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Abstract

This paper analyses an electricity market in which a monopolist that employs fossil-fuel base-load and peak-load technologies competes against a fringe of renewable energy (RE) generators. The optimal technology and electricity mix can be decentralised by levying technology-dependent capacity taxes/subsidies in addition to technology-/state-dependent emission taxes. Whenever base-load capacity is taxed (subsidised), peak-load capacity is subsidised (taxed). A decline in RE capacity costs and an increase in the share of consumers on real-time prices predominantly raises emission taxes and brings them closer to their Pigouvian level, albeit with some qualifications. Capacity taxes/subsidies disappear when all consumers are on real-time prices and RE is about to fully crowd out conventional base-load capacity.

JEL-Codes: Q420, Q480, Q580, H230, L130.

Keywords: intermittent renewable energy, peak-load technology, base-load technology, emission tax, capacity tax/subsidy.

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1 Motivation

Reducing fossil-fuel electricity generation and expanding renewable energy supply are paramount to cutting pollution and tackling global warming. This transition from conventional electricity generation to renewable energy (RE) poses challenges and opens opportunities. On the one hand, the intermittence of RE sources such as wind and solar makes it more difficult to balance electricity supply and demand at each point in time. It requires more flexibility from market participants in their production and consumption patterns. On the other hand, the smaller scale at which investment in wind and solar energy is possible, relative to big power stations, enables new firms to shake up traditionally imperfectly competitive electricity markets. Fossil-fuel incumbents in a previously cosy market environment are potentially threatened by a competitive fringe. The decline in RE costs and the distribution of smart meters jointly reinforce this competition. With smart meters, more customers can ultimately face real-time prices, which provide incentives to shift demand to windy or sunny periods. Together with decreasing RE costs, more flexible customers raise the competitive pressure on traditional fossil-fuel based generators.

Intensified competition should simplify the optimal environmental policy. A messy set of second-best emission and capacity tax and subsidy formulas, which account for imperfect competition and environmental externalities, should converge towards a simple Pigouvian emission tax, which fully internalises environmental damage, as markets become more competitive through lower RE costs and more flexible consumers, at least in principle. This paper analyses whether this reasoning holds on closer inspection.

To this end, a simple analytical model of capacity investment and electricity generation and consumption is introduced. A monopolist faces a competitive fringe. The monopolist employs a base-load and a peak-load technology using fossil fuels, while the competitive fringe consists of RE generators using an intermittent RE source. For simplicity, we refer to this source as wind, and there are two states of nature, a non-windy and a windy one. The peak-load technology allows electricity to be dispatched quickly and can be used to back up base-load capacity when the RE source is unavailable. While some customers face real-time prices, which depend on the state of nature, others pay a time-invariant price per electricity unit, irrespective of the state of nature.

In a multi-stage game, the monopolist chooses its base-load and peak-load capacities before the potential RE firms decide on whether to enter the market and build up RE capacity. Afterwards, electricity providers and competitive retailers interact in state-contingent wholesale markets, and retailers interact with consumers in the retail market. Prior to any decision of the market participants, the government determines the level of technology-dependent capacity taxes or subsidies in addition to technology- and partly state-dependent emission taxes. This policy set enables the government to address the distortions caused by pollution, imperfect competition and strategic investment incentives.

The paper analyses the effects of declining RE capacity costs and increasing consumer flexibility on optimal policies, with increasing flexibility defined as a rising share of customers on real-time prices. The optimal emission taxes on both base-load and peak-load electricity generation indeed increase as consumers become more flexible. Fundamentally, and in line with our notion above, growing flexibility shifts electricity demand from non-windy to windy periods and thus intensifies the competition between the RE technology on the one hand and the conventional base-load and peak-load technologies on the other hand. In response to eroding monopoly power, emission taxes move closer to full internalisation of environmental damage.

