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The black paradox[☆]

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ABSTRACT

We model competition between an oil monopolist and competitive suppliers of coal and renewable energy in a dynamic general equilibrium framework. We show that market power—which disrupts the order of extraction—may lead to higher long-run emissions by encouraging early extraction of dirty fuels such as coal which would otherwise remain in the ground permanently; simply banning coal burning may be better than Pigovian taxation. Market power can of course be corrected by production subsidies to the monopolist, but when distribution affects welfare a better option is to offer subsidies to renewable energy, which force the oil monopolist to reduce her (limit) price but are never actually paid out.

1. Introduction

It is well known that, in order to avoid a rise in global average temperature of over 2 °C, the majority of fossil fuels must remain in the ground. And economists agree that the best way to achieve this outcome would be through a uniform global price on carbon emissions while eliminating other market imperfections. However, agreement on implementing such a price has proved elusive, while the oil market is characterized by market power exercised by OPEC, which holds back oil extraction in order to drive up prices and hence net revenue. In the absence of an agreement on a global tax, it seems reasonable to suppose that OPEC's market power should act as a proxy (albeit imperfect) for the Pigovian tax and thus help to move the economy towards the first-best allocation; in the words of Solow (1974, p.8), "the monopolist is the conservationist's friend". There is, however, a problem with this idea: non-OPEC fossil fuels. OPEC's market power does not just reduce consumption of its own fossil fuels, it raises extraction rates of other fossil fuels. Furthermore, the oil stocks owned by the members of the OPEC cartel are among the cheapest and cleanest, thus coinciding closely with those that should be extracted in first best (see for instance the analysis of McGlade and Ekins, 2015). Where the 'other' fuels are dirtier than OPEC's oil, shifting the balance of production towards them will push emissions up; if this composition effect outweighs the decrease due to higher prices, total short-run emissions will rise. And if the other fuels would have stayed in the ground forever in the absence of market power—due to rising damage costs and declining costs of clean alternatives—OPEC's market power will drive up long-run emissions.

Market power in the oil sector thus leads to a sub-optimal order of extraction, causing inevitable welfare losses and also potentially raising long-run emissions. The relevant empirical cases can be put into two classes: firstly, where market power in the oil sector brings forward the extraction of other fossil fuels, such as coal; and secondly, where it distorts the order of extraction across different oil reserves, slowing the extraction of cheap (OPEC) oil but bringing forward the extraction of 'expensive' oil such as from the North Sea or Alberta. In this paper we focus on the first class.

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We investigate the mechanism in a simple model in which competitive coal and renewable energy firms compete with an oil monopolist to supply energy to electricity and vehicle sectors. We show that the presence of market power may lead not only to reduced overall welfare, but also higher long-run emissions, and that this is especially likely given the application of a Pigovian tax. In our static model, high oil prices let in dirty coal in the electricity generating sector, and emissions go up if the coal is sufficiently dirty, trumping the effect of higher prices (and lower oil consumption) in the vehicle sector. Our dynamic model includes oil scarcity and economic growth, which drives up both energy demand and the social cost of carbon. As in the static model, given a simple Pigovian tax OPEC's market power may let coal enter the electricity generating sector; however, in the dynamic model long-run emissions are then certain to increase relative to first best, where all coal remains underground.

In our welfare analysis we consider the following regulatory options: (i) a Pigovian tax alone; (ii) the tax plus an oil production subsidy; (iii) the tax plus a subsidy to renewables which forces the monopolist to lower prices to exclude the renewable alternative; and (iv) simply banning coal. Given a standard welfare function, both (ii) and (iii) deliver first best. However, under an alternative function in which rents and transfers accruing to the monopolist are counted as costs, the renewable subsidy policy comes close to first best whereas the oil production subsidy does not. Under a coal ban the path of fossil fuel use is closer to first best than under Pigovian taxation, but since market power is not dealt with welfare is still far from the first-best level.

The importance of market power in the oil sector is shown by a wide range of evidence. To quote Hassler et al. (2010) (p.460):

> Analyses of the world oil market that are based on perfect competition and a finite amount of oil typically predict (i) that the oil price satisfies the Hotelling rule, i.e., increases so that the rate of return on storing oil is equal to the return on the capital market, (ii) that oil consumption follows a decreasing path, and (iii) that extraction is sequential in the sense that sources with lower extraction costs are depleted before high-cost sources are used. All these predictions are problematic to reconcile with data.

Further to point (i), Hart and Spiro (2011) marshal evidence which contradicts the assumption of high scarcity rents in the oil sector.[1] Further to (ii), Hart (2016) shows how increasing consumption paths for non-renewable resources arise in general equilibrium with economic growth driven by technological progress, and heterogeneous resource stocks. And further to (iii), the simultaneous extraction of crude oil from the immense and easily accessible Ghawar field in Saudi Arabia, the North Sea, and the Athabasca oil sands of Alberta — with the Saudis in particular earning vast rents — is a clear demonstration of the presence of significant market power in the sector.[2] Asker et al. (2019) study the extent of this misallocation, showing convincingly that OPEC production costs are only a small fraction of the global oil price, while the margins of other producers (such as Nigeria) are close to zero, an observation which rules out scarcity as explaining the Saudi rents.[3]

Despite the seemingly obvious exercise of market power in the oil market, its implications for climate policy have received relatively little attention. There is a substantial literature on imperfect competition in the oil market, mainly with a homogeneous resource (oil) but with extraction costs varying between a low-cost cartel and a high-cost fringe; see for instance Groot et al. (2003) and Benchekroun et al. (2009). However, few of these papers include climate damages; exceptions include de Sa and Daubanes (2016) and Benchekroun et al. (2020). de Sa and Daubanes set up a monopoly–fringe model in which the oil monopolist sets the price at the limit to exclude the fringe, and test the effects of alternative policies. There is no social utility function or regulatory optimization problem, hence they do not consider optimal policy. Benchekroun et al. (2020) focus on the distorting effects of market power on the order of extraction of cheap and expensive resources. However, because their framework is stationary (in the sense that there is no growth or technological progress, and climate damages are linear in the stock) total extraction is fixed by construction.

Another strand of literature — where more attention is paid to climate policy — analyses competition between an oil monopolist and a clean backstop, with limit pricing often used by the monopolist, as in Hoel (1978). Hoel (1984) is related to our paper in that he analyses theoretically competition between multiple resource in differentiated markets (including the analysis of market power), and Wang and Zhao (2013) consider the case where a monopolist extracting a nonrenewable resource faces competition from a renewable perfect substitute with a capacity constraint and find that there will be limit pricing in equilibrium, while van der Meijden and Withagen (2019) find that with perfect substitutability between oil and a clean backstop there may be limit pricing, and whether or not this is the case will have important effects on the reaction of initial emissions in response to climate policy.

[1] If scarcity rents are substantial, why do prices not rise systematically and steeply (in accordance with Hotelling's model)? Hart and Spiro (2011) pose this question, and use very simple analysis to show that scarcity rents have been marginal historically, that they almost certainly do not dominate resource prices today and that, at the very least, there will be other factors shaping resource prices in the upcoming decades. They also discuss a range of earlier empirical literature — such as Heal and Barrow (1980) and Ellis and Halvorsen (2002) — in which the authors fail to find evidence for significant scarcity rents. Furthermore, Hart and Spiro argue that there is no reason to expect high scarcity rents for crude oil or coal anyway, due to a combination of the long time to exhaustion and the relatively modest expected price of the backstop resource at that time.

[2] Herfindahl (1967) showed that given perfect competition and perfectly substitutable resources, lower-cost resources will be extracted first. Subsequently there has been a lot of attention paid to the fact that resources may not be perfect substitutes globally, and this may lead to simultaneous extraction; see Gaudet and Salant (2015) for a recent review, and Chakravorty and Krulce (1994), Amigues et al. (1998), and Chakravorty et al. (2008) for examples focusing on heterogeneous demand, capacity constraints, and pollution respectively. However, none of these examples are plausible reasons for why (for instance) Saudi Arabian and Norwegian oil is extracted simultaneously. The indisputable reason for this is that Saudi Arabia (together with the rest of OPEC) restricts supply to drive up the price, and thereby it lets competitors with higher costs enter the market. Another indication of market power is the price discrimination practised by OPEC members: they typically charge their own citizens much less for oil than they charge buyers on the international market.

[3] Furthermore, in work in progress (*The welfare impact of market power — The OPEC cartel*) the same authors estimate the welfare impact of OPEC's market power to be 5 trillion USD, without including climate damages.

By contrast to the dearth of papers on implications for climate policy of market power in the fossil fuel market, there is a large literature on the implications of scarcity rents, despite the plentiful evidence, as discussed above, that scarcity rents are in fact small. For a thorough introduction to this 'green paradox' literature, see Jensen et al. (2015).[4] In this literature there is typically only one market failure, and the point is that arbitrary emissions tax paths might make things worse. To understand the mechanism, assume that oil is an essential input and the oil price is pure scarcity rent; then the oil price rises at the interest rate, and if the 'emissions tax' rises at the interest rate as well (typically presented as a 'constant ad valorem tax' in this literature) it will simply shift the rental income from the resource owners to the regulator without changing the extraction path. If the tax rises even faster than this then it will shift extraction towards the present, increasing damages. Theory tells us directly that in this set-up a Pigovian tax path will always deliver first best; and the resolution of the 'paradox' is that a Pigovian tax will typically be declining when measured ad valorem, but increasing per barrel. For instance, if we follow the baseline model of Golosov et al. (2014) then the Pigovian tax rises at the growth rate (their Proposition 1), which is lower than the interest rate. Of course, if we implement something other than a Pigovian tax then all sorts of effects may arise.[5]

In this paper we analyse optimal climate policy in an economy in which the social cost of carbon increases over time due to growth, as is standard in the literature (see e.g. Golosov et al., 2014) but not included by, for instance, Benchekroun et al. (2020). This growth is crucial to the link between the early extraction of coal and increases in total long-run emissions. Furthermore (and by contrast to de Sa and Daubanes, 2016) our focus is on welfare analysis, using both theoretical results and numerical simulations, and including second-best policy options. There are therefore links to many other literatures, including on how to make sure that coal remains in the ground (see for instance Harstad, 2012), strategic environmental policy (Liski and Tahvonen, 2004; Kagan et al., 2015; Jaakkola, 2019), and second-best policy when the only instrument is an emissions tax (pioneered by Barnett, 1980 and reviewed by Requate, 2006). Other related literature includes Coulomb and Henriet (2018) and Daubanes et al. (2020); Coulomb and Henriet show that optimal carbon taxation may raise the profits of competitive oil and gas owners, by penalizing the competition, while Daubanes et al. show that if global supply of a dirty input such as coal is sufficiently inelastic, if one country develops a cleaner alternative such as shale gas, global emissions may nevertheless increase.

The remainder of the paper is set out as follows. In Section 2 we develop a static two-sector model the purpose of which is to show conditions under which an oil monopolist may choose to sell to the vehicle sector alone, setting a limit price to exclude the cheapest alternative, while ceding the electricity sector to coal or renewables; we also perform policy analysis and simulations which prepare the ground for the dynamic model. We go on to present the full dynamic model in Section 3, solve it in Section 4, and perform numerical simulations in Section 5. Section 6 concludes.

2. A static, partial equilibrium model

We begin with a static version of the full dynamic model. In both models there are three alternatives for primary energy—namely oil, coal, and renewables—which are supplied to two intermediate energy sectors, vehicle power and electricity. The main purpose of the static model is to show how an oil monopolist may choose to sell to the vehicle sector alone, setting a limit price to exclude the cheapest alternative, while ceding the electricity sector to coal or renewables. We also see that the presence of market power can lead to higher emissions *ceteris paribus*, and that first best can be achieved either through a subsidy to oil, or (more cheaply for the regulator) through subsidies to renewables.

