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ECONOMIC ASPECTS OF THE ENERGY TRANSITION

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ABSTRACT

I make three points relating to the transition from fossil fuels to non-carbon energy. One is that the economic cost of moving from fossil fuels to renewable energy in electricity generation is very low, and probably lower than many estimates of the economic benefits from this change. The second is that, if it were to move the economy away from fossil fuels and from oil in particular, a carbon tax would have to be much great than generally believed, in the range of $400 per ton CO2 or above. Finally, decarbonization of the economy implies electrification, the replacement of fossil fuels by electricity in for example space heating. Currently electricity is far too expensive for this to be politically realistic: this is because its price does not reflect its marginal cost but this plus a wide range of fixed costs that are recovered in the per kilowatt hour charge. If we are to electrify the economy then the price of electricity will need to be nearer to its marginal cost, which raises questions about the business models of utilities.

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1 Overview

Decarbonizing our economies is one way of solving the climate problem. This would require decarbonizing the following: electric power generation; transportation; space, water and process heating; and agriculture. All are significant sources of greenhouse gases. In the U.S. transportation recently overtook power generation as the main source of greenhouse gases, and current trends suggest that this will soon happen at the global level too.

Only on the first of these have we made any significant progress. In electricity generation, the transition from fossil fuels is clearly under way. In the U.S. the share of electric power generated by coal has fallen from over 50% to 21% in the last fifteen years, and in the U.K. there is a similar story, falling to 5% in 2018 from 30% in 2014.[1] In this paper I review some of the microeconomic issues raised by this transition in power production. One is the cost of the transition, and in particular what exactly should be charged to the transition as opposed to the normal operation of the energy system. I argue that the net cost of the transition to renewable energy in the U.S. is much smaller than generally believed, and indeed is an order of magnitude less than the benefits from reducing emissions from fossil fuels. Closely connected to this is the issue of intermittency and the costs of integrating intermittent power sources into the grid - either by storage or by spatial diversification. Then there is the question of how to provide incentives to move away from fossil fuels - a common suggestion being the use of a carbon tax, and I will argue that this is likely to be far less effective than is widely assumed and that we need to think of alternatives. Tied to this are a set of questions about electricity pricing: the other side of the coin of decarbonization of the economy is electrification, and this will only happen if electricity prices provide consumers with the right incentives. Currently they don't.

[1]See https://www.mjbradley.com/sites/default/files/MJBAcoalretirementissuebrief.pdf and https://en.wikipedia.org/wiki/Energy_in_the_United_Kingdom

2 Costs of decarbonizing power production

In 2017 I published a paper estimating the investment required to make all electric power generation in the US carbon-free by 2050 [6]. I gave a wide range of estimates, the best case being \$1.28 trillion and the worst being \$3.97 trillion. In the short time since that paper was published, costs have fallen faster than I anticipated, both for renewable energy sources such as wind and solar photovoltaic, and also for energy storage devices such as lithium ion batteries. I am therefore redoing my earlier calculations with the best current cost estimates. Over the three decades between now and mid century, costs will of course change again, so that the numbers here are still only suggestive estimates. With two exceptions, I am taking U.S. Energy Information Agency current costs, as of mid 2019, and projecting these forward. As costs have tended to fall rather than rise, I expect that this will produced an overestimate of the cost of a carbon-free power system, but any estimate of the size of the error is guesswork.

My conclusion is that the likely net investment required to go carbon-free is now as little as \$0.179 trillion. I no longer think it is useful to give a worst case scenario, as the drop in costs and increases in efficiency over the last decade now seems obviously irreversible, and it is clear that prices will only move one way. This figure of \$0.179 trillion includes offsets from fuel savings as we no longer need to buy coal or gas, and also includes capital cost offsets reflecting the fact that most coal plants in the US have to be replaced well before 2050 as they are already near the ends of their useful lives. The cost of replacing them should therefore not be charged to the conversion to non-carbon energy sources. Each of these offsets is of the order of one trillion dollars, so they have big impacts on the final numbers. Although the cost of replacing old coal plants should not be regarded as a cost of conversion to carbon-free energy sources, it is nevertheless a real cost that has to be paid, and if we include it in the total then the cost increases from \$0.179 trillion to \$1.18 trillion. But the bulk of this is replacing very old power plants that are unsafe and obsolete, and need to be replaced whether we convert to clean energy or not. My earlier estimates also included both of these offsets, so the cost including both offsets has fallen from $1.28 trillion to $0.179 trillion. This low number reflects the fact that renewable power from wind and solar PV plants is now less expensive than power from gas, coal or nuclear plants, as documented for example by Lazards' studies of the levelized cost of electricity from alternative sources.[2] If it were not for the intermittency of renewables, we would save money by converting to clean power. As it is, we need to invest in storage to manage the intermittency and this leaves us with a small net cost to converting the power sector to non-carbon energy sources. On an annualized basis, assuming we complete the transition to renewable power by 2050, the two costs are $6.1bn and $41bn.

