverage). Otherwise demand and supply find ways for spatial or structural "leakage". Public support for taxes on carbon intensive goods is not always strong and particularly controversial when low-income consumers bear high costs.

On the other hand, there are indirect or "systemic" benefits of taxation and they are increasingly addressed in the literature. Two examples are:

1) Carbon taxation may create incentives for innovation which drives technological evolution in general. Although this argument has recently been refuted empirically [4].
2) It not only directly affects the quantity consumed or produced but because of peer effects in networks causes "ripples" of behaviour change throughout society. This has recently been termed "social multiplier effect" [5].

This is important because in the last two decades our understanding of the economy as a complex adaptive system matured. Understanding redistributive policies as interventions into dynamical and complex systems is ever more important. Taxation and redistribution have been studied many times in static comparative models [6], which are also useful because they are relatively easy to implement and interpret (I also work on an international static-comparative version of my tax model), but it is time to understand the dynamics of redistribution.

Carbon taxation of household consumption

The two aforementioned effects are very interesting but quite complicated already. My aim here is to distill basic dynamics of a global carbon tax on the consumption of households. I focus only on the minimal and obviously essential feedbacks. I am just getting started with this whole research area myself, so it is always good to begin rather rudimentary. The model I am building here is in Vensim and it is a toy-model-precursor for a bigger, more sophisticated, version I build in parallel in Python.

One key to understanding carbon taxation already is the definition of a carbon tax. The carbon tax rate is dependent on two variables: the carbon price and the carbon intensity of a good (or a process when relating to production but remember, here I am concerned with taxing consumption of households).

$$carbon\ intensity * carbon\ price = tax\ rate$$

$$dimensions: \quad \frac{kg}{\$} * \frac{\$}{kg} = dmnl$$

So obviously if the intensity is high, the tax rate will be high and if it is low, the tax rate will be low, given the same price.

Importantly, a tax is good for two things:

1) A direct reduction effect on the quantity of consumption.
2) Collecting revenue that can be recycled.

It reduces emissions by reducing consumption and it generates a budget that can be used to do further "good". There are two straightforward applications for recycled revenue. One is to redistribute revenue in case the tax puts a heavy burden on low income households, probably because their consumption of essential goods is affected. Another is to reinvest the revenue in technology to further reduce the carbon intensity. This could be investment in innovation or more direct actions such as retrofitting housing or subsidies for electric vehicles.

In other words, the outcomes of recycling affect the carbon intensity through various channels, by restructuring consumer spending or by upgrading technology. This in turn affects the tax rate which determines revenue available. Basically, the tax is involved in characteristic feedbacks loops, even without considering more complex features like networks between agents or alike.

Therefore a first step is to capture this behaviour in a simple model. Below I depict the essence of the feedbacks and then walk you through the Vensim version.

Figure 1 shows the feedbacks involved. Based on the level of consumption and the tax rate there is some revenue collected that feeds government finances. These financial resources can be redistributed back to consumers or invested into tackling the carbon intensity.

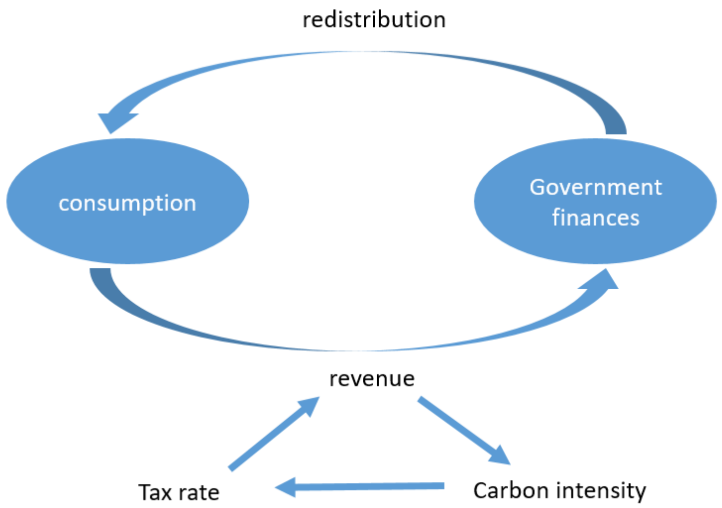

Figure 1: Essence of tax feedbacks

The model

Almost exclusively what is in Figure 1 is what I implemented into a first Vensim model of the tax. The only necessary additions are a few exogenous quantities determining the evolution of the whole system:

1) the economic growth rate determining how consumption evolves through time
2) an exogenous rate of technological improvement. Technology will improve anyway, even if no targeted reinvestment exists, at some base rate.