2.1. The static model

Aggregate production is a function of aggregate labour–capital A and energy E, as follows:

$$Y = \zeta A^{1/\eta} E^{1-1/\eta}, \tag{1}$$

where $\eta > 1$, $\zeta = \eta/(\eta-1)[\alpha/(1-\alpha)]^{1-\alpha(1-1/\eta)}/\alpha$ is a strictly positive constant introduced to yield a simpler demand function (see below). Energy E is a function of intermediate inputs of vehicle energy, V, and electricity, W:

$$E = V^{1-\alpha} W^{\alpha}. \tag{2}$$

Producers of both the energy composite E and final goods Y take input prices as given. Solving the profit maximization problems of both types of producers gives the demand functions for vehicle energy and electricity:[6]

$$V = A p_v^{-\epsilon} p_w^{-\delta} \tag{3}$$

and

$$W = \frac{\alpha}{1-\alpha} \frac{p_v}{p_w} V, \tag{4}$$

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[4] There are two sets of papers in this literature: the first set is from the 1990s, and focuses on how different paths of an *ad valorem* tax affect extraction of a resource the price of which is pure scarcity rent. For an example and further references see Ulph and Ulph (1994). The second set of papers is the 'green paradox' literature, including Sinn (2008), and can be seen as a revival of the previous literature.

[5] A paper from this literature with some relevance to ours is Michielsen (2014). Michielsen follows the green paradox tradition in focusing on scarcity rather than market power in the oil sector, but considers two alternative energy sources—coal and renewables—which are imperfect substitutes for oil. The conclusion is that the green paradox effect (increased short term emissions in response to stringent future climate policy) may be reversed if short run increases in oil uses reduce short run coal use.

[6] See Appendix A for the derivation.

where p_v and p_w are the prices of vehicle energy and electricity respectively, and where

$\epsilon = \eta - \alpha(\eta - 1)$ and $\delta = \alpha(\eta - 1)$.

Vehicle energy V and electricity W may be produced using oil, coal, or renewables, the quantities of which are denoted Q, C, and R (in energy units). The production functions are as follows:

$$V = Q_v + (C_v + R_v)/\beta$$
and
$$W = Q_w + C_w + R_w, \tag{5}$$

where $\beta > 1$. So the three types of energy are perfect substitutes in each sector, but coal and renewables are less suited to the transport sector, and are only competitive there when their prices are below the oil price (per energy unit) by a factor β.[7]

The markets for vehicle energy and electricity are competitive, hence we have

$$p_v = \min\{p_q, \beta p_c, \beta p_r\}$$
and
$$p_w = \min\{p_q, p_c, p_r\}, \tag{6}$$

where p_q, p_c, and p_r are the input prices. Later on we introduce a Pigovian emissions tax and production subsidies for oil and renewables; all are applied at the primary resource level, and the input prices p_q, p_c, and p_r are defined inclusive of them.

Oil, coal and renewables are extracted using the final good, and the unit extraction costs are x_q, x_c, and x_r respectively; all are constant, implying that all three primary inputs (oil, coal, renewables) are inexhaustible in this version of the model. Furthermore, each unit of fossil fuel i burnt leads to emissions of ϕ_i units of carbon to the atmosphere, where i may be c or q, and $\phi_c > \phi_q$. Letting G denote emissions, total emissions from sectors V and W are thus

$$G_v = \phi_q Q_v + \phi_c C_v \text{ and } G_w = \phi_q Q_w + \phi_c C_w, \tag{7}$$

and total private unit costs of each of the three inputs are $x_q + \phi_q\tau$, $x_c + \phi_c\tau$, and x_r, where τ is the tax per emitted unit of carbon. Hence the tax applies equally to all emissions but given the different emission intensities, it will be higher per unit of energy for coal. We assume a constant marginal external cost ψ per unit of emissions making the total social unit costs equal to $x_q + \phi_q\psi$, $x_c + \phi_c\psi$, and x_r. We use a dagger to denote socially optimal values, hence the Pigovian tax rate is given by $\tau^\dagger = \psi$.

Finally, coal and renewables are extracted competitively, hence priced at marginal cost, so

$$p_c = x_c + \phi_c\tau \text{ and } p_r = x_r - \sigma_r, \tag{8}$$

where σ_r is a subsidy to renewable energy production. By contrast, the stock of oil is owned by a single monopolist who (given the inexhaustible stock) sets the quantity of extraction to maximize profits, knowing the reaction of the competitive coal and renewables sectors; she is unable to price discriminate between the vehicular and electricity sectors.

2.2. Solution to the static model

We now solve for the allocation of resources in the static model, and concomitant emissions. We start with first best, then solve for the decentralized market equilibrium in the presence of possible emissions taxes τ and production subsidies to oil and renewables σ_q and σ_r. The solution in first best is straightforward, and is identical to the market allocation assuming competitive oil supply and Pigovian taxation. So prices of the primary energy inputs are equal to extraction costs plus marginal damages, and quantities given in Eqs. (3) and (4). Focusing on oil in particular we have

$$p_q^\dagger = x_q + \phi_q\psi. \tag{9}$$

In Fig. 1 we show the oil market in competitive equilibrium, both with and without Pigovian taxation. Competitive oil supply is given by its constant unit cost and the equilibrium is found at the intersection between the green supply curve and the red demand curve. In both cases, for our parameterization (discussed below) oil is used in both sectors and coal is the cheapest competitor.

Now consider the decentralized equilibrium allowing for the oil monopolist's ability to exercise market power and option to implement limit pricing, focusing on key results which build intuition for the dynamic model.[8] First define p_{-q} as the price of the cheapest alternative to oil, so (Eq. (8))

$$p_{-q} \equiv \min\{x_c + \phi_c\tau, x_r - \sigma_r\}. \tag{10}$$

Then note that depending on the price set by the monopolist, oil will be used in only sector V, in both sectors, or not at all. Of these three cases we are—for obvious reasons—mainly interested in the first two, which we define as follows.

[7] The vehicle sector should be thought of as including all sectors where oil has a clear advantage over coal and renewables relative to the electricity sector; hence it includes both automobiles and planes, and also feedstock to the chemical industry (see Marx, 2014 on competition between coal and oil in the latter sector). Regarding the assumption of perfect substitutability, note for instance the rapid transition away from oil in electricity generation starting in 1973, as described by Hawk and Schipper (1989). A similar rapid shift from oil to electricity is currently getting started in the vehicle sectors of many countries, although this is driven largely by factors other than a rise in the relative price of oil inputs.

[8] The general solution of the market model is presented in Appendix B.

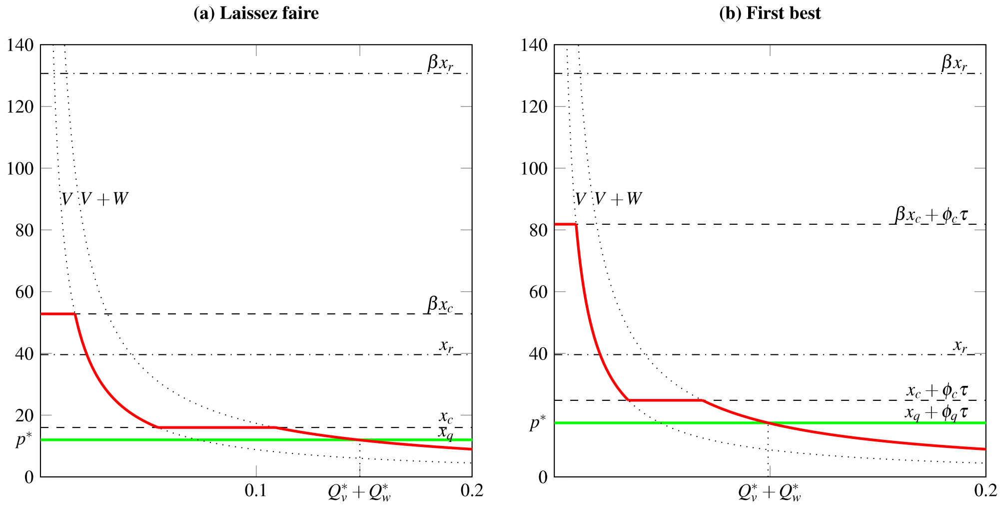

Fig. 1. Supply and demand for oil given competitive markets, in two cases: (a) laissez faire, and (b) first best. The light green and dark red lines represent supply and demand respectively, whereas the dashed and dot–dashed lines show supply of coal and renewables respectively, for the two markets (vehicle and electricity). The dotted lines show demand for oil from the vehicle market alone (assuming that the electricity market is supplied with the cheapest alternative in each case), and from both markets jointly (assuming no competition from other inputs). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Definition 1.

- Case I, $p_q \in (p_{-q}, \beta p_{-q}]$ oil is used only in sector V;
- Case II, $p_q \le p_{-q}$ oil is used in both sectors.

Demand Eqs. (3) and (4) imply that the monopolist's marginal revenue in the two cases is given by

$$MR_{q,I} = \frac{\epsilon - 1}{\epsilon} p_q \quad \text{and} \quad MR_{q,II} = \frac{\eta - 1}{\eta} p_q, \tag{11}$$

where $(\eta - 1)/\eta > (\epsilon - 1)/\epsilon = (\eta - 1)/\eta \cdot (1 - \alpha)/[1 - \alpha(\eta - 1)/\eta]$.

We are left with two questions. Firstly, will the oil monopolist cede the electricity sector to her competitors, or sell to both sectors? And secondly, will the monopolist's price be an interior solution or a limit price? We begin with the second question.

Lemma 1 (*Limit Pricing*)**.** *Define the marginal cost of oil production, $MC_q = x_q + \phi_q \tau - \sigma_q$. Then sufficient conditions for limit pricing are as follows, conditional on the monopolist selling a positive quantity in the sector V only (Case I) or in both sectors (Case II):*

$$\text{Case I,} \qquad MC_q > \beta \frac{\epsilon - 1}{\epsilon} p_{-q};$$

$$\text{Case II,} \qquad MC_q > \frac{\eta - 1}{\eta} p_{-q}.$$

Proof. Follows by setting marginal revenue in the two cases equal to marginal cost and determining when the resulting price lies outside the interval where the corresponding case applies. See Appendix B for details. □

To understand the importance of this lemma, note that $(\eta - 1)/\eta$ is the energy share, which is around 0.05, and $(\epsilon - 1)/\epsilon$ is strictly lower than the energy share. So for reasonable values of x_q, p_{-q}, and β (the disadvantage of coal and renewables in powering vehicles), the oil monopolist will always choose a limit-pricing strategy unless marginal costs are driven down by substantial production subsidies σ_q.