In the same vein, a decline in RE capacity costs also raises the optimal emission taxes on base-load electricity generation, which faces increasingly fierce competition from RE in windy periods. In contrast, however, the emission tax on peak-load electricity production decreases in response to lower RE capacity costs. As explored in detail in the analysis, a cross-market effect drives this decline, which leads to an even larger gap between environmental damage and optimal tax level, while aggregate demand and monopoly power remain unchanged in the non-windy periods, in which the peak-load technology is employed, even if RE capacity costs fall.

An optimal policy also needs to counteract a further distortion: the monopolist faces incentives to strategically over- or underinvest in base-load and peak-load capacities to crowd RE firms out or, more surprisingly, in, depending on RE capacity costs and consumer flexibility. To this end, capacity taxes and subsidies can be used. Interestingly, whenever base-load (peak-load) capacity is to be taxed, peak-load (base-load) capacity is to be subsidised. For intermediate shares of flexible consumers, base-load capacity is to be taxed (subsidised) if RE costs are sufficiently high (low), while the opposite is true for peak-load capacity. Similarly, for intermediate RE costs, base-load capacity is to be taxed (subsidised) if consumer flexibility is sufficiently high (low), while the opposite is true for peak-load capacity.

However, these capacity taxes and subsidies completely vanish if RE capacity costs are very low and all consumers face real-time electricity prices. Under these circumstances, the emission tax on base-load electricity production reaches its maximum and is closest to its Pigouvian level. Nevertheless, the notion that environmental policy moves towards a simple Pigouvian emission tax as RE capacity costs decline and consumer flexibility increases needs to to be qualified, since these changes drive the emission tax on peak-load electricity generation in the opposite direction.

The underpinning analysis of the optimal technology mix provides some perhaps surprising results. For instance, while an increase in consumer flexibility shifts demand from non-windy to windy periods, the optimal adjustment requires more fossil-fuel base-load capacity, and not more RE capacity. Also, the paper clarifies conditions under which a decline in RE costs and an increase in consumer flexibility causes more, and not less, environmental damage.

This paper complements the existing literature on environmental policy and the optimal energy mix with intermittent RE sources. Ambec and Crampes (2012) characterise the optimal energy mix in a model with a competitive electricity sector employing one fossil-fuel technology and one or two RE technologies. They show that the optimal solution can be decentralised in a competitive economy with state-dependent prices if all consumers are, in the terminology of the current paper, flexible. With inflexible consumers, a second-best energy mix can only be decentralised if the government intervenes, or if both conventional and RE power stations are owned by the same entity. Helm and Mier (2019) explore the diffusion of renewable energy in perfectly competitive markets with one fossil-fuel and one RE technology when RE capacity costs decline, assuming that all consumers are on real-time prices. They conclude that diffusion is efficient and analyse how price caps cause inefficiencies. Garcia et al. (2012) consider a framework with 'learning-by-doing' economies of scale in which competitive investors can choose which sites they invest in and how much they invest in each site. They show that a single feed-in tariff leads to overinvestment in the most suitable sites, while a renewable portfolio standard causes underinvestment in the conventional technology.

Ambec and Crampes (2019) and Helm and Mier (2021) add a storage technology to the technology mix. In particular, they outline how the socially optimal energy mix can be decentralised under perfect competition without an emission tax using second-best policies. Ambec and Crampes (2019), who assume that all customers are on time-invariant retail prices, consider feed-in tariffs, consumption taxes, renewable portfolio standards, price caps and capacity subsidies in their policy mix, while Helm and Mier (2021), who assume that all customers are on real-time prices, focus on a combination of consumption taxes and capacity subsidies.[1]

In contrast to the papers mentioned so far, the current contribution explicitly distinguishes between conventional base-load and peak-load technologies and allows for imperfect competition as well as for continuous degrees of flexible and inflexible consumers. As will be explored in detail, the presence of both base-load and peak-load technologies critically shapes the competition in an electricity market with intermittent RE sources and the changes in the optimal environmental policies in response to declining RE costs and increasing consumer flexibility.