2.1 Methodology

The method that I use for these calculations is the same as in the earlier paper, and is entirely straightforward. I calculate the amount of wind and solar PV nameplate capacity that would be needed to produce all the mWh of electricity currently produced by coal and gas plants,[3] and then calculate the cost of this capacity. I then make an estimate of the amount of storage capacity needed to deal with the intermittency of the renewable sources. Together with an allowance for improving the grid, this gives the total gross cost of the transition to renewables. Against this I set the offsets mentioned above: the savings in fossil fuel costs that result from replacing coal and gas by wind and solar, and also the allowance for the fact that all coal-fired power stations and many gas-fired ones would anyway have to be replaced before 2050, so that the cost of replacing them is not properly attributable to the

[2] https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf

[3] Coal and gas produce 61% of total annual mWh, and total annual mWh are about 4 billion.

energy transition. I assume that the savings in fossil fuel costs grow linearly from now to 2050, and that fossil fuel plants are replaced at a constant rate.

The most debatable assumption in this process is the assumption about how much storage would be needed to cope with the intermittency of the renewable capacity that we install during the transition. Unfortunately there is no firm formula for calculating the storage needed to manage the integration of renewables into the grid. The number depends on the extent to which demand can be managed by appropriate incentive programs, the number of dispatchable power plants, and the covariances between the outputs of the renewable energy plants in use: clearly large negative covariances will reduce the need for storage. I assume that we need sufficient storage capacity to hold the output that all renewable plants produce over a period of two days. There are studies that suggest that this is an appropriate amount, and indeed is perhaps too large. For a review of the issues this raises and references to the literature see [5]. A recent paper by Shaner et al [12] studies the possibility of meeting US power demand purely from renewable energy from an engineering perspective and looks at the trade-off between storage and "overbuilding," i.e. constructing more renewable capacity than is strictly needed to meet demand, so as to take advantage of spatial diversification. They assume **all** demand is met from renewable energy or storage, whereas here I am merely replacing output from existing fossil fuel plants by renewables, keeping in place existing hydro, geothermal and nuclear capacities. So about 66% of the annual output of mega-watt hours is coming from renewables and storage. Shaner et al cite several earlier engineering studies of the possibility of meeting US demand purely from renewables: these generally conclude that by choosing locations to exploit low or negative covariances is it easily possible to meet 80% of demand from renewables without storage, and that meeting the last 20% purely from renewables is very expensive, with the last 2% being especially so.[4] I am avoiding this problem by assuming existing

[4]Note that to use low or negative covariances of output at renewable power stations to

non-fossil supplies to remain in place.

The other assumption that I am making is that there is no seasonality to patterns of demand and supply: I can just work with annual totals. This is a simplification, and from some preliminary calculations seems to be one that does no great violence to the total costs involved.

The key facts and assumptions that underlie the calculations that follow are the following:

1. The U.S. produces about 4 billion mWh of electric power each year
2. 61% of this comes from coal and gas
3. I assume that we replace the 61% of 4 bn mWh from coal and gas by wind and solar in equal amounts
4. I assume that we need enough storage capacity to hold two days of the output of renewable energy
5. I assume that we need to increase the milage of high voltage grid lines by 25%
6. Total electricity production remains constant from now to 2050.

2.2 Data

Table 1 lists all the key parameters used in the calculations, and their values.

With the exceptions of the costs of storage and of solar power, all of these represent current values as given by the Energy Information Agency or an equivalent source.[5] It is reasonable to expect equipment costs to fall

reduce storage needs, it is necessary to construct extra capacity, known as "overbuilding."