Now we return to the two cases: will the monopolist cede the electricity market to her competitors (Case I) or take both markets (Case II)? Given limit pricing, these alternatives boil down to (I) setting $p_q = \beta p_{-q}$ and selling only to the vehicle sector, or (II) setting $p_q = p_{-q}$ and selling to both sectors. Comparing the profits in the two cases (given in Eqs. (B.3) and (B.6)), we can derive conditions under which the monopolist chooses to supply only sector V or both sectors. The monopolist will choose to sell to only sector V (Case I) if

$$\frac{\pi_{q,I}^{LP}}{\pi_{q,II}^{LP}} = \frac{1 - \alpha}{\beta^{\epsilon}} \cdot \frac{\beta p_{-q} - MC_q}{p_{-q} - MC_q} > 1. \tag{12}$$

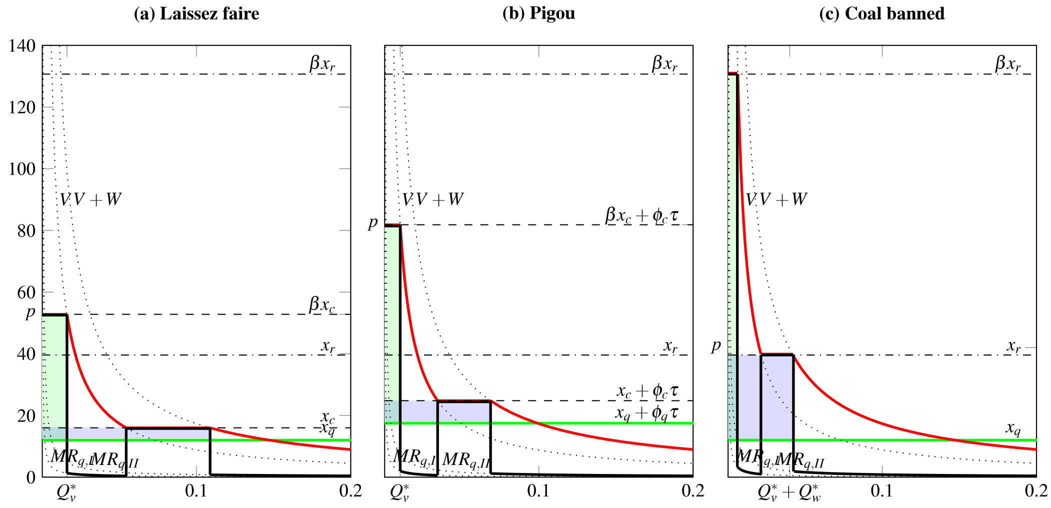

Fig. 2. Supply and demand for oil given an oil monopolist, in three cases: (a) Laissez faire; (b) Pigovian taxation; (c) Coal banned. Lines as in Fig. 1, plus lines showing marginal revenue: the dotted lines $MR_{q,I}$ and $MR_{q,II}$ show MR assuming an interior solution, and the thick black lines show actual MR in the presence of competition. The optimal prices and quantities p^* and Q^* maximize net revenue, in the first two cases through limit pricing and focusing on the vehicle market, which we can see is optimal because the light green area is larger than the darker blue area; in the third case, when coal is banned, the oil monopolist takes both markets (blue area larger). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Profits $\pi_{q,I}^{LP}$ and $\pi_{q,II}^{LP}$ are illustrated in Fig. 2, in laissez faire (2a), under Pigovian taxation (2b), and when coal is banned (2c).[9] We can see by inspection that for our choice of parameters strategy I gives higher profits in the first two cases, whereas strategy II dominates when coal is banned. The figure also illustrates the optimality of limit pricing. For sake of intuition, focus on laissez faire and assume that the monopolist focuses only on the vehicle sector. In the absence of competition, the oil monopolist would set quantity where $MR_{q,I}$ crosses x_q, leading to a very small quantity and a very high price. Since this price is higher than p_{-q}, in the presence of competition the monopolist sets the highest price compatible with excluding this competition. To induce an interior solution we must reduce $x_q - \sigma_q$ to close to zero in the figure.

2.3. Policy, welfare, and emissions

Assuming a standard welfare function (more on this shortly) there are two market failures in the static model: the costs of emissions are external and the oil supplier has monopoly power. We would thus in general expect two policy instruments to be needed to implement the first best outcome. We assume that the first market failure is addressed using Pigovian taxation so that $\tau = \tau^\dagger = \psi$. With regard to the second, various alternatives are available, the most obvious of which is a subsidy σ_q to oil production. In addition to this option, we show how subsidies $\sigma_{r,v}$ and $\sigma_{r,w}$ to use of renewable energy may also deliver first best.

Lemma 2. *Necessary conditions on optimal production subsidies to oil—in addition to a Pigovian tax $\tau^\dagger = \psi$—are as follows in the respective cases, i.e. if the social optimum involves oil to only the vehicle sector (Case I) or to both sectors (Case II):*

$$\text{Case I, } \sigma_q^\dagger = \frac{x_q + \phi_q \tau^\dagger}{\epsilon}; \qquad \text{Case II, } \sigma_q^\dagger = \frac{x_q + \phi_q \tau^\dagger}{\eta}. \tag{13}$$

Proof. At an interior market solution we have $MR_{q,I} = MC_q$ and $MR_{q,II} = MC_q$ in the respective cases, where $MR_{q,I}$ and $MR_{q,II}$ are given by Eq. (11), and $MC_q = x_q + \phi_q \tau - \sigma_q$. Put these together and solve for $p_q = p_q^\dagger$ (Eq. (9)) to find $\sigma_q^\dagger$ in each case. □

Proposition 1. *Sufficient conditions for a social optimum are the application of the subsidies in Lemma 2, and furthermore that the higher subsidy payment in Case I is only paid to oil sold to the vehicle sector.*

Proof. For some parameter values, when the social optimum is Case I the appropriate subsidy (Eq. (13)) will incentivize the monopolist to sell to both sectors. Hence the additional condition that the subsidy is only paid to oil sold to the vehicle sector. See Appendix C for details. □

[9] See Hoel (1984) Fig. 2 for a related construction with linear demand.

Note that $1/\eta$ is one minus the income share of energy, which is about 5 percent, and $1/\epsilon$ is even larger. Hence the optimal subsidy is around 95 percent of the price, and the policy involves huge transfers to an agent who already benefits from a vast flow of monopoly rent. In a standard welfare-maximization according to the Kaldor–Hicks criterion — focusing on allocation of productive resources, not distribution — this fact is irrelevant. However, in reality transfers to the super-rich oil monopolist are likely to be seen as undesirable. To quantify this idea, we complement our standard welfare calculations with a welfare measure in which such transfers are pure losses.[10] Then the oil subsidy does not result in first best, but there is an alternative instrument that delivers first best according to both welfare criteria: to subsidize renewables, driving down p_{-q} hence driving down the oil price under limit pricing.[11]

Proposition 2. *An alternative method of achieving a Pareto-optimal allocation is by — in addition to a Pigovian tax $\tau^\dagger$ — ensuring that if it is socially optimal to use oil in a given sector, the private cost of using renewables in that sector is equal to the social cost of oil, hence forcing the monopolist to set the socially optimal price in order to compete. This implies the following sector-specific subsidies to renewables, to be offered only if renewables are not used on the socially optimal path in the relevant sector:*

$$\sigma^\dagger_{r,v} = x_r - \frac{x_q + \phi_q \tau^\dagger}{\beta} \text{ and } \sigma^\dagger_{r,w} = x_r - x_q - \phi_q \tau^\dagger. \tag{14}$$

Proof. The private cost of renewables in the respective sectors is $\beta(x_r - \sigma_{r,v})$ and $x_r - \sigma_{r,w}$, and the social cost of oil is given by Eq. (9). The result follows directly. □

Renewables are less competitive in the vehicle sector, explaining why the renewables subsidy is larger in the vehicle sector than the electricity sector; this could be achieved through a subsidy both to the generation of electricity using renewables, and to the use of electricity in the vehicle sector. Note that since the subsidies are only offered where oil is ultimately chosen, no subsidy payments are actually made.[12]

The focus of economists' efforts to influence climate policy has been the imposition of a (Pigovian) carbon tax. However, we know that a regulatory regime that corrects one externality (emissions) but not the other (market power) will lead to lower welfare than first best, and could even reduce welfare compared to laissez faire. We investigate this in the next section. Furthermore, given the difficulties involved in applying Pigovian taxes (and dealing with market power) we also consider the conceptually simple option of banning coal use.

Welfare effects are our central focus, but we are also interested in the effects of alternative policies on the flow of emissions in isolation: could an economy with uncorrected market power in the oil sector suffer from higher emissions than the same economy where the distortions from market power have been corrected, despite the intuition that 'the monopolist is the conservationist's friend'? The answer is yes. Market power in the oil sector will increase energy prices in general and hence lead to lower overall energy use, which will tend to decrease emissions. However, since coal causes more emissions per unit of energy, if the reduced oil supply leads to coal being used instead of oil in the electricity sector, the net effect becomes ambiguous. The case where emissions can potentially increase due to market power in this static setting is thus when the monopolist chooses to supply only sector V (see Eq. (12)), and where coal is cheaper than renewables (i.e. $x_c + \phi_c \tau < x_r$).[13]

In the dynamic setting we will see that the range of cases is much larger, due to distortions to the order of extraction.

2.4. Numerical simulations

We now turn to the parameterization of the static model, which is behind Figs. 1 and 2, and which we also use to further investigate the welfare effects of different regulatory regimes. The parameter choices, with brief explanations, are summarized in Table 1.[14] Three parameters merit further discussion: α, β, and x_c. Firstly, α, the balance between sectors V and W. We have denoted these sectors 'vehicle' and 'electricity', but the key distinction is that in the first sector oil has an inbuilt advantage over other energy

[10] This downgrading of producer surplus is common in the literature on regulation under asymmetric information; see for instance Caillaud et al. (1988). For clarity we choose the extreme case of zero weight, which could be justified formally through a welfare function in which social returns to increasing wealth of an individual are a decreasing function of the wealth of that individual. For instance, we could assume that (when compared to a fixed individual i, wealth w_i) returns to increasing wealth of individual j approach zero as w_j approaches infinity.

[11] We thank an anonymous reviewer for suggesting this policy option.

[12] If it is not possible to differentiate the subsidy between the sectors, the optimum could be implemented by setting the general subsidy to $\sigma_{r,v} = \sigma_{r,w} = x_r - x_q - \phi_q \psi$ and complementing this policy with an oil subsidy that induces the monopolist to sell to both sectors. In this case a subsidy would need to be paid out, but it would typically be lower than the oil subsidy required without a renewables subsidy.

[13] The condition for an actual emissions increase when moving from competitive pricing to market power with limit pricing — given that inequality (12) holds and that $x_c + \phi_c \tau < x_r$ — is that

$$\frac{(1-\alpha)\phi_q + \alpha\beta\phi_c}{\phi_q} > \beta^\epsilon \left(\frac{x_c + \phi_c \tau}{x_q + \phi_q \tau}\right)^\eta,$$

a condition which applies both in laissez faire (when $\tau = 0$) and under Pigovian taxation (when $\tau = \tau^\dagger = \psi$).

[14] Note that we use units of barrels of oil equivalent for energy, and 2020 USD for money. The extraction cost of oil is based on an estimate of 10 from Asker et al., updated to 2020 USD.

Table 1
Parameter choices, with brief explanations.

α	0.5	Vehicle and electricity sectors equally large.
η	1.05	Energy share ≈ 5 percent.
ψ	1	Normalized.
ϕ_q	5.5	Damages 5.5 USD/boe, i.e. ≈ 47 USD/ton carbon (i.e. 'Nordhaus' damages).
ϕ_c	$1.6\phi_q$	Emissions greater than from oil by factor 1.6.
x_q	12	Estimate, per boe, based on Asker et al. (2019) Fig. 3.
x_c	16	Estimate, per boe, based on BP Statistical Review of World Energy 2020.
x_r	$3.3x_q$	Renewables costs significantly above oil extraction costs.
β	3.3	Renewables and coal expensive for vehicles.

Table 2
Welfare gains from alternative instruments, as a percentage of the welfare gain from first-best regulation, and emissions falls from regulation in percent.