As in the current paper, Twomey and Neuhoff (2010) explore the implications of market power in electricity markets. However, since they take the RE capacity as given, their focus is very different from that of the current analysis. They argue that forward contracting does not mitigate the negative effects of market power.[2] Extending Ambec

[1] Considering a dirty and a clean conventional technology and RE technologies, Abrell et al. (2019) also explore optimal policies in the absence of an emission tax and evaluate such policies empirically. Their optimal strategy includes an energy demand tax in addition to either feed-in tariffs or RE output subsidies. In contrast to Ambec and Crampes (2019) and Helm and Mier (2021), the capacities of the conventional technologies are not endogenously chosen.

[2] Murphy and Smeers (2005) and Zöttl (2010) consider market power with investment and output decisions. They provide a robust analysis of the market equilibrium in Cournot models, assuming that all consumers are on real-time prices. Since they do not explore any policies and do not consider RE, their approach and focus substantially differs from the current paper despite a shared interest in strategic interactions in electricity markets.

and Crampes (2019) and allowing for consumers on real-time prices, Ambec and Crampes (2021) conclude that an increase in the share of flexible consumers raises social welfare, but that the marginal impact on social welfare declines with the share of flexible consumers.[3] In contrast to them, the focus of the current analysis is on how changes in the share of flexible consumers affect optimal policies in the case of imperfect competition. In the presence of base-load and peak-load technologies, the mechanisms through which consumer flexibility influences the outcome are different. Then, for instance, increasing consumer flexibility causes a shift from conventional peak-load to base-load technologies rather than, as in Ambec and Crampes (2021), from a conventional technology to RE.

Holland et al. (2022) extend the previous models with competitive electricity markets and all customers on real-time prices to allow for a range of intermittent renewable and conventional dispatchable generation technologies and for a storage technology in a multiperiod model. Their comparative statics shows, for instance, that increasing emission taxes can raise or lower electricity consumption, and that declining RE costs can increase or decrease emissions. These points are picked up in section 3 below. Holland et al. (2022) calibrate their model to quantify the long-run policy effects for the USA, but do not aim at identifying optimal policies.[4]

The current paper is also related to the literature on the efficiency of electricity markets with time-invariant retail prices, particularly to Borenstein and Holland (2005). They analyse a perfectly competitive electricity market with conventional technologies and demand fluctuation, but without pollution. They show that with at least some consumers on a time-invariant price, both output and capacity is not even second best in a laissez-faire equilibrium, and that a second-best outcome requires inflexible customers to be taxed or subsidised. In contrast, in the current setting with supply fluctuations instead of demand fluctuations, inflexible consumers themselves do not prevent second-best output and capacity levels (as discussed at the end of section 4), but monopoly power and the environmental externality obviously do. However, the share of customers on a time-invariant electricity price indirectly affects monopoly power and thus optimal environmental policy.

The remainder of the paper is organised as follows: In the next section, the model is presented. Section 3 characterises the socially optimal outcome as a benchmark for the ensuing analysis and explores how this outcome changes as RE costs decline and consumer flexibility increases. Afterwards, section 4 explores the market equilibrium and the government's optimal environmental policy. Sections 5 and 6 than successively analyse how the optimal environmental policy responds to a decline in RE costs and an increase in consumer flexibility. Section 7 summarises the analysis and concludes the paper with some remarks on a feed-in tariff as an alternative policy instrument.

[3]The magnitude of the social gains from real-time pricing are contentious. See, for instance, Gambardella et al. (2020) and Borenstein (2005).

[4]See also Pommeret and Schubert (2022) who provide a dynamic analysis of energy transition paths and calibrate their model to the Spanish system.