Figure 2 depicts the Vensim diagram. I conceptualized consumption and government finances as a stock variable in my model while in reality they are yearly flows. But this does not matter. Any system dynamics model is basically a set of differential equations and whether they are first or second order depends on perspective. I am interested in how consumption changes and yearly emissions emerging from that. Therefore I just model consumption and government revenues as the “levels” of interest and economic growth, revenue and redistribution etc. as change rates. In this version the carbon price is fixed and an exogenous quantity. In another twist, further down, I endogenize the carbon price.

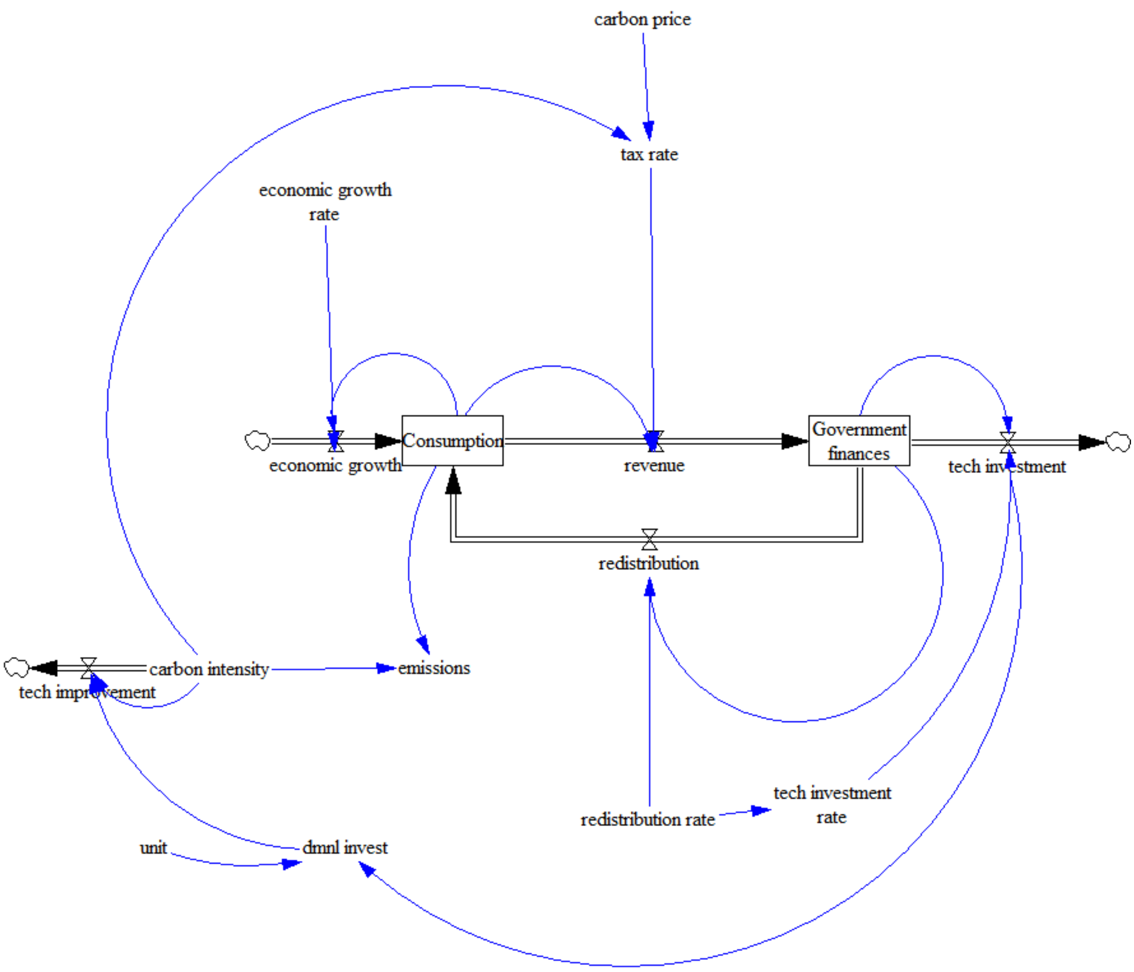

Figure 2: Vensim model version 1

Another modelling challenge to emphasize is the direct effect of the tax on the quantity consumed. Consumers behave in line with a certain price elasticity of demand, that is depending on a 1% increase of price, the quantity consumed will decrease by X%.

The model here is coarse and bulky. We do not differentiate by different products. Consumption is just one homogenous quantity. Thus for now it is reasonable to set the price elasticity equal to one – a middle ground.