[5]The EIA figure for the cost of solar capacity is \$1.9/W: industry sources that I talk with suggest that it is out-of-date and far too high. Many sources cite actual costs of close to \$1/W - see for example https://news.energysage.com/solar-farms-start-one/ and https://www.seia.org/research-resources/solar-market-insight

Parameter	Value
Cost of wind capacity	$1,500/kW
Wind capacity factor	0.42
Cost of solar PV capacity	$1.1/W
Solar PV capacity factor	0.26
Cost of storage	$75/kWh
Cost of high voltage lines	$2,000,000/mile
Miles of HV lines needed	50,000
Cost of coal capacity	$3,000/kW
Cost of coal	$50/ton
Cost of gas capacity	$1,000/kW
Cost of gas	$3/mmbtu

Table 1: Parameter values for the cost of the energy transition in the U.S.

and capacity factors to rise over the next three decades, so that these figures are probably overestimates of the costs we will encounter. [6] The cost of storage, which today is in the region of $125/kWh, is widely expected to be at or below $100/kWh by the end of 2020, and to continue falling after that. So looking forward as far as 2050, a cost of $75/kWh does not seem unreasonably optimistic. The declines in the cost of storage are likely to be more significant than those in the costs of wind and solar power, and so seem to merit anticipation.

2.3 Results

All calculations are available in an Excel spreadsheet on my web site.[7] Table 2 shows the various elements of the calculations:

These figures show that the annual incremental cost of transitioning to fossil-fuel-free electricity generation system, if the total investment is spread

[6] https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf and https://www.energy.gov/eere/wind/downloads/2017-wind-technologies-market-report, presentation, slide 38,

[7] https://geoffreyheal.com/publications/publications-on-climate-change/

Category	**Cost $ trillions**
Capacity costs	$1.68
Storage costs	$1.08
Grid costs	$0.1
Fuel savings	-$1.12
Capacity replacement offsets	-$1.01
Total fuel offsets only	**$1.189**
Total all offsets	**$0.179**
Annual rate all offsets	$0.0061
Annual rate fuel offsets only	$0.041

Table 2: Costs of the energy transition in the U.s.

over the period from 2021 to 2050, is $6.1 billion. This a fraction of what the US currently invests in the energy sector.[8] This incremental cost estimate does not include the cost of replacing fossil fuel power plants that come to the ends of their lives, as these would have to be replaced, and these costs incurred, even if there were no transition to carbon-free electricity. Hence the costs of these replacements are not properly attributable to decarbonization. However these costs do have to be incurred, as the power plants will need to be replaced, and if we included these costs the total annual investment rises to $41 billion. This difference emphasizes the fact that many fossil fuel plants will need replacement in the period from now to 2050. The total of $41 billion a year is less than current energy infrastructure investment levels. But it must be emphasized that the increase from $6.1 billion to $41 billion has nothing to do with the cost of the transition to clean energy: it reflects the fact that we have a lot of very old power stations that badly need to be replaced. It is important to distinguish the cost of failing to keep our infrastructure up-to-date from the costs of the energy transition.[9]

[8] Roughly $50bn annually.

[9] A similar issue arises with the U.S.'s nuclear power stations, which provide about 20% of the megawatt hours generated annually in the U.S. All but two or three will also be well beyond their usable lives by 2050, and will have to be replaced. I am implicitly assuming here that they are replaced by non-fossil, non-renewable power (nuclear, hydro,

2.4 Environmental Benefits

The costs of replacing fossil fuels by renewable energy are low, of the order of tens of billions per year. Studies of the benefits suggest that they are far greater, making the replacement of fossil fuels an unusually attractive investment. Phasing out coal and gas in electricity generation would reduce CO_2 emissions by about 2 billion tons per year.[10] Suppose the social cost of carbon to be $100 per ton (this is a controversial issue - estimates range from $30 to $600). Then the social benefits from stopping the CO_2 emissions from coal and gas in power generation in the U.S. amount to $200bn annually, roughly an order of magnitude greater than the costs. Furthermore, these benefits will continue for ever, whereas the costs are fully paid by 2050. Of course, the benefits will not reach the full $200bn until 2050: if we assume that fossil fuels are phased out linearly between now and then, on average greenhouse gas emissions will fall by 1bn tons per year between now and 2050, with a value of $100bn, with the full $200bn applicable after 2050. As greenhouse gases are a global public bad, many of these benefits will accrue to countries other than the U.S.