2 The Energy Sector and the Government

A monopolist incumbent employs two conventional technologies, a base-load technology A and a peak-load technology B. It competes against a competitive fringe of potential electricity generators which rely on a renewable energy (RE) technology R. Technology R uses an intermittent source of energy, such as wind or solar power. This source is only available in state 1 of nature, in which it is windy or sunny, but is unavailable in state 0 of nature, in which it is non-windy or non-sunny. State 0 of nature prevails in $\sigma \in (0,1)$ periods, while state 1 occurs in $1-\sigma$ periods, with all periods exhibiting equal length and total time normalised to unity. In contrast to the RE technology R, the conventional technologies A and B rely on fossil fuels, such as gas or coal, as a source of energy and generate dispatchable electricity.

The monopolist incumbent chooses its capacities K_A and K_B as well as its electricity supply Q_A, Q_{B0} and Q_{B1}. Each unit of capacity K_A and K_B enables the monopolist to generate up to 1 unit of electricity at each point in time. Technology B can be ramped up and switched off quickly and can thus produce different levels of electricity Q_{B0} and Q_{B1} in states 0 and 1, respectively. By contrast, technology A cannot be switched on and off quickly and can only produce the same electricity level Q_A across the two states of nature. In line with their flexibility, or lack of flexibility, the technologies A and B are referred to as base-load technology and peak-load technology, respectively.[5] The fixed cost of one unit of capacity K_A (K_B) is F_A (F_B), and the constant variable cost of generating electricity with technology A (B) is c_A (c_B). Each unit of electricity generated with technology A (B) causes environmental damage δ_A (δ_B). Assume that costs for base-load and peak-load capacity and electricity and environmental damage are related as follows:

Assumption 1. *Technology and Environmental Damage.*
(i) $F_A > F_B$, *(ii)* $c_A < c_B$, *(iii)* $\delta_A \leq \delta_B$, *(iv)* $c_A + F_A < c_B + F_B$, *(v)* $c_A + \frac{F_A}{\sigma} > c_B + \frac{F_B}{\sigma}$, *(vi)* $c_A + \delta_A + F_A < c_B + \delta_B + F_B$, *(vii)* $c_A + \delta_A + \frac{F_A}{\sigma} > c_B + \delta_B + \frac{F_B}{\sigma}$.

Compared with the peak-load technology B, the base-load technology A exhibits higher fixed costs but lower variable costs, and it causes weakly lower environmental damage (properties (i)-(iii)). Technology A allows the monopolist to generate electricity at lower private and social costs if employed at full capacity across both states of nature (properties (iv) and (vi)), but would be more expansive if used at full capacity only in the non-windy state (properties (v) and (vii)). That is, technologies A and B exhibit all the characteristics associated with base-load and peak-load technologies.[6] For later reference,

[5] Most contributions related to the current analysis make the strong assumptions of fully flexible conventional technologies (see references above). A notable exception is Eisenack and Mier (2019). They also distinguish between different forms of dispatchability, but their take on the optimal technology choice with intermittent power sources is very different from the current approach.

[6] See, for instance, Borenstein (2012) for a discussion of different technologies and their economic implications. As a result of the cost structures described in assumption 1, technology A would be anyway employed across the two states of nature, whereas technology B would only be used in the non-windy

assumption 1 encompasses a comprehensive set of inequalities, although some of them are redundant. For instance, properties (iii) and (iv) imply property (vi).

The competitive fringe consists of a continuum of potential firms with mass N using an intermittent RE source to generate electricity. For simplicity, let us use the example of wind power. Each of these potential fringe firms decides whether it enters the market. If it does so, it installs one unit of RE capacity K_R. Each RE capacity unit can generate up to 1 unit of electricity at each point in time in each of the $1-\sigma$ windy periods (state 1) at a production cost of zero. Thus, in the windy periods, the instantaneous aggregate RE electricity supply is $Q_R = K_R$ if the RE firms choose to fully utilise their capacity. RE firms cannot supply any electricity in the σ non-windy periods (state 0).