	Welfare gain from regulation (percent of max)		Emissions flow remaining after regulation (percent)
	Standard welfare function	Adjusted welfare function	
Laissez faire	0	0	100
Naive Pigou	−24	−13	63
Ban coal	40	−14	42
Pigou + σ_q	100	−16	99
Pigou + σ_r	100	100	99

sources, as for road vehicles, aeroplanes, and also in the chemical sector.[15] Based on EIA expenditure data we assume that these two sectors are equally large, hence the choice of α. However, note that the choice is somewhat arbitrary given the stylized nature of the model. Turning to β, the size of this parameter is the answer to the question of how much more expensive it would be to run a vehicle on electricity generated from (for instance) coal, rather than on petrol from oil, given that the costs of the primary inputs (per unit of energy) were equal. Again the answer is somewhat arbitrary since the real-life trade-offs are about both cost and performance (e.g. range), and differ between transport modes (passenger cars/trucks/aeroplanes). However, the fact that electricity still cannot compete in its most favourable market (private cars) without fossil taxes and electric subsidies—despite the fact that the oil price is around 5 times higher than coal (per unit of energy)—suggests that a value for β of 3.3 is conservative. Finally, stating a single, constant unit cost for renewable energy is also a bold simplification. Since renewables are approximately competitive with coal when factoring in pollution damages, we could assume $x_r = x_c + \phi_c\psi = 2.1x_q$. However, we set x_r higher since renewables also involve costs linked to uncertainty of supply.[16]

To study the welfare effects we measure how well our second-best instruments perform compared to first-best, following for instance Hart (2019). Given a standard welfare criterion, this implies that we compare the welfare improvement from Pigovian taxes alone with the effect of Pigovian taxes combined with subsidies to correct for the effects of market power. Given the alternative welfare criterion in which transfers to the oil monopolist are social costs, we compare two regulatory regimes—both Pigovian taxation alone, and Pigovian taxation combined with oil production subsidies—with first best in which no rents or transfers accrue to the monopolist, which can be achieved through a combination of Pigovian taxation and differentiated subsidies to renewable production. The results are shown in Table 2.

In Table 2 we see that Pigovian taxation alone is bad for welfare in the static model—according to both welfare criteria—because it increases the market power of the oil monopolist in the vehicle market. It does, however, lead to significant emissions reductions as fuel prices rise significantly in both markets. Banning coal is better for welfare since prices actually fall in the vehicle market since the oil producer opts to take both markets, while coal being pushed out also leads to a substantial drop in emissions; however, welfare actually declines according to the alternative criterion, because transfers to the monopolist increase enormously, as can be seen from Fig. 2. As expected, subsidizing the oil producer yields first best according to the standard criterion, but is disastrous according to the adjusted criterion, whereas the renewable subsidy is optimal according to both criteria; emissions are almost unchanged as the price fall in the vehicle sector outweighs the effect of the shift out of coal (and price rise) in the electricity sector.

3. The dynamic general equilibrium model

We now present the full dynamic general-equilibrium model. All the equations of the static model apply also to the full model. The difference lies in extensions: we introduce both a finite stock of oil and an atmospheric stock of carbon, and we allow many of the parameters of the static model to vary over time. More specifically we include exogenous productivity growth, declining unit costs of renewable energy production, and a decline in β, the handicap facing coal and renewables in the vehicle sector.

[15] For vehicles mobile energy is required and batteries are expensive and have low energy-density, whereas in the chemical sector oil is an ideal feedstock for production of other compounds including plastics.

[16] The correct size of this cost premium is in practice an increasing function of the scale of renewable production in relation to readily controllable sources; with today's low levels of renewable production it is lower. See for instance IEA (2020).

3.1. Aggregate production and utility

We use the same production functions (1), (2) and (5) as in the static model with the difference that A and β now are time varying. In particular, we assume that their time paths are

$$A(t) = A_0 e^{gt} \text{ and } \beta(t) = \bar{\beta} + [\beta(0) - \bar{\beta}]e^{-kt}.$$

The growth of A is intended to capture a combination of increasing productivity and capital stock. The time path of β is motivated by the technology initially being immature, giving a relatively large productivity gap; as is clear by inspection of the equation above, as time passes the technology matures and costs level off.[17]

Utility is a function of aggregate production and the stock of pollution S. Ideally we would assume (following Nordhaus, 2008; Golosov et al., 2014, and many others) that a given level of pollution would cause the loss of a given proportion of production or utility, hence for instance $U = \int_0^\infty e^{-\rho t} \log\{[Y(t) - X(t)]F(S(t))\}\mathrm{d}t$, where $X(t)$ is the quantity of final goods sent to the energy sector,[18] F is a decreasing function and $F(0) = 1$, and ρ is the pure rate of time preference. However, for simplicity we assume instead utility

$$U = \int_0^\infty e^{-\rho t}[Y(t) - X(t) - A(t)F(S(t))]\mathrm{d}t, \tag{15}$$

where F is an increasing function and $F(0) = 0$, and ρ is the discount rate. As long as $Y - X$ and A grow at almost equal rates (implying that fluctuations in energy availability do not exert a major influence on the growth rate) then the two formulations are approximately equivalent. The latter is much simpler because it implies that damages are a straightforward function of pollution and A (which is exogenous). Furthermore, we assume that damages are a linear function of S, that S is equal to cumulative carbon emissions, and that there is a constant exogenous discount rate (the pure rate of time preference) ρ. These assumptions are broadly in line with (although much simpler than) models such as DICE (Nordhaus, 2008) and many others, in which damages are approximately linear in S, and S is closely linked to cumulative emissions.[19]

Given the above assumptions we can write

$$u(t) = Y(t) - X(t) - \tilde{\psi} A_0 e^{gt} S(t),$$

and

$$U(t) = \int_t^\infty e^{-\rho t} \left(Y(t) - X(t) - \tilde{\psi} A_0 e^{gt} S(t)\right) \mathrm{d}t,$$

where $\tilde{\psi}$ is a positive parameter, A_0 is initial labour–capital, and $U(t)$ is discounted total utility at time t. Since $\dot{S}(t) = G(t)$, where $G(t)$ is carbon emissions, the marginal social cost of emissions at time t is then as follows:

$$-\frac{\partial U(t)}{\partial G(t)} = \frac{\tilde{\psi} A_0}{\rho - g} e^{gt},$$

and we can define

$$\tau^\dagger(t) = \psi e^{gt}, \tag{16}$$

where $\psi = \tilde{\psi} A_0/(\rho - g)$. Hence the marginal social cost of emissions grows at the growth rate g.

3.2. The two energy sectors

Since the production functions (5) remain valid, the prices (6) still apply. Furthermore, the prices (8) are also still valid but the unit production cost of renewables x_r and the tax τ are assumed to change over time. The cost x_r is assumed to approach a limit of $\bar{x}_r$, with the current cost being $x_r(t)$. As in the case of β above, because this technology is immature the gap between the two is assumed to decline at a constant exogenous rate h, so $x_r(t) = \bar{x}_r + [x_r(0) - \bar{x}_r]e^{-ht}$. On the other hand, the unit production costs of oil and coal are assumed constant in the benchmark model (up to the exhaustion of the stocks) at x_q and x_c.[20] We assume both that $x_q < x_r(0)$ and that $x_c < x_r(0)$, so fossil fuels are used at $t = 0$ in both sectors in a perfect market without pollution damages or scarcity. The definitions and equations for input costs are summed up in Table 3.

4. Solving the model

We now solve the model. Or—more accurately—we derive the key equations which determine the solution to the model. We cannot derive the qualitative properties of the solution without a numerical specification, because the general solution includes discrete switches between inputs, and also potentially switches between interior solutions and limit pricing.

The intratemporal equilibrium is the same as in the static model, hence demand for V and W is given by (3) and (4), and the problem is to analyse supply. We start with the Pareto-optimal solution. Next we introduce market power and find the market solution as a function of the tax path imposed by the regulator; the laissez-faire allocation is then obtained trivially by setting the tax to zero at all times. Finally we investigate optimal regulation by comparing the regulated market solution with first best. We assume that oil will be exhausted in all cases.

[17] See Hart (2019) for theoretical and empirical support for this approach.

[18] Hence $X(t) = x_q Q + x_c C + x_r R$

[19] Note that for the welfare analysis below we assume, without loss of generality, that $S(0) = 0$.

[20] For theoretical and empirical support for this assumption see Hart (2016).

Table 3
Summary of definitions and equations for input costs.

	Oil	Coal	Renewables
Unit costs of primary inputs	x_q	x_c	$x_r(t) = \bar{x}_r + (x_r(0) - \bar{x}_r)e^{-ht}$
Damage costs per unit	$\phi_q \psi e^{gt}$	$\phi_c \psi e^{gt}$	0
Unit cost of W, market	$x_q + \phi_q \tau(t)$	$x_c + \phi_c \tau(t)$	$x_r(t)$
Unit cost of V, market	$x_q + \phi_q \tau(t)$	$\beta(t)(x_c + \phi_c \tau(t))$	$\beta(t) x_r(t)$
		$\beta(t) = \bar{\beta} + (\beta(0) - \bar{\beta})e^{-kt}$	

4.1. The Pareto-optimal solution

By the first welfare theorem, a market equilibrium with perfect markets will be identical to the social planner's Pareto-optimal solution. In such an equilibrium, prices p_c and p_r will simply be equal to unit costs including damage costs, $x_c + \phi_c \psi e^{gt}$ and $x_r(t)$.[21] Given that $p_{-q}(t)$ is the price of the cheapest alternative to oil, we now define $p^{\dagger}_{-q}(t)$ as the corresponding social cost:

$$p^{\dagger}_{-q}(t) = \min\{x_c + \phi_c \psi e^{gt}, x_r(t)\}.$$

And the social cost of oil (the sum of extraction cost, damage cost, and scarcity rent) is

$$p^{\dagger}_q(t) = x_q + \phi_q \psi e^{gt} + \mu e^{\rho t}, \tag{17}$$

where μ is the unique rent such that when oil is exhausted its price is equal to the cheapest alternative in the vehicle sector, $\beta p^{\dagger}_{-q}(t)$.[22]

4.2. Monopolistic oil supply

With monopolistic oil supply, the oil monopolist solves a dynamic profit maximization problem given by

$$\max_{p_q(t)} \int_0^{\infty} e^{-\rho t} \left[p_q(t) - x_q - \phi_q \tau(t) + \sigma_q(t)\right] Q[p_q(t), t] \, dt \text{ s.t. } \int_0^{\infty} Q(t) \, dt \leq S_q(0),$$

where $Q[p_q(t), t]$ is the total demand for oil at time t given that the oil monopolist sets price p_q. Oil demand is the same as in the static model. Since coal and renewables are supplied competitively, the price of the potential alternative to oil is given by $p_{-q}(t)$, analogously to the static model (Eq. (10)). The Hamiltonian of this problem is

$$\mathcal{H} = e^{-\rho t} \left[p_q(t) - x_q - \phi_q \tau(t) + \sigma_q(t) - e^{\rho t} \lambda\right] Q[p_q(t), t],$$

where λ is the shadow value of the remaining stock of oil, which is constant since $\partial \mathcal{H} / \partial S_q = -\dot{\lambda} = 0$. Maximizing the Hamiltonian with respect to p_q, at a given t, is the same problem as maximizing profit in the static model (as in Appendix B) where the private per unit cost of the oil producer, $MC_q(t)$, now includes the scarcity rent:

$$MC_q(t) = x_q + \phi_q \tau(t) - \sigma_q(t) + e^{\rho t} \lambda. \tag{18}$$

At each point in time, the monopolist chooses the supplied quantity $Q(t)$ to maximize $\mathcal{H}$:

$$p^*_q(t) = \arg\max_{p_q(t)} \left[p_q(t) - x_q - \phi_q \tau(t) + \sigma_q(t) - e^{\rho t} \lambda\right] Q(p_q(t)). \tag{19}$$

As in the static case, this maximization may yield an interior solution or limit pricing with oil used in both sectors or just in sector V. If $x_q + \phi_q \tau(t) - \sigma_q(t) + e^{\rho t} \lambda > \beta x_{-q}(t)$ it is optimal to not supply any oil. Over time, the solution will typically switch between the different cases. However, Lemma 1 from our static analysis shows that the privately optimal choice will almost always be limit pricing as long as regulation does not correct for market power. (In first best there will of course never be limit pricing.)