Given the fact that the model is data-driven a few problems come up. The problem with the data is that it only comes in monetary terms. We actually do not know much about the quantity of goods consumed. I know what the global level of household consumption currently is -- 60 trillion $ PPP but I do not know what the breakdown into physical items is. The quantity effect thus is difficult to model. We would need to model the quantity effect as a reduction in expenditure volume. In micro-economic class-room models this is easier because one clearly distinguishes prices and quantity consumed. I would even go so far and say this is one of the biggest conceptual problems I am currently facing. In a static tax model this is no problem yet, once you go dynamic, it becomes tricky. The quantity effect only affects consumption once! The revenue is then determined by the new quantity. This whole step-wise procedure is easy to program in static models despite only relying on monetary data. For the dynamic version, I opted for a simple workaround. Since the price elasticity equals one, the initial total quantity effect (expressed as $ PPP) would be

$$Quantity\ effect := tax\ rate * price\ elasticity * consumpion = tax\ rate * consumption$$

This expression is conceptually the same as the revenue flow. So for now I just do not bother further and just assume it is integrated into the revenue flow. This is far from perfect and needs to be rectified in a more serious model version.

Table 1 below lists the most important parameters in the model and one important equation that translates investment into reduced carbon intensity. So far this relationship is just a fantasy assumption but I will update this based on data in subsequent versions. It is a linear assumption. Each marginal dollar investment has the same effect which is reasonable if you assume that the money is invested into programs like retrofitting or EV subsidies. Then every dollar really does cause the same amount of carbon removal. If it would be invested into innovation the whole process would likely be highly non-linear.

Table: 1 Model settings

Parameter	**Value**	**Unit**	**Source**
Consumption initial	60e12	$	World Bank
Gov. finance initial	0	$	Endogenous
Carbon(CO2e) intensity	0.327	kg/$	World bank
CO2e	19.6	gigaton	Carbon intensity * consumption
Economic growth rate	3%	Dmnl	~Average GDP growth rate pre pandemic
Carbon intensity base decline rate	-1%	Dmnl	~Average decline pre pandemic
Carbon price	50	$/ton	Value occasionally used in literature
Equation			
Carbon intensity decline due to tech investment	investment*10^-12		Fantasy construct, will be updated in future version

The million-dollar question is "What can we learn from the model?". "Does anything interesting happen in the model"? At this stage it is more about calibrating, reconceptualising and finding out whether the model makes sense at all. Let us have a look at few quantities and dynamics. The model runs for 20 years, integrated at a time step of 0.0625 using Euler's method. The Runge-Kutta method does not change the results.

In Figure 3 the base run is depicted with the parameters from Table 1. Consumption grows in line with the economic growth rate, carbon intensity declines in line with the tech improvement rate. There is a maximum of tech investment at time point 3. This due to the fact that the pool of government finances first needs to build up and then can release a flow of money. The shape of this curve is sensitive to various parameters including the growth rate which postpones the maximum to a later date.