The fixed capacity cost of one unit of RE capacity consists of two elements. The first element is the basic investment cost $H(\alpha)$, which captures the cost of a wind turbine for a given state of technology α and is firm-independent. The second element is the firm-specific set-up cost h, which reflects firm-specific management and technological know-how, a firm's location-specific construction costs (e.g., of onshore and offshore wind parks) and costs of connecting the installation to the electricity network (e.g., because of locations being more or less remote), among other things.[7]

Let us assume that these firm-specific costs are uniformly distributed over the support $\left[0, \overline{h}\right]$, where the lower bound is set to zero for simplicity. Then, ranking the potential RE firms in ascending order of their capacity costs, the capacity-cost function $g(k;\alpha) = H(\alpha) + \overline{h}k/N$ represents the relationship between the k-th firm (or, equivalently, the k-th RE capacity unit) and its fixed capacity cost $H(\alpha) + h_k$ for given technology parameter α. The functions $g(K_R;\alpha) = H(\alpha) + \overline{h}K_R/N$ and $G(K_R;\alpha) = \int_0^{K_R} g(k;\alpha)dk = H(\alpha)K_R + \overline{h}K_R^2/\left(2N\right)$ show the capacity cost at the margin and the aggregate capacity costs of K_R units, respectively, with the aggregate capacity K_R being equal to the mass of RE firms in the market.

An increase in the parameter α captures an improvement in RE technology that strictly reduces the fixed investment cost $H(\alpha)$, with the upper and lower boundary of the technology parameter α denoted by α^{min} and α^{max}, respectively. That is, $\partial H(\alpha)/\partial\alpha < 0$, with $H(\alpha^{min}) > H(\alpha) > H(\alpha^{max})$.

Taking the arguments together, the derivatives of the capacity cost at the margin show the following properties: $\partial g(K_R;\alpha)/\partial K_R = \overline{h}/N =: \widehat{h} > 0$, $\partial^2 g(K_R;\alpha)/\partial K_R^2 = 0$, $\partial g(K_R;\alpha)/\partial\alpha = \partial H(\alpha)/\partial\alpha < 0$ and $\partial^2 g(K_R;\alpha)/\partial K_R\partial\alpha = 0$. Additionally, let us assume that the conditions $H(\alpha^{min}) > (1-\sigma)\left(c_A + \delta_A + F_A\right)$ and $\overline{h} + H(\alpha^{max}) \leq (1-\sigma)\, c_A$ are satisfied. These conditions state that, in principle, RE might not be competitive against the base-load technology and vice versa. Later, the analysis focuses on the range of cost parameter α that captures the relevant situation in which each technology is employed in

state, even if technology A could quickly be ramped up and switched off. The dispatchability assumption about technology A, however, helps to streamline some technical arguments later on without affecting the results.

[7] Heterogeneous RE capacity costs are often assumed. See, e.g., Ambec and Crampes (2019).

some state of nature. In any case, RE generation causes no environmental damage.

A consumer's gross benefit, or willingness-to-pay, for electricity is captured by the instantaneous utility function $U(Q)$, which is identical for all individuals. This continuously differentiable function is non-negative, strictly increasing and strictly concave over the relevant range of electricity consumption. That is, $U(Q) \geq 0, U'(Q) > 0$ and $U''(Q) < 0$. Additionally, the conditions $U'(0) > c_B + \delta_B + (F_B/\sigma)$ and $U'(N) < \left[\overline{h} + H(\alpha^{max})\right] / (1 - \sigma)$ are satisfied. This means that on the one hand, marginal utility is sufficiently high for low consumption levels to make the peak-load technology economically viable. On the other hand, the marginal utility is sufficiently low for high consumption levels to ensure that neither the entry of all RE firms nor the infinite consumption of base-load or peak-load electricity can constitute a socially optimal solution or a market equilibrium.