4.3. Optimal regulation

In this section we show how a regulator can implement first best under our standard welfare criterion, through Pigovian taxation combined either with differentiated oil production subsidies or differentiated renewable subsidies.[23] In both cases, policy should be set to induce the monopolist to set the oil price equal to the social cost including the scarcity rent μ from the planner's problem at each point in time, i.e. $p_q(t) = p^{\dagger}_q(t)$ (Eq. (17)), corresponding to the solution of the monopolist's intratemporal maximization in (19).

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[21] We formally set up the first best optimization problem and derive the optimality conditions in Appendix D.

[22] If oil is never exhausted, $\mu = 0$. Note also that when $p^{\dagger}_q(t) \leq p^{\dagger}_{-q}(t)$, $Q_v = V$ and $Q_w = W$; when $p^{\dagger}_{-q}(t) < p^{\dagger}_q(t) < \beta p^{\dagger}_{-q}(t)$ then $Q_v = V$ and $Q_w = 0$; and when $p^{\dagger}_q(t) > \beta p^{\dagger}_{-q}(t)$ then $Q = 0$.

[23] The other cases of interest — laissez faire and naive Pigovian taxation — are both trivial to implement, requiring (respectively) no policy instruments, and an emissions tax ψe^{gt} per unit of emissions.

Proposition 3. *Analogous to the static model (Proposition 1), a Pareto-optimal allocation can be achieved by—in addition to a Pigovian tax $\tau^\dagger = \psi e^{gt}$—committing*[24] *to apply the following rules to determine the production subsidy to oil:*

$$\sigma_q^\dagger(t) = \begin{cases} \frac{1}{\eta}\left(x_q + \phi_q \tau^\dagger\right) - \frac{\eta-1}{\eta}\mu e^{\rho t} & \textit{when } p_q^\dagger(t) \le p_{-q}^\dagger(t), \textit{ Case II,} \\ \frac{1}{\epsilon}\left(x_q + \phi_q \tau^\dagger\right) - \frac{\epsilon-1}{\epsilon}\mu e^{\rho t} & \textit{when } p_{-q}^\dagger(t) < p_q^\dagger(t) \le \beta p_{-q}^\dagger(t), \textit{ Case I,} \\ -\mu e^{\rho t} & \textit{when } p_q^\dagger(t) > \beta p_{-q}^\dagger(t). \end{cases} \tag{20}$$

In Case I the subsidy is only paid to oil sold to the vehicle sector. This solution is one of a continuum of related solutions along which the share of the surplus going to the oil monopolist varies, and is the solution in which this surplus is minimized.

Proof. At an interior market solution we have $MR_{q,I} = MC_q$ and $MR_{q,II} = MC_q$ in the respective cases, where $MR_{q,I}$ and $MR_{q,II}$ are given by a time-varying version of Eq. (11), and MC_q is given by Eq. (18). Put these together and set $p_q = p_q^\dagger$ to find the following conditions for $\sigma_q^\dagger$ in each case:

$$x_q + \phi_q \tau(t) - \sigma_q^\dagger(t) + \lambda e^{\rho t} = \begin{cases} \frac{\eta-1}{\eta} p_q^\dagger(t) & \text{when } p_q^\dagger(t) \le p_{-q}^\dagger(t) \text{ i.e. Case II,} \\ \frac{\epsilon-1}{\epsilon} p_q^\dagger(t) & \text{when } p_{-q}^\dagger(t) < p_q^\dagger(t) \le \beta p_{-q}^\dagger(t) \text{ i.e. Case I.} \end{cases}$$

There is a continuum of combinations of λ, $\tau(t)$ and $\sigma_q(t)$ that fulfil these conditions: we could start from any $\lambda \ge 0$ and then find time paths of τ and σ_q that fulfil the conditions for all t. To obtain the first two conditions in the proposition set $\tau = \tau^\dagger$ and $\lambda = 0$, and substitute for $p_q^\dagger$ using (17). Finally, the regulator must (credibly) announce a tax of $\mu e^{\rho t}$ which applies on any oil sold after the time at which oil is (optimally) exhausted. As in the static model (Proposition 1), it is necessary to restrict the higher (Case I) subsidy to oil sold to the vehicle sector in order to rule out the possibility of the monopolist raising profits by taking the higher subsidy and selling to both sectors. □

The optimal subsidy $\sigma_q^\dagger(t)$ is made up of two terms, the second subtracted from the first (on the last row, the first part is multiplied by zero). The first term compensates for the monopolist's incentive to sell oil at a markup; it is proportional to the monopolist's costs (excluding scarcity) and will thus increase as these costs increase due to the Pigovian tax. The second term (which is subtracted) increases over time at the discount rate in order to account for the growing current-value scarcity rent $\mu e^{\rho t}$; it therefore encourages the monopolist to bring forward extraction. Since $\rho > g$, the growth rate of the second term will be higher than that of the first term. After the time of optimal exhaustion of oil, the second term remains in order to ensure that the monopolist cannot profit from saving oil beyond this time.[25]

Proposition 4. *Analogous to Proposition 2, an alternative way to achieve a Pareto-optimal allocation is to use—in addition to a Pigovian tax—sector-specific subsidies to renewables, to be offered only during the periods when renewables are not used in the relevant sector:*

$$\sigma_{r,v}(t) = x_r(t) - \frac{x_q + \phi_q \psi e^{gt} + \mu e^{\rho t}}{\beta} \textit{ and } \sigma_{r,w}(t) = x_r(t) - x_q - \phi_q \psi e^{gt} - \mu e^{\rho t}. \tag{21}$$

Proof. The private cost of renewables in the respective sectors is $\beta(t)[x_r(t) - \sigma_{r,v}(t)]$ and $x_r(t) - \sigma_{r,w}(t)$, and the social cost of oil is given by Eq. (17). The result follows directly. □

As in the static model, a regulator can force the monopolist to lower the oil price by offering a subsidy to renewable energy, although in equilibrium no subsidies will actually need to be paid out. Again, the goal is to induce the oil price $p_q(t) = p_q^\dagger(t)$. Initially, this will (by assumption) induce oil to be used in both sectors. There follows a period during which oil should be used in the vehicle sector but not in the electricity sector; in this period renewables should only be subsidized in the vehicle sector. After that period, oil should not be used at all and no subsidies are required.

4.4. Welfare and emissions

As in the static model, we measure the welfare effects of alternative regulatory regimes—naive Pigou, banning coal, Pigou plus oil subsidies, and Pigou plus renewable subsidies—on a scale of 0 (laissez faire) to 100 (first best). Under the standard welfare criterion we are interested in utility U as defined in Eq. (15), whereas under our alternative welfare measure—excluding payments to the monopolist over and above compensation for costs—we have

$$U^A = U - \int_0^\infty e^{-\rho t} \left[p_q(t) + \sigma_q(t) - \tau(t)\phi_q - x_q\right] Q(t) \mathrm{d}t. \tag{22}$$

We also remain interested in emissions in isolation, and in particular whether carbon emissions might be higher under naive Pigovian taxation rather than optimal climate policy, implying that market power drives emissions up *ceteris paribus*. Recall that in

[24] Note that problems of commitment and time consistency may arise in a policy problem involving two agents who can act strategically, in this case the regulator and the monopolist. Since such issues are beyond the scope of this paper we simply assume that the regulator can commit to a policy path from $t = 0$.

[25] Note that the subsidy at any point in time is given by the same expression but with different parameter values. Setting η on the first row or ϵ on the second row to infinity gives the expression on the last row. The parameter thus changes values at points in time where there is a switch between used energy sources in some sector. At such points, the subsidy makes a discrete jump.

Table 4
Additional parameter choices, with brief explanations.

$x_r(0)$	$3.3x_q$	Renewables significantly more expensive at $t = 0$
$\bar{x}_r$	x_q	Renewables very cheap in long run
$\beta(0)$	3.3	Renewables and coal initially expensive for vehicles
$\bar{\beta}$	2	Lower cost of renewables for vehicles in long run
g	0.02	2 percent overall annual growth rate
h	0.03	3 percent annual reduction in gap between long-run and current renewable costs
k	0.03	3 percent annual reduction in gap between long-run and current 'penalty factor' β.
ρ	0.05	5 percent annual interest rate
$A(0)$	1	Normalized

the static model, market power raises emissions if (i) it causes a shift from oil to coal; and (ii) the rise in emissions flows due to coal's dirtiness outweighs the decline due to the overall rise in energy prices. In the dynamic model we are interested in total emissions over time, and the conditions for an increase differ substantially. For simplicity we focus on the following sufficient conditions, which we phrase in general terms in the following two remarks.

Remark 1. Assume an economy with two fossil-fuel stocks F_1 and F_2, with different characteristics. Then the following two conditions are sufficient for overall emissions to be higher under some sub-optimal climate policy P_2 than under optimal climate policy P_1: (i) the stock of F_1 is exhausted under both policies, P_1 and P_2; (ii) use of F_2 is greater under sub-optimal policy P_2 than in first best, P_1.

Remark 2. Assume that F_2 is a mature technology with constant costs in laissez faire. Then it will become less competitive over time relative to clean alternatives under either of the following two conditions: (i) clean costs are declining, which is expected as these technologies are immature; or (ii) the price of carbon emissions increases over time, which is optimal in a growing economy according to standard assumptions.

Together, Remarks 1 and 2 show that a policy or market failure that encourages early extraction of an expensive resource is likely to increase total long-run emissions. In terms of our model, the conditions in Remark 1 will be satisfied if oil is always exhausted, coal is not used in first best, but coal is used under naive Pigou because the monopolist cedes the electricity market to the cheapest competitor, which (for t below some critical level) is coal. Coal is not used under first best because by the time oil is phased out of the electricity sector, renewables are cheaper. Remark 2 shows that a key factor behind the result is the distortion to the order of extraction. When oil is exhausted at time T, the cheapest competitor may be renewables, but when the oil monopolist lets in competitors at $t = 0$ the cheapest competitor may be coal. The general phrasing of the remarks reminds us that they are also applicable to situations in which rival owners of oil stocks (e.g. OPEC, Norway, and Canada) compete with one another oligopolistically.

5. Numerical simulations

We now simulate the model numerically in order to test the welfare effects of alternative policies.[26] The choices of the remaining parameters, with brief explanations, are summarized in Table 4 (recall Table 1 above).

5.1. First best

We illustrate the unit costs of the inputs, in the respective sectors, in Fig. 3. There we see (panel (a)) that the private costs of electricity generation from oil and coal are constant and approximately equal, whereas renewable costs start high and decline. However, the social costs of coal and oil (panel (b)) are both increasing due to increasing damages driven by growth, and furthermore coal costs are much higher due to coal's greater emissions. The story is similar in the vehicle sector, but there oil has a big initial advantage compared to coal and renewables. Renewables however gradually catch up due to their price decrease over time, combined with the increase in damages associated with oil use. Note that we ignore exhaustion (and hence scarcity rent) throughout in the figure.

If we continue to assume that scarcity is not a factor (equivalent to assuming that oil use is abandoned before stocks run out), then the first-best allocation of primary energy can be read off directly from Fig. 3. In the electricity sector (panel (b)), oil will be used initially, and then (around year 20) there will be a transition to renewables. In the vehicle sector the pattern is the same, but the transition occurs after around 70 years. The equations which must be satisfied at these transition points are as follows.

Oil to renewables, W: $$x_q + \psi\phi_q e^{gt} = \bar{x}_r + (x_r(0) - \bar{x}_r)e^{-ht}.$$

Oil to renewables, V: $$x_q + \psi\phi_q e^{gt} = [\bar{\beta} + (\beta(0) - \bar{\beta})e^{-kt}][\bar{x}_r + (x_r(0) - \bar{x}_r)e^{-ht}].$$

[26] The algorithms used in the simulations are described in Appendix E.