In addition to the greenhouse gas benefits from switching to renewable energy, there are substantial benefits from reducing other forms of atmospheric pollution in the areas where fossil fuels are being burned - pollution from SO_2, NO_x and $PM_{2.5}$ and PM_{10}. The costs of these pollutants in the U.S. have been estimated at between $361 and $888 billion per year [1][9].

3 Carbon Taxes

There is strong agreement amongst economists that a carbon tax is an effective method to reduce carbon emissions. For example, The Initiative on

geothermal, etc.), as replacing them by renewables would probably increase the need for storage and or grid enhancements.

[10]See U.S. Energy Information Agency, https://www.eia.gov/tools/faqs/faq.php?id=74&t=11

Global Markets (IGM) at the University of Chicago Booth School of Business maintains a representative panel of economists. A carbon tax was favored by almost all these economists, and there was a greater divergence with views by the general public than for any other question [11].[11] Every environmental economics text sees the internalization of external costs as a necessary step on the road to efficiency. Carbon emissions create externalities, and a tax will internalize them [10]. The Pigouvian framework is the default setup when it comes to thinking about environmental policy, as a Pigouvian tax drives a wedge between producers and consumer prices and in a static one-period model generally reduces the equilibrium quantity.

However, fossil fuels are an exhaustible resource with a limited supply. Scarcity rents can be a significant portion of the price to ensure that the limited supply is optimally allocated between periods [8]. For example, Saudi Arabia's production cost are in the range of $5-8 per barrel, yet the oil price in 2019 was around $60 per barrel. In the standard Hotelling model, all resources are used up, and a tax is paid out of the scarcity rents of producers. The tax might slightly shift consumption patterns over time, but does not change the cumulative use of the resource.

The point that Wolfram Schlenker and I make in a recent paper [7] is that the Pigouvian and Hotelling frameworks lead to rather different conclusions when it comes to thinking about the effectiveness of a carbon tax. Pigou emphasizes the impact of a tax on substitution between commodities, in this case between energy sources. Hotelling on the other hand empha-

[11] The statement "A tax on the carbon content of fuels would be a less expensive way to reduce carbon-dioxide emissions than would a collection of policies such as corporate average fuel economy requirements for automobiles" was agreed to by 92.5% of economists, while only 22.5% of the general public agreed, as measured by the Chicago Booth Kellogg School Financial Trust Index survey. Suport for a carbon tax is growing among various policy circles. The New York Times reported that "Republican Group Calls for Carbon Tax" (2/7/17), and the Financial Times noted that "Leading Corporations Support US Carbon Tax" (6/20/17). The Carbon Pricing Leadership Coalition (www.carbonpricingleadership.org) is a coalition of international and national organizations and corporations dedicated to promoting a carbon tax.

Fuel	units	CO_2, mt	Price, $	Tax, $
Coal	mt	2.86	50	143
Gas	mmbtu	0.053	3	2.65
Oil	bbl	0.35	60	17.6

Table 3: Impact of $50 carbon tax on fossil fuels

sizes the impact of a tax on an exhaustible resource on the time-path of consumption of that resource. It can lead to the substitution from present to future consumption, so that less of the resource is consumed by any date but the same amount is consumed overall. One of the clear conclusions of the Hotelling model of equilibrium in a resource market is that if there is a substitute for the resource - think of renewable energy - available at a price in excess of the marginal extraction cost of the resource, then all of the resource will be consumed eventually, and a carbon tax can only change this under rather stringent conditions. Carbon taxes reduce carbon emissions less once these dynamic considerations are incorporated. To be precise, the only way in which a carbon tax will reduce consumption of and emissions from fossil fuels is by pricing the most expensive grades of fossil fuel out of the market.

Table 3 shows the impact of a $50 per ton CO_2 tax on the costs of the three fossil fuels, coal, gas and oil. Column 2 shows the units in which these are measured, and column 3 the amount of CO_2 produced by burning one unit of each in metric tons. Column 4 shows the current price and column 5 the carbon tax per unit resulting from a $50 carbon tax. Clearly the impact on coal will be huge: the tax is three times the current price. And the impact on gas will also be substantial, as the tax is roughly the same as the current wholesale price. But with oil whose price has been ranging between $65 and $40 per barrel, the impact is less dramatic. The marginal extraction cost of oil from many sources is less than $10, so that the tax can readily be paid from the scarcity rent and even if passed on to the consumer it will only raise the price to a level that is within the range of prices in the recent past (in 2014 the price was in excess of $100 per barrel).