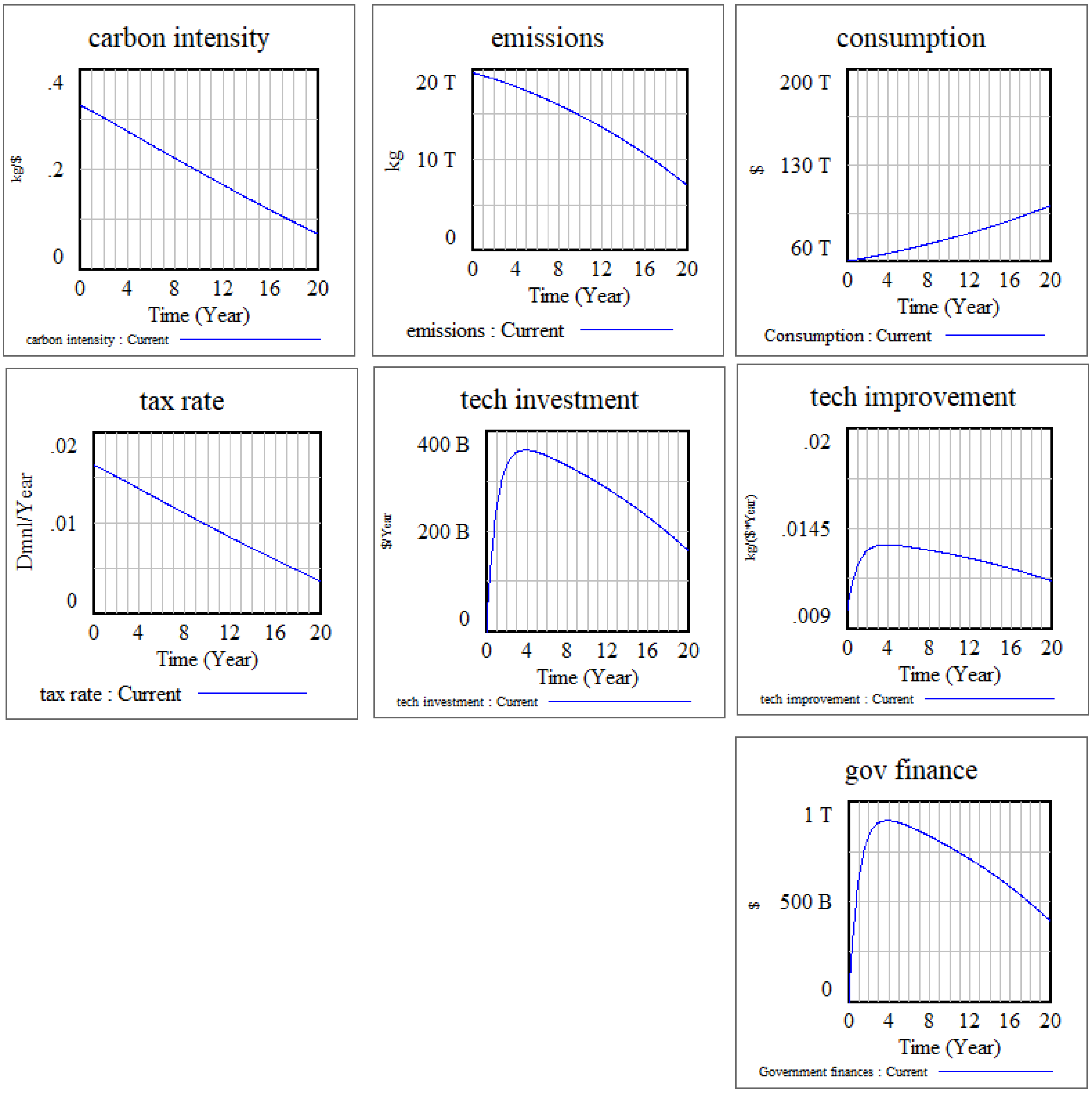

Figure 3: Exploratory results run #1

I tested the sensitivity of the model on various parameters, the growth rate, the share of government finance that goes to technology investment and more. To report them all here would be lengthy. A few interesting observations behaviours are:

1. Increasing the tech investment rate accelerates emissions declines, making it convex downward depending on the rate. If the tech investment rate is 0, it is just a straight line.
2. Higher economic growth rates (>3%/yr) lead to more emissions in the near future and steeper declines later on because than the amount of money channelled into technology investment grows exponentially.

3. The tax rate declines over time because the carbon price is constant and the carbon intensity declines.

Point 3 is the next reasonable thing to look into. What if we hold the tax rate constant? In order to do so we must increase the carbon price whenever the carbon intensity decreases. Therefore the carbon price should just be inversely proportional to the carbon intensity.

$$\text{carbon price} \propto \frac{1}{\text{carbon intensity}}$$

This changes the shape of technology investment curve, as it is now low in the beginning and then continuously accelerates due to an ever going carbon price. To my surprise however, it does not accelerate carbon removal by much given that all other parameters are the same as before. This is partly due to the fact that the price initially is now lower than the constant price in the model version before.

Note in the graph below the tax rate is not zero, it is equal to 1% throughout (Some of the Vensim Graphs have issues with axis scaling and I do not know yet why).