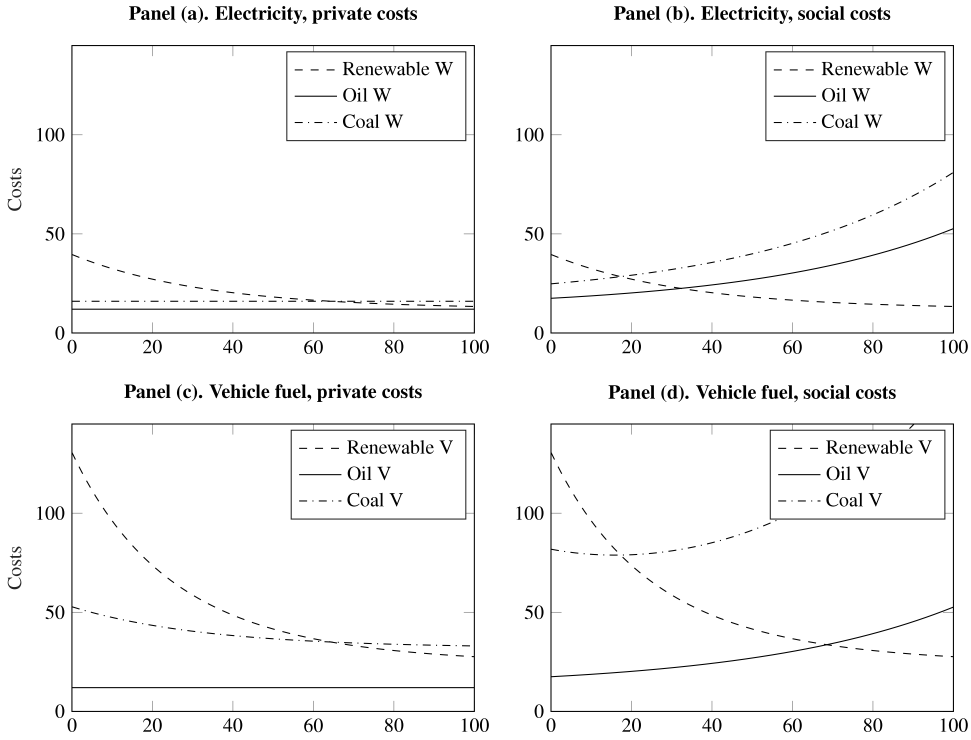

Fig. 3. Private and social costs of producing the intermediate energy inputs, electricity and vehicle fuel, as a function of the choice of primary input. Note that the scarcity rent of oil is not included since this varies between scenarios.

However, in our benchmark model we assume that oil stocks do run out, after 40 years given first-best resource allocation. The transversality condition tells us that there must be a smooth transition from oil to renewables in the vehicle fuel market, at the time of exhaustion T, so renewable costs $\beta(T)x_r(T)$ must be equal to the oil price (including tax and scarcity rent) $x_q+\phi_q\psi e^{gT}+\mu e^{\rho T}$. Thus we can solve for μ to derive the path of the market price of oil in first best. In Fig. 4(a) we see that—for our chosen parameterization—in the electricity market, oil is used initially, then there is a switch to renewables after about 19 years. In the vehicle market oil is used for 40 years, then there is a switch to renewables (Fig. 4(b)). Hence, in first best, all of the initial oil stock is burned, and none of the coal.

The emissions path in first best is summarized in Fig. 5(a), where we see that all emissions come from oil, emissions are relatively flat as the influence of the growing global economy is counteracted by the influence of the increasing social cost of emissions (and hence fossil fuel input use in first best). Furthermore, there is a step down in emissions after about 19 years when oil is no longer used in the electricity sector.

5.2. Laissez faire

Now continue with the benchmark model, but consider laissez faire (Fig. 4(c) and (d)). Now coal is used in the electricity sector up to the time at which renewables take over, after 67 years. So we know the electricity price p_w throughout:

$$p_w(t) = \min\{p_r(t), p_c(t)\},$$

where $p_r(t)$ and $p_c(t)$ can be read off from the unit costs of primary inputs in Table 3. Meanwhile, oil is used for vehicle fuel, and it is set at the limit price to keep coal and renewables out of the vehicle market, up to the time of exhaustion. So

$$p_q(t) = \min\{p_r(t), p_c(t)\}\beta(t).$$

The initial oil price is therefore considerably higher in laissez faire than in the first-best allocation, which might be thought to be good for the climate. However, in fact the high initial price leads to coal being burnt in the electricity sector, until renewables outcompete it after 67 years (Fig. 4(c)). And oil will still be exhausted, although somewhat later than in first-best, after around 60 years, after which there is a period of coal use before renewables take over (Fig. 4(d)). Putting all this together, long-run emissions are of course much higher in laissez faire, since the entire oil stock is burnt (as in first-best), and furthermore coal is burnt in the electricity sector for 67 years.

The laissez faire emissions path is summarized in Fig. 5(b), where total emissions from oil are the same as first best, since oil is exhausted. However, emissions are shifted to the future because the oil price declines over time in laissez faire, due to

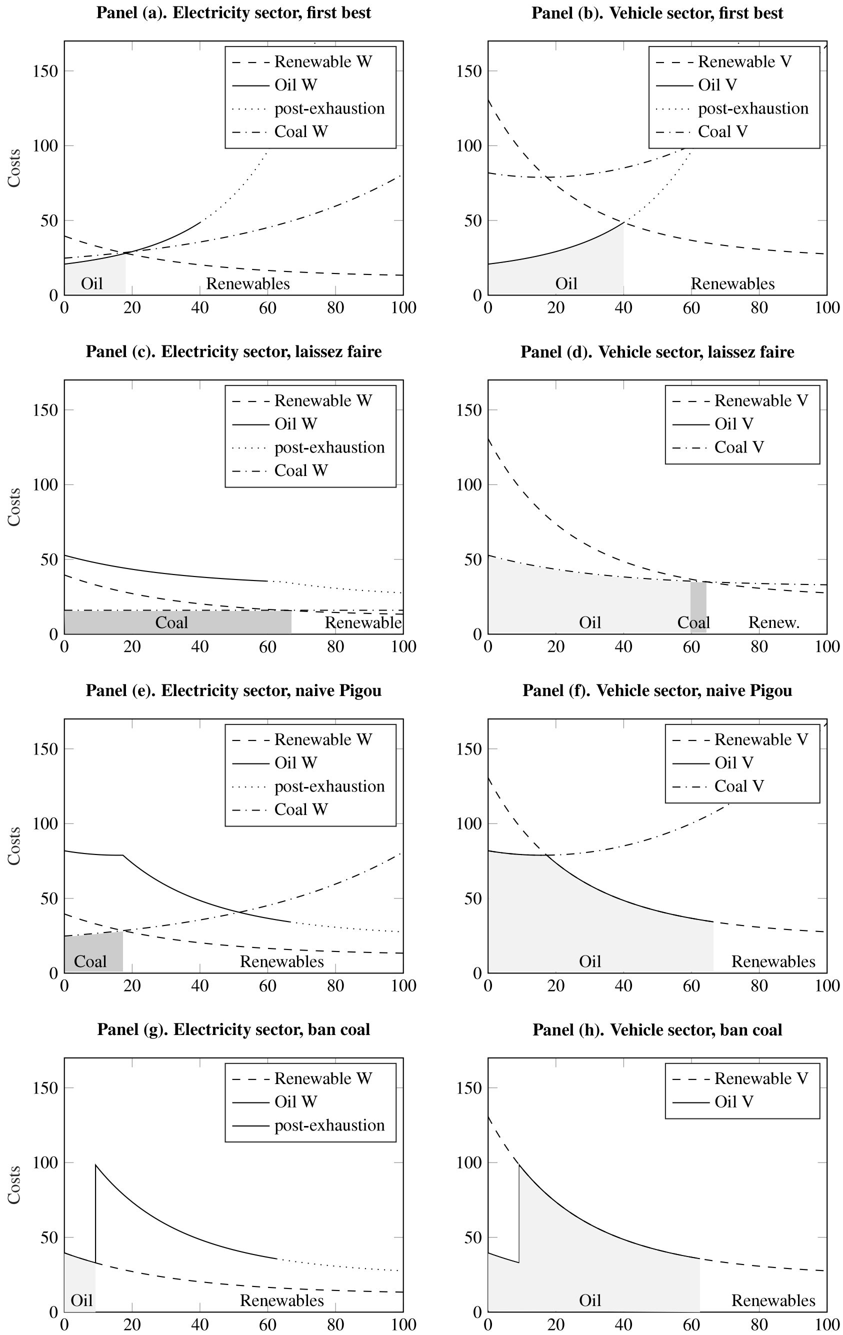

Fig. 4. Input costs per unit of production and input choices over time, in the two sectors and four scenarios. Note that the shaded areas have no physical interpretation, they merely emphasize which input is being used, and at what price, over time.

the increasingly stiff competition from coal and renewables. Meanwhile coal is used in the electricity sector, and briefly for both electricity and vehicles, hence total emissions are dramatically increased compared to the other scenarios.

5.3. Policy analysis

Now we analyse the results of alternative policies—naive Pigou, banning coal, subsidizing renewables + Pigou, and subsidizing oil production + Pigou—according to our two welfare criteria, and in terms of their effects on emissions. The results are summarized in Table 5, as well as being illustrated in Figs. 4 and 5.

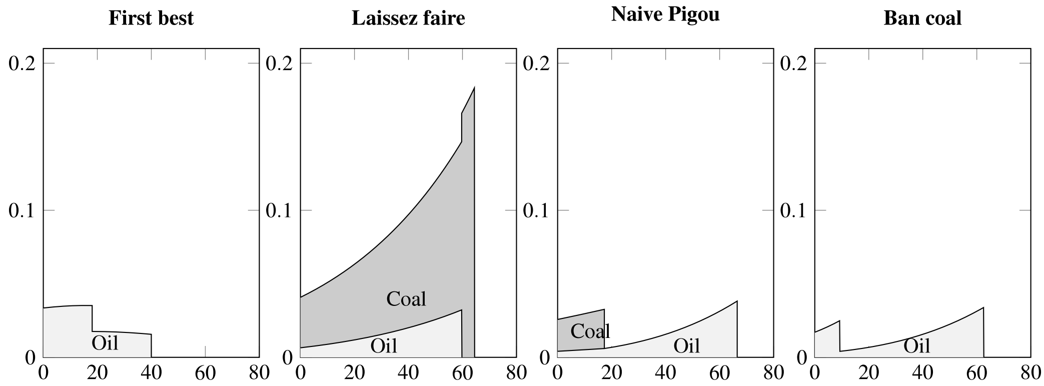

Fig. 5. Carbon emissions from oil and coal over time, in the four scenarios first best, laissez faire, naive Pigou, and ban coal.

Table 5
Welfare gains from alternative instruments, as a percentage of the welfare gain from first-best regulation, and emissions falls from regulation in percent.

	Welfare gain from regulation (percent of max)		Total emissions remaining after regulation (percent)
	Standard welfare function	Adjusted welfare function	
Laissez faire	0	0	100
Naive Pigou	35	23	24
Ban coal	53	26	17
Pigou + σ_q	100	17	17
Pigou + σ_r	100	78	17

First, naive Pigou. The effect of adding the tax to the price of coal is to dramatically bring forward the time at which renewables replace coal in electricity generation; this occurs after 19 years (Fig. 4(e)). On the other hand, the tax on emissions from oil has no effect on the allocation of resources, or emissions, because oil is still priced at the limit (to keep coal and renewables out of the market), and it is still exhausted before renewables can outcompete oil in the vehicle market. In our parameterization this occurs after around 67 years (Fig. 4(f)). The result is that total carbon emissions in the second-best regulated market—with unaddressed market power and a Pigovian tax—are actually higher than in first best, because the high initial price of oil lets coal into the electricity market, as explained in Remarks 1 and 2. The higher emissions in this scenario are clearly seen in Fig. 5(c), where we see that oil is exhausted (as in all scenarios) but also that a significant quantity of coal is used initially in the electricity sector, adding to total emissions when compared to laissez faire.