3.1 A Formal Model of Carbon Tax Impact

To formalize these issues, we assume a fossil fuel which is sold at a price p_t with a marginal extraction cost of m. There is a carbon tax of τ per unit: this tax is based on the chemical characteristics of the fuel and does not depend on its price. The fossil fuel competes with a renewable resource which is available in unlimited amounts at marginal and average cost $R > m$. This is a perfect substitute for the fossil fuel (a "backstop technology"), so if the fuel is consumed we must have

$$p_t \leqq R \tag{1}$$

Demand for the fuel is given by $D(p_t)$. We know that the market price of the fuel will rise exponentially away from $m + \tau$ at rate r, and that $p_t = h_0 e^{rt} + m + \tau \leqq R$ if the fuel is sold. Heal and Schlenker [7] establish the following result:

Theorem 1. *A dynamic competitive equilibrium with a carbon tax τ, with $m + \tau < R$, is characterized by $\int_0^T D(p_t)\,dt = \int_0^T D(h_0 e^{rt} + m + \tau)\,dt = S_0$ and $p_T = h_0 e^{rT} + m + \tau = R$. These determine the initial rental rate h_0 and the date T at which $p_t = R$ and the fossil fuel is exhausted. There is no interval over which the fossil fuel and the renewable energy source are both used. If the tax rate is raised to $\tau' > \tau$, $m + \tau' < R$, then the above remains true so that* ***total fossil fuel consumption is not changed****. The tax increase* ***decreases*** *the initial rental rate h_0 and* ***increases*** *the date T at which the fossil fuel is exhausted. If the tax is so high that $m + \tau > R$ then the fossil fuel is never consumed.*

In simple terms, the tax either has no effect at all on the cumulative consumption of the fossil fuel, or it drives it out of the market completely. In the former case, the tax reduces the scarcity rent and extends the time period over which the fuel is used, as shown in figure 1.

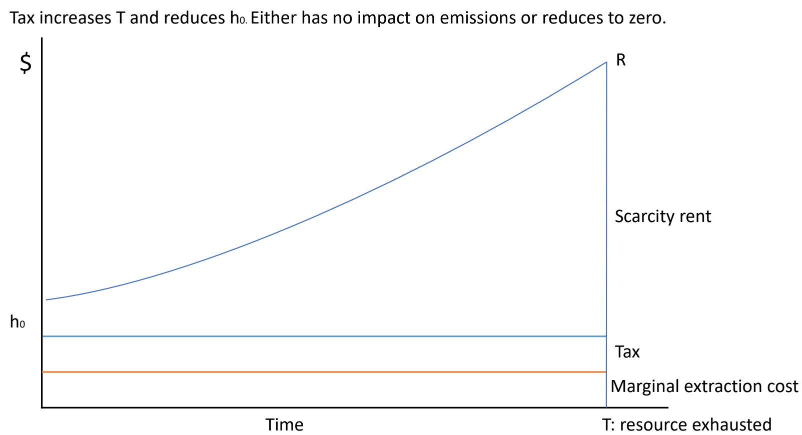

Figure 1: Equilibrium with single fossil fuel

3.1.1 Many fuel grades

We now introduce a more comprehensive model in which there are I different fuel sources with differing marginal extraction costs m_i, numbered in increasing order of extraction costs, $m_1 < m_2 < ..... < m_I$ and $m_I < R$. The initial stock of the $i-th$ fuel is $S_{i,0}$. In this case we can establish a more nuanced result:

Theorem 2. *Competitive equilibrium: dates T_i, $i = 1, 2, ...I$, $T_i < T_{i+1}$, and initial rents $h_{0,i}$, $i = 1, 2, ..., I$ such that for all i, $p_{i,t} = m_i + \tau + h_{i,0}e^{rt}$, $T_{i-1} \leq t \leq T_i$ and $\int_{T_{i-1}}^{T_i} D(p_{i,t})\, dt = S_{i,0}$. The price moves continuously so that*

$$p_{i,T_i} = m_i + \tau + h_{i,0}e^{rT_i} = p_{i+1,T_i} = m_{i+1} + \tau + h_{i+1,0}e^{rT_i}\ \forall i \tag{2}$$

and the last price of the fuel equals that of renewable energy: $p_{I,T_I} = R$.