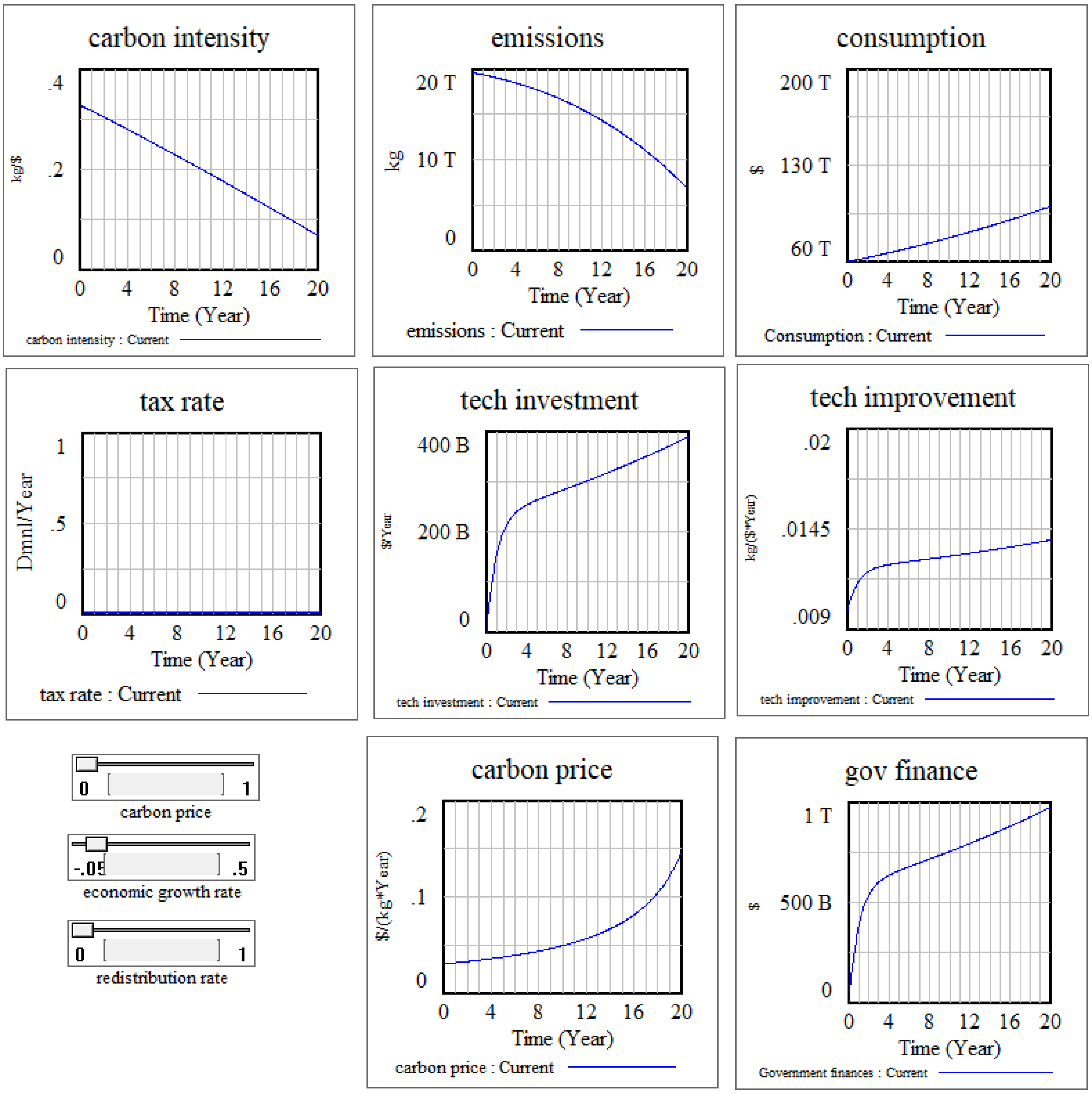

Figure 4: Exploratory results run #2

Discussion

The idea is to construct a model that distils the basic interaction dynamics of a carbon tax with household consumption. The model in its current form is almost too simplistic but it captures realistic trajectories of household consumption and emissions over time.

There are certainly many possible additions. For instance, redistribution for now is just a flow back and forth between household consumption and government finances but it does not have any effect per se. It is plausible that the amount of redistribution is coupled to the sentiment among the population. In particular so coupled to the sentiment of lower-income households that rely on carbon intensive goods like driving as it did happen in France with the yellow-vest movement. Implementing such a feature would create a trade-off between redistribution and technology investment. So far more technology investment is always better because it accelerates carbon removal. This would make the search for the optimum of revenue spending more challenging. Nevertheless, one clear result from the model already now is that it is best to keep the need for redistribution in any carbon tax small so that revenue can be spend on direct carbon removal for deep decarbonization. This could mean to predominantly tax the rich and their consumption.

Coupling redistribution with social sentiment potentially would induce chaos as we know it from the Goodwin model for example (due to coupling among quantities). Another plausible feedback is implementing a carbon budget and a function that describes global warming (a better one than Nordhaus did). More warming could mean more pressure on the economy to change course.

Many technical details still have to be refined including the nature of the effect that the tax has on consumption behaviour or the relationship between investment and technology improvement. It could also very well be that technology in the future removes carbon faster than today’s technology bringing time preference considerations into play.

The whole system is also pretty much isolated from the “rest of the economy”. I did not consider the overall budget of the government but only what is generated by the tax itself. There are no industrial sectors considered and production does not have any role other than being implicit in the carbon intensity of consumption. Interaction with other policy instruments is not considered either but could prove useful.

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