Now turn to the coal ban. In terms of the flow of fossil fuels, the coal ban does a reasonable job of approximating first best, as can be seen from Fig. 5. This is also reflected in the high welfare according to the standard criterion. However, on the adjusted welfare criterion it does not perform much better than naive Pigou, because the coal ban hands even greater market power over to the oil monopolist.

Finally, the two alternative ways of achieving first best according to the standard welfare criterion. Here we see a radical difference according to the adjusted criterion, where the oil subsidy performs disastrously as it entails enormous additional payments to the oil monopolist, whereas the renewable subsidy achieves 78 percent of the theoretically available welfare gain; the shortfall is accounted for by the scarcity rents captured by the oil monopolist.

5.4. Sensitivity analysis

We here discuss the sensitivity of the results—long-run emissions and welfare—to variations of parameter values, combining qualitative discussions of the effects of changes in parameters with numerical evaluations of some aspects. We focus on the second-best market allocations under naive Pigou and laissez faire, since the results in first best and under a coal ban are straightforward and intuitive.

We begin by outlining some basic properties of the second-best market solutions which we take as given, since (as shown in Section 2.2) big changes to the structure of the model or the parameters would be needed to change them. Firstly, limit pricing is practised throughout. And secondly, the solutions have the following structure, as seen most clearly in Fig. 5:

P1, an initial period (possibly of zero length) in which oil is used in both sectors (Case II);
P2, a period in which oil is used only in sector V (Case I); and
P3, a period after oil has been exhausted or abandoned.

Given these basic properties, we investigate the timing of the switches between the periods (P1, P2, and P3), and the choice of energy source in P2 in the electricity sector, and P3 in both sectors. In both naive Pigou and laissez faire P1 is of zero length and in P2 we have

$$Q(t) = A(t)\beta(t)^{-\epsilon} p_{-q}(t)^{-\eta} \text{ and } W(t) = \frac{\alpha}{1-\alpha} A(t)\beta(t)^{1-\epsilon} p_{-q}(t)^{-\eta}, \tag{23}$$

where the transition time T to P3 is defined implicitly by

$$\int_0^T Q(t)\mathrm{d}t = S_q(0) \text{ or } \beta(T)p_{-q}(T) = x_q - \sigma_q(T) + \phi_q \tau(T). \tag{24}$$

What is the effect of parameter shifts?[27] Consider first a decrease in x_r and hence the price of renewables. When limit pricing is against renewables, such a decrease will drive down p_{-q}, hence moving oil emissions towards the present and thus increasing discounted damages from such emissions. We thus have an effect similar to the green paradox but driven by a different mechanism compared to the standard case. When limit pricing is against coal, a decrease in the price of coal is unambiguously bad for emissions: it moves oil emissions towards the present, increases coal use at all points in time where it is used, and lengthens the period during which coal is used. Finally, an increase in β—the cost premium for alternatives to oil in the vehicle sector—will increase market power, decrease use of both energy sources, and postpone the exhaustion of oil (the end of P2). Hence, overall emissions will decrease (weakly).

Regarding when the monopolist will choose to leave oil in the ground, the results are less clear. The relevant condition is that the highest possible price of oil, βp_{-q}, must be lower than the private cost of oil extraction (net of any policy) before the stock of oil has run out. An increase in p_{-q} or β decreases oil use per unit of time, but extends the period during which oil is at all profitable to extract. Which effect dominates depends on the time profile of the change.

Whether the monopolist will choose to supply one sector (Case I) or both (Case II) is determined by Eq. (12). Differentiate w.r.t. p_{-q}, MC_q, and β to show that Case I is favoured by an increase in the gap between oil costs (including the shadow price of the remaining oil stock in the dynamic model) and the price of the cheapest alternative, and by an increase in the disadvantage to non-oil fuels in the vehicle sector.[28] Finally, an increase in α (and hence in the relative size of the electricity sector) favours Case II[29]: if the value of α is increased from 0.5 to 0.58 the monopolist initially supplies both sectors and if it is increased to 0.78, the monopolist supplies both sectors until renewables outcompete coal and hence there is no coal use in the naive Pigou solution.[30]

The result that naive Pigovian taxation will lead to higher emissions than in first best is also dependent on the assumption that coal is initially cheaper than renewables, even under such taxation; in our baseline parameterization this holds for the first 17 years. A substantial shift in parameters—such as a drop of almost 50 percent in renewable costs $x_r(0)$—would be needed to make renewables cheaper than coal at $t = 0$, as can be seen in Fig. 4(a). Given such a shift emissions would be identical under the two scenarios, although welfare would of course be lower in naive Pigou.

In terms of welfare effects we start by identifying how the different decentralized solutions deviate from first best. They all have the following properties: too little initial oil use; oil supplied to only the vehicle sector when it should be supplied to the electricity sector as well; too little overall energy use; and too much coal use (except for ban coal). We now list how these aspects would be affected by parameter variations:

- An increase in p_{-q} decreases initial oil and overall energy use in a given period, but may also induce the monopolist to sell to both markets (which would increase oil and overall energy use). If the increase in p_{-q} comes from an increase in the price of coal it leads to less coal use but if it is induced by an increase in the price of renewables it increases coal use.
- An increase in MC_q does not affect oil use within a given period (since the monopolist sets a limit price) but it tends to induce the monopolist to sell to only the vehicle market and hence decrease initial use of oil and energy. This also leads to increased coal use.
- An increase in β moves the monopolist towards only supplying the vehicle sector and hence decreased oil and energy use. If oil is used in only the vehicle sector, oil and energy use would decrease in response to an increase in β. If a change in β induces the monopolist to sell only to the vehicle sector, that increases coal use (if that is the cheapest alternative) but if the monopolist already supplies only sector V, then the increased oil price will decrease coal and energy use.

Finally, we study the effects of shifting α—the relative size of the electricity sector—in detail, as shown in Table 6. Starting with welfare, the key lesson is that a larger vehicle sector (lower α) gives higher welfare losses under second-best policy (naive Pigou and ban coal), which is expected because it is in the vehicle sector where the oil monopolist exercises most market power; this effect is especially strong under 'ban coal' where the monopolist's market power is already very strong. Turning to emissions, we see that a larger vehicle sector makes total emissions less sensitive to regulation: vehicle emissions are the most intractable to the regulator, and when these make up a bigger proportion of the total, overall emissions are reduced less by regulation.

[27] When considering a change in a parameter we assume that the value of the parameter changes in the same direction at all points in time but without any further specification of the time profile of the changes.

[28] The latter result follows given the assumption of limit pricing so that the conditions in Lemma 1 hold.

[29] Note that this result is not quite as straightforward as it looks in Eq. (12), since ϵ is a function of α. However, for reasonable parameters the direction of the effect is unambiguous.

[30] Note that these parameter changes lead to countervailing effects on the shadow price of oil, tending to diminish the overall effects. For instance, an increase in α raises the shadow price of oil, which works against the first-order effect favouring Case II.

Table 6
A new version of Table 5 (welfare gains from alternative instruments, and emissions falls from regulation) for alternative values of α.

	Welfare gain from regulation (percent of max)						Total emissions remaining after regulation (percent)		
	Standard welfare function			Adjusted welfare function					
	Value of α			Value of α			Value of α		
	0.4	0.5	0.6	0.4	0.5	0.6	0.4	0.5	0.6
Laissez faire	0	0	0	0	0	0	100	100	100
Naive Pigou	0	35	62	4	23	43	27	24	22
Ban coal	−12	53	86	−33	26	54	21	17	15
Pigou + σ_q	100	100	100	17	17	20	21	17	15
Pigou + σ_r	100	100	100	77	78	79	21	17	15

6. Conclusions

The key conclusion from the benchmark model is that an oil monopoly may — if not accounted for by the regulator — increase total carbon emissions by encouraging the use of coal which would (in first best) remain in the ground. In our very simple set-up with a single economy and a focus on the optimal allocation of productive resources (and no attention paid to the distribution of income), the policy implication is that if a Pigovian tax is applied, there should also be a large subsidy to oil production. However, under the (arguably more relevant) alternative welfare criterion, the oil subsidy is welfare-decreasing and better options are a coal ban, or best of all a subsidy to renewables designed to erode the oil owner's market power.

The model is stylized, and many of the results would change in more sophisticated settings. Nevertheless, the fundamental mechanisms and qualitative results may frequently carry over into such settings. For instance, we assume that the primary energy inputs are perfect substitutes, which allows us to derive very clean results which highlight the intuition; if we assumed imperfect substitutability, all energy sources would typically be used simultaneously, and large subsidies to renewables in the vehicle sector would not be costless — nor would they lead to first best — since they would lead to a sub-optimal increase in the use of renewables as well as forcing down the oil price. The importance of this effect would depend on the assumed elasticity of substitution: with a high elasticity, use of renewables would remain low, and the effect on welfare would be modest.

Our most basic result is that market power in a sector with cheap energy inputs can — even in the presence of Pigovian taxation — distort the order of extraction, 'let in' more expensive or dirtier inputs, and thus increase total long-run emissions (summarized in Remarks 1 and 2). This result is clearly relevant in many other situations than that modelled here. Most importantly, the simultaneous extraction of oil stocks with dramatically different unit extraction costs — as documented by Asker et al. (2019) — shows this mechanism at work: in first best, many of the more expensive and dirtier stocks, such as in Alberta, would remain in the ground, but Pigovian taxation alone would almost certainly not be enough to achieve this outcome.

A promising direction for future work would be to focus on oil and gas, and model a monopolist (or cartel) with a large homogeneous stock, and a series of competitors with smaller stocks which were also more expensive to extract: oligopoly in the oil market, or (to quote Loury, 1986), oiligopoly.

Appendix A. Derivation of demand functions for vehicle energy and electricity

Let p_e denote the price of the energy composite E. The final goods producers' first order condition with respect to energy use gives

$$Y = \frac{p_e E}{1 - \frac{1}{\eta}}.$$

Combining this with the final goods production function (1) and solving for E yields

$$E = \left(\frac{\eta - 1}{\eta} \frac{\zeta}{p_e} \right)^{\eta} A. \tag{A.1}$$

Turning to the profit maximizing problem of the energy composite producers, the first order conditions with respect to V and W give

$$\begin{aligned} \frac{p_v}{p_e} &= (1-\alpha)\frac{E}{V} \\ \frac{p_w}{p_e} &= \alpha \frac{E}{W}. \end{aligned} \tag{A.2}$$

Combining these delivers (4). Substituting (4) in energy composite production function (2) gives

$$E = \left(\frac{\alpha}{1-\alpha} \frac{p_v}{p_w} \right)^{\alpha} V. \tag{A.3}$$

Substituting this in first order condition (A.2) and rewriting gives

$$p_e = \left(\frac{p_v}{1-\alpha} \right)^{1-\alpha} \left(\frac{p_w}{\alpha} \right)^{\alpha}. \tag{A.4}$$

Finally, combining (A.1) and (A.3), rewriting, and substituting for p_e from (A.4) and for ζ delivers (3).

Appendix B. Market solution of static model

The prices of coal and renewables p_c and p_r are given in (8), and the price of the cheapest alternative to oil, p_{-q} is defined in (10). The oil monopolist chooses p_q to maximize profit. Recall that MC_q denotes the private per unit cost of the oil producer, i.e. the extraction cost x_q plus the emissions tax $\phi_q\tau$ minus subsidy σ_q.

If $p_q > \beta p_{-q}$, or there is no oil left, then oil is not used all. If $p_{-q} < p_q \leq \beta p_{-q}$ then she sells only to the vehicle sector (Case I in Section 2.2) and if $p_q \leq p_{-q}$, she sells oil to both sectors (Case II in Section 2.2) . We will treat the cases in turn.