The key conclusions here are that if extraction cost plus tax of grade j is less than the backstop price, i.e. $m_i + \tau < R$, then the carbon tax will merely delay consumption of the fuel, but if the tax raise the cost of grade j above the backstop price, i.e. $m_j + \tau > R$ (but $m_j < R$), then with the tax,

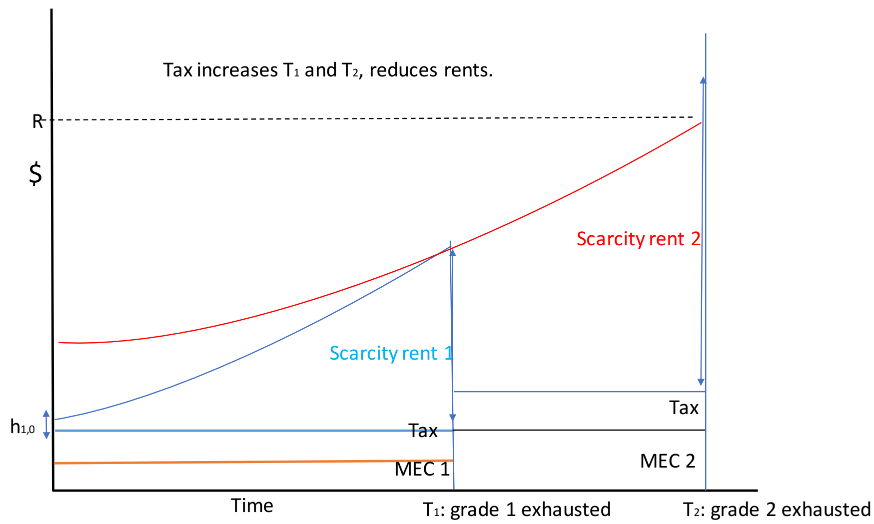

Figure 2: Equilibrium with two grades

grade j will never be used and total consumption and emissions will fall as a result of the tax. In general the tax delays the use of all grades and may in addition force the most expensive grades out of the market: the latter effect **reduces** emissions whereas the former merely **reschedules** them. A key insight is that there are two distinct mechanisms through which tax affects consumption, rescheduling and reduction. Figure 2 shows how this process works in the case of $I = 2$. The scarcity rent on each grade is reduced, and the time over which it is used extended. And if it were the case that $MEC2 + tax > R$ then the more expensive grade would never be used.

Figure 3 shows the results of simulating this model with data on the world oil market from Rystadt. It shows prices (red) and consumption levels (blue) from 2020 to 2160 for carbon taxes of \$0, \$50, \$100, \$200 and \$400 per ton of CO2 emitted.

As the tax rises, the consumption profile is flatter, starting lower and falling less rapidly, but extends for longer. On the price side, initial prices

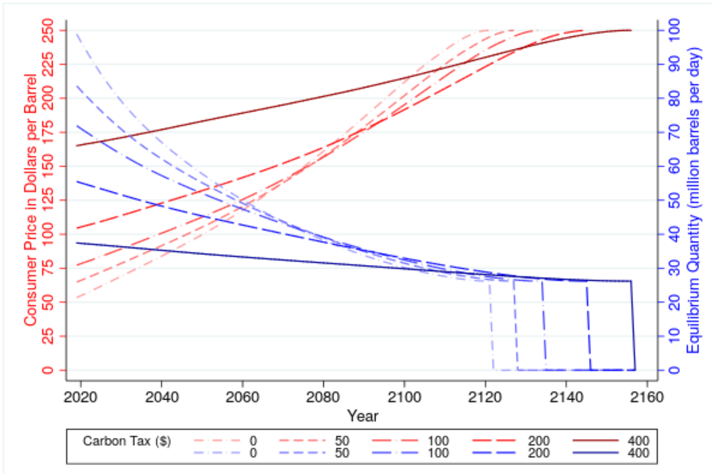

Figure 3: Taxes, price and quantity in the oil market

rise with the tax, but the price profiles cross and ultimately the prices are lower for high taxes than for lower or no taxes. Figure 4 summarizes some crucial conclusions from the analysis: it shows the carbon tax needed to achieve any specified reduction in cumulative oil use. If we want to reduce cumulative oil consumption by for example 30%, then we need a tax of about \$500 per ton of CO2: if we wanted to reduce oil consumption by two thirds we would need a tax of over \$600 per ton CO2.

A theoretical insight into what is happening here comes from the Slutsky equation,

$$\frac{\partial x_n}{\partial p_n} = \frac{\partial h_n}{\partial p_n} - \frac{\partial x_n}{\partial W} x_n$$

which tells us that the impact of price change on regular demand $\frac{\partial x_n}{\partial p_n}$ is the sum of two effects, the impact on compensated demand (the substitution effect $\frac{\partial h_n}{\partial p_n}$) plus the impact of the change in real income on demand (the income effect $\frac{\partial x_n}{\partial W} x_n$). For oil substitution effect is roughly zero (as there are no real substitutes for oil in many of its applications) so we need a large income change for a large reduction in demand.

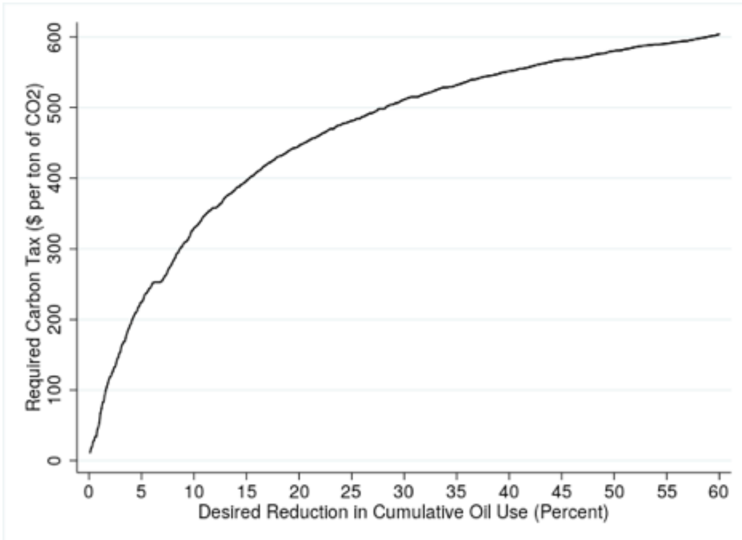

Figure 4: CO2 tax and oil consumption

4 Alternatives to a carbon tax

It seems very likely from the previous section that a tax high enough to be effective in reducing oil demand, would be too high to be politically acceptable: a tax that reduces oil consumption by 50% would be about \$575 per ton CO2, which translates into a tax of \$201 per barrel of oil or \$4.9 per gallon (or €1.26 per liter), more than doubling the current U.S. retail prices of gasoline. Recent experience with the political fall-out from attempts to raise fuel prices (such as with the *gilets jaunes* in France) suggests that few politicians would venture to propose such taxes. A cap and trade system would achieve the same outcome, but the same problem would appear in a different guise: the permit price would be very high, raising the retail price of fuel to a similar level.

What are the alternatives? Renewable energy has been a huge success story - what has made it so? In the U.S., a combination of federal tax subsidies (production and investment tax credits) plus state-level renewable portfolio standards have worked well, and in the E.U., feed-in tariffs have driven rapid adoption. Perhaps the world needs equivalent measures to drive the replacement of oil. It may be worth noting that renewable portfolio standards and feed-in tariffs go some way towards disguising the costs of the policy: they are of course ultimately reflected in the cost of energy, but not in a way that makes it easy for the average consumer to recognize.

In both the U.S. and the E.U., the main drivers of greater vehicle fuel efficiency have been emission standards, the corporate average fuel efficiency standard (CAFE) in the U.S., its EU equivalent, the CO2 emission performance standards. Like renewable portfolio standards and feed-in tariffs, these hide the cost of the policy from the consumer. An alternative would be to combine with direct subsidies to electric vehicles and to the charging infrastructure that they need.

These suggestions run contrary to mainstream economics, which recommends Pigouvian taxes and is generally strongly against subsidies or regulations. But sadly we seem to be in a second-best situation where the first-best is politically inaccessible, so we are forced to look at policies that no economics textbook would recommend.