No oil used

In this case, all energy will be supplied by coal or renewables depending on which source has the lowest price. The energy prices in the sectors are then

$$p_v = \beta p_{-q} \text{ and } p_w = p_{-q}.$$

Using these prices, the supplied quantities are given by (3) and (4).

Case I: oil only in vehicle sector ($\beta p_{-q} \geq p_q > p_{-q}$)

When oil is sold only to the vehicle sector, $Q = V$ and the price in the electricity sector is given by $p_w = p_{-q}$. The demand for oil is given by (3):

$$Q_I = Ap_q^{-\epsilon}p_{-q}^{-\delta}.$$

The associated marginal revenue is $MR_{q,I}$ in (11) and profits are

$$\pi_{q,I} = (p_q - MC_q)Ap_q^{-\epsilon}p_{-q}^{-\delta}.$$

Assuming an interior solution, profits are maximized by setting marginal revenue equal to marginal cost and the profit maximizing price is now a markup of $\epsilon/(\epsilon-1)$ over marginal private cost:

$$p^*_{q,I} = \frac{\epsilon}{\epsilon-1}MC_q$$

$$\text{and profits} \qquad \pi^*_{q,I} = A\frac{(\epsilon-1)^{\epsilon-1}}{\epsilon^\epsilon}MC_q^{1-\epsilon}p_{-q}^{-\delta}. \tag{B.1}$$

There will be limit pricing—with $p_q = \beta p_{-q}$ and $p_w = p_{-q}$—if

$$\frac{\epsilon}{\epsilon-1}MC_q > \beta p_{-q} \tag{B.2}$$

$$\text{giving profits} \qquad \pi^{LP}_{q,I} = \frac{A}{\beta^\epsilon}\frac{\beta p_{-q} - MC_q}{p_{-q}}p_{-q}^{1-\eta}. \tag{B.3}$$

Case II: oil in both sectors ($p_q \leq p_{-q}$)

When selling to both sectors, the demand for oil, $Q = V + W$, can be derived using (3) and (4):

$$Q_{II} = \frac{A}{1-\alpha}p_q^{-\eta}$$

$$\text{yielding profits} \qquad \pi_{q,II} = \frac{A}{1-\alpha}(p_q - MC_q)p_q^{-\eta}.$$

Again, profits are, in an interior solution, maximized by setting marginal revenue equal to marginal cost resulting in a markup of $\eta/(\eta-1)$ over marginal private cost:

$$p^*_{q,II} = \frac{\eta}{\eta-1}MC_q \tag{B.4}$$

$$\text{and profits} \qquad \pi^*_{q,II} = \frac{A}{1-\alpha}\frac{(\eta-1)^{\eta-1}}{\eta^\eta}MC_q^{1-\eta}. \tag{B.5}$$

If $p^*_{q,II} > p_{-q}$ there will be limit pricing with

$$\text{and profits} \qquad \pi^{LP}_{q,II} = \frac{A}{1-\alpha}\frac{p_{-q} - MC_q}{p_{-q}}{p_{-q}}^{1-\eta}. \tag{B.6}$$

Appendix C. Incentives to sell to both sectors under oil subsidies

Recall (Proposition 1) that the application of the oil subsidies and a Pigovian tax is not sufficient to ensure a social optimum when this involves oil sales only to the vehicle sector (Case I); for some parameter values, it is necessary to add the condition that subsidy payments are only paid to oil sold in this sector. To prove that this extra condition may be necessary, consider the case where, for the optimal oil price $p_q^\dagger = x_q + \phi_q \psi$, we are in Case I (i.e., $p_{-q} < p_q^\dagger < \beta p_{-q}$) where oil should be used in the vehicle sector but not in the electricity sector. The subsidy that induces the optimal price, if the monopolist chooses to supply only the vehicle sector, is given in (13). The monopolist's marginal cost is then

$$MC_q = \frac{\epsilon - 1}{\epsilon} p_q^\dagger. \tag{C.1}$$

Substituting this in the monopolist's profit given in (B.1) yields

$$\pi_q^I = \frac{A}{\epsilon} \left(p_q^\dagger\right)^{1-\epsilon} p_{-q}^{-\delta}. \tag{C.2}$$

If, instead, the monopolist considers selling to both sectors with this subsidy, the profit maximizing price can be found by substituting (C.1) into (B.4)

$$p_q^{II} = \frac{\eta}{\eta - 1} \frac{\epsilon - 1}{\epsilon} p_q^\dagger. \tag{C.3}$$

At this price, the monopolist can actually sell to the electricity sector if $p_q^{II} < p_{-q}$. We know that $p_q^\dagger > p_{-q}$, but since $\eta/(\eta-1)\cdot(\epsilon-1)/\epsilon < 1$ there will be parameters for which the monopolist can set a price low enough to take both markets. The resulting profit can be computed by substituting (C.1) into (B.5)

$$\pi_q^{II} = \frac{A}{\epsilon} \left(\frac{\eta}{\eta - 1} \frac{\epsilon - 1}{\epsilon}\right)^{-\eta} \left(p_q^\dagger\right)^{1-\eta}. \tag{C.4}$$

Taking the ratio of the profits the monopolist gets when supplying both markets and only the vehicle sector we get

$$\frac{\pi_q^{II}}{\pi_q^I} = \left(\frac{\eta}{\eta - 1} \frac{\epsilon - 1}{\epsilon}\right)^{-\eta} \left(\frac{p_{-q}}{p_q^\dagger}\right)^{\delta}. \tag{C.5}$$

The first term on the RHS is greater than 1, and the second is less than 1 so in general the ratio of profits is ambiguous. For our chosen parameters it is easy to see both that the monopolist can take both markets (C.3), and that the profit from selling to both sectors is larger than the profit from selling only to the vehicle sector (C.5).

Appendix D. Dynamic first-best optimization problem

We here set up and solve the full first-best optimization problem:

$$\max \int_0^\infty e^{-\rho t} \left(Y(t) - x_q Q(t) - x_c C(t) - x_r(t) R(t) - (\phi_q Q(t) + \phi_c C(t)) \psi e^{gt}\right) \mathrm{d}t,$$

where $Y(t)$ is a function of $A(t)$, $Q_v(t)$, $Q_w(t)$, $C_v(t)$, $C_w(t)$, $R_v(t)$ and $R_w(t)$, and the maximization is subject to

$$\int_0^\infty Q(t) \mathrm{d}t \le S_q(0),\ Q_v(t) \ge 0,\ Q_v(t) \ge 0,\ C_v(t) \ge 0,\ C_w(t) \ge 0,\ R_v(t) \ge 0,\ R_w(t) \ge 0.$$

The Hamiltonian can be written

$$\mathcal{H} = e^{-\rho t} \left(Y - x_q Q - x_c C - x_r R - (\phi_q Q + \phi_c C) \psi e^{gt} + \mu e^{\rho t}\right),$$

yielding FOCs

$$\frac{\partial \mathcal{H}}{\partial Q_v} \le 0 \Rightarrow x_q + \phi_q \psi e^{gt} + \mu e^{\rho t} \ge \frac{\partial Y}{\partial V}$$

$$\frac{\partial \mathcal{H}}{\partial Q_w} \le 0 \Rightarrow x_q + \phi_q \psi e^{gt} + \mu e^{\rho t} \ge \frac{\partial Y}{\partial W}$$

$$\frac{\partial \mathcal{H}}{\partial C_v} \le 0 \Rightarrow x_c + \phi_c \psi e^{gt} \ge \frac{1}{\beta} \frac{\partial Y}{\partial V}$$

$$\frac{\partial \mathcal{H}}{\partial C_w} \le 0 \Rightarrow x_c + \phi_c \psi e^{gt} \ge \frac{\partial Y}{\partial w}$$

$$\frac{\partial \mathcal{H}}{\partial R_v} \le 0 \Rightarrow x_r \ge \frac{1}{\beta} \frac{\partial Y}{\partial V}$$

and

$$\frac{\partial \mathcal{H}}{\partial R_w} \le 0 \Rightarrow x_r \ge \frac{\partial Y}{\partial W}$$

with equality whenever the input is used in the considered sector. The optimal solution is thus to always use the cheapest energy source in each sector (including the scarcity value for oil). Since μ is constant, the solution boils down to finding the value of μ such that the first order conditions and the resource constraint on the stock of oil are fulfilled.

Appendix E. Numerical algorithms

We will here describe the algorithms used to derive our numerical results. In all cases, the key to solving the model is finding the oil price at all points in time. Given the oil price, the prices of V and W are given by

$$p_v(t) = \min\{p_q(t), \beta(t)p_{-q}(t)\} \text{ and } p_w(t) = \min\{p_q(t), p_{-q}(t)\}.$$

The quantities V and W can then be computed using (3) and (4). Combining them, as in (2), these quantities give E that, used in (1), allows us to compute Y.

Emissions are given by $G = \phi_v V + \phi_w W$, where ϕ_v and ϕ_w are equal to ϕ_q, ϕ_c or 0 depending on what energy source is used in that sector. Total emissions are

$$\text{Emissions} = \int_0^\infty G(t)\mathrm{d}t.$$

The cost of energy supply is given by $X = x_v V + x_w W$ where x_v and x_w are equal to x_q, x_c or x_r depending on what energy source is used in the sector. The standard welfare measure (15) can be computed as

$$\int_0^\infty e^{-\rho t}\left[Y(t) - X(t) - \psi e^{gt}G(t)\right]\mathrm{d}t.$$

What we have described so far applies to all solutions. How to derive the oil price and how to compute the integral in (22), that gives the difference between the standard and alternative welfare measures, differs between the solutions and we will now describe how to do that for each solution.

First best

In the first best solution, the oil price is given by (17). Due to smooth pasting, we know that the oil price at the time of exhaustion, T, must be equal to the price of the cheapest alternative. At that point, oil is only used in the vehicle sector and we must have that $p_q^\dagger(T) = \beta(T)p_{-q}(T)$. We assume that $T = 40$ and this allows us to solve for μ. We now have the oil price at all points in time. When using the alternative welfare measure in (22), it matters which policy is used to implement first best. If it is implemented using an oil subsidy, we can combine (17) and (20) to get

$$p_q(t) + \sigma_q(t) - \tau(t)\phi_q - x_q = \frac{1}{\eta}p_q^\dagger(t) \text{ or } p_q(t) + \sigma_q(t) - \tau(t)\phi_q - x_q = \frac{1}{\epsilon}p_q^\dagger(t)$$

depending on whether oil should be used in both sectors or only in sector V.

If we, instead, implement first best using a sector specific subsidy to renewables, (22) can be computed using that

$$p_q(t) + \sigma_q(t) - \tau(t)\phi_q - x_q = p_q^\dagger(t) - \psi e^{gt}\phi_q - x_q.$$

Other solutions

In the other solutions the monopolist will always set a limit price. Depending on whether the monopolist chooses to supply both sectors or only sector V, the oil price is

$$p_q(t) = p_{-q}(t) \text{ or } p_q(t) = \beta(t)p_{-q}(t),$$

where $p_{-q}(t)$ includes a Pigouvian tax on emissions from coal in the naive Pigou solution but not in laissez faire or ban coal. The monopolist's sector choice is made based on (12) where the marginal cost includes the monopolist's scarcity value on the stock of oil. The solutions thus relies on finding a scarcity value such that the monopolist chooses what sectors to supply at each time based on (12) and exactly exhausts the oil stock at the time when oil extraction becomes unprofitable based on the marginal cost including scarcity.

For computing (22), we note that

$$p_q(t) + \sigma_q(t) - \tau(t)\phi_q - x_q = p_q^\dagger(t) - x_q$$

in laissez faire and ban coal while

$$p_q(t) + \sigma_q(t) - \tau(t)\phi_q - x_q = p_q^\dagger(t) - \psi e^{gt}\phi_q - x_q$$

in naive Pigou.

Appendix F. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.euroecorev.2022.104211.

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