4.1 Electricity pricing

As mentioned earlier, decarbonization generally implies electrification: replacing internal combustion engines by electric motors, and replacing oil and gas heating by electric heating, of course with the electricity generated from non-fossil sources. This means ensuring that electricity pricing provides consumers with the right incentives. In particular it means that we need the cost of using an extra kWh of electricity to reflect its marginal social cost. Currently in New York City, and in most other large cities in the U.S., electric heating is many time more expensive than oil or gas heating.[12] This reflects the fact that power prices are in the range \$0.15 to \$0.20 per kWh,

[12]See https://www.ny-engineers.com/blog/can-electric-heating-have-a-lower-cost-than-gas-heating for details.

which is way above the marginal social cost of electricity from renewable sources.[13] The marginal social cost of power from renewable sources is close to zero, as wind, solar and hydro all have essentially zero operating costs. So we would need much lower power prices to provide the correct incentives to use clean power rather than fossil fuels. Perversely, not only are renewable energy prices way above marginal social costs, but fossil fuel prices are below marginal social costs.

This immediately raises an old problem in pubic utility pricing: renewable energy has low marginal costs but substantial fixed costs, and the costs of the grid are also fixed. All of these fixed costs need to be covered, and can not be recovered from pricing power at or near marginal cost. In most countries the present pricing regime rolls all these fixed costs into the marginal price of power, resulting in a price that is way too high for efficiency. However if we price closer to marginal cost, as needed for efficiency, then we bump into the iconic problem of Dupuit's bridge [3]: break-even pricing is inconsistent with efficient use of the resource once it is built.

The classic response to this conundrum has been to recommend two-part tariffs, with a fixed charge or connection or membership charge recovering the fixed costs and a usage tariff covering the variable costs. There are results establishing that two-part tariffs where the fixed charge is personalized - depends on individual characteristics - can lead to an efficient pattern of resource use: this is proven in Brown and Heal [2]. The intuition behind this result is, to quote Brown and Heal, that "One might reasonably conjecture that if an allocation is Pareto optimal, then the sum over all individuals of this willingness to pay, should, together with payments for the goods actually bought, cover the total costs of firm i." In simple partial equilibrium terms, buying electricity at marginal cost generates consumer surplus, which if the outcome is efficient should in total exceed the losses incurred by the firm in selling at marginal cost, and in this case two-part tariffs or price discrimi-

[13] Though possibly not above the marginal social cost of power from coal - see .

nation can appropriate enough of this surplus to cover the losses. A more recent related result is in Edlin, Eplebaum and Heller [4], who model a perfectly price-discriminating monopolist with increasing returns in production interacting with a competitive sector and show that under certain conditions perfect price discrimination leads to a Pareto efficient outcome. When these results first appeared, personalized fixed charges in a two-part tariff system seemed a remote and unrealistic concept: in today's information-rich and privacy-poor world they seem far less speculative. This seems to be a topic which merits revisiting within the context of utility pricing rather than in the generic general equilibrium models cited above, as is the nature of the utility business model and how it can adapt to a world of zero marginal cost electricity and distributed generation.

5 Conclusions

This paper presents two new findings on decarbonization. A positive finding is that removing fossil fuels from electricity generation is now feasible and inexpensive. For the U.S. economy, one of the largest emitters of greenhouse gases, it can be done at a cost that is less than current expenditure on energy capital equipment. The costs of renewable energy are roughly the same worldwide, so that the costs are likely to be low anywhere else in the world. The reason the cost is so low is that the capital costs of renewable energy have fallen dramatically over the last decade, and there are of course no fuel costs, so that a modest increase in capital costs leads to a huge saving in fuel costs.

Less positive is that a carbon tax, which is widely assumed to be the best way to wean economies off fossil fuels, would have to be of the order of $500 per ton CO2 or more to move us away from oil. Intuitively this is not surprising: many oil fields are very profitable and in addition the demand for oil is highly inelastic because in some of its main uses there are few substitutes. In transport we are only just beginning to see the emergence of electric vehicles, and in heating space, water and industrial processes we still have few alternatives. Contrast this with the situation in power generation, where wind and solar have become highly competitive over the last five years, so that they now provide strong price competition for coal and gas. Because a carbon tax would need to be so high, it seems sensible to seek alternatives. Probably a modest carbon tax will have to be supplemented by emissions standards for buildings and transportation.

Another important issue is that decarbonization means electrification: they are two sides of the same coin. With present electricity tariffs, electrification would be outrageously expensive and impossible to sell politically. To provide the right incentives and ensure efficient use of electricity we need prices near marginal cost, which for renewable energy is close to zero, posing problems for funding of fixed-cost-intensive renewable energy. So we need to rethink the utility pricing model and find a pricing system that does not try to recover fixed costs in the unit price.

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