Acting as price takers, consumers purchase electricity in the retail market, which connects electricity generators with final customers. A share θ of consumers pay real-time retail prices. As explored below, these consumers face either price p_0 or p_1, depending on whether the state of nature is 0 (non-windy) or 1 (windy), and consume the corresponding electricity, either Q_0 or Q_1. The other consumers, whose share is $1-\theta$, pay a time-invariant retail price $\overline{p}$ and consume $\overline{Q}$ irrespective of the state of nature. Normalising the number of consumers to unity, the shares θ and $1 - \theta$ also stand for the number, or mass, of customers in the two groups.

Competitive firms in the retail sector buy electricity from the monopolist and RE generators in the wholesale market and sell electricity to consumers in the retail market. Let us assume that these retailers face no other costs than the wholesale price of electricity. They purchase electricity for each point in time in state-contingent wholesale markets. Competing in Bertrand fashion in the retail market, the firms of the retail sector choose prices p_0, p_1 and $\overline{p}$.

The government has technology-specific capacity taxes in addition to technology- and state-specific emission taxes at its disposal. The capacity taxes τ_A and τ_B are to be paid for each unit of base-load and peak-load capacity, respectively. The emission taxes t_{A0} (t_{B0}) and t_{A1} (t_{B1}) are levied on each electricity unit generated by the base-load (peak-load) technology in the non-windy and windy periods, respectively.[8] In section 7, feed-in tariffs are briefly discussed as alternative policy instrument. While firms and consumers aim at profit and utility maximisation, respectively, the government's objective is to maximise the aggregate benefit from electricity consumption net of total fixed and variable generation costs and of environmental damage, as detailed in the next section.

Firms, consumers and the government are engaged in a four-stage game. The government chooses its policies in the first stage. In the second stage, the monopolist decides on its base-load and peak-load capacities. In the third stage, the potential RE firms simultaneously and non-cooperatively decide whether they enter the market and invest in

[8]If emissions per output unit are constant in output, then each tax per emission unit can obviously be converted into a tax per output unit. The latter interpretation is adopted for notational convenience.

one unit of RE capacity each. Market interactions in the wholesale and retail markets take place in the fourth stage. This game is solved for its subgame-perfect Nash (SPN) equilibrium.

3 Welfare Optimum in a Changing Environment

Before the equilibrium of the game is determined, let us explore the socially optimal outcome and how it changes as the RE capacity costs decline and consumer flexibility increases. The welfare-maximising outcome serves as a benchmark and enables us to determine optimal policies.

3.1 Optimal Capacities and Electricity Generation

As stated above, and explored in section 4, some costumers pay a time-invariant retail price and thus consume a constant amount of electricity across states of nature in market equilibrium. To have a meaningful socially optimal outcome as benchmark, let us determine the welfare optimum that is second-best in the sense that the share $1-\theta$ of individuals consuming electricity $\overline{Q}$ invariantly across states of nature is taken as given. Moreover, let us focus on the range of cost parameter α for which each of the three technologies A, B and R is used in at least one state of nature. (Lemma 2 below proves that such a relevant range exists.) Obviously, the RE technology R only generates electricity in the windy state of nature. By contrast, the peak-load technology B is only used in the non-windy state of nature when the RE technology R is not available (i.e., $Q_{B1}=0$). This follows directly from the fact that when employed permanently, the base-load technology A can produce electricity at lower social costs than the peak-load technology B. Then, the aggregate benefit from electricity consumption net of total fixed and variable generation costs and of environmental damage is given by the welfare function

$$\begin{aligned} W = \sigma &\left[\theta U(Q_0) + (1-\theta)\, U(\overline{Q}) - (c_A+\delta_A)\, Q_A - (c_B+\delta_B)\, Q_{B0}\right] \\ &+ (1-\sigma)\left[\theta U(Q_1) + (1-\theta)\, U(\overline{Q}) - (c_A+\delta_A)\, Q_A\right] \\ &- F_A K_A - F_B K_B - G(K_R;\alpha) \end{aligned} \tag{1}$$

s.t.

$$\begin{aligned} &Q_A \le K_A,\ Q_{B0} \le K_B,\ Q_R \le K_R, \\ &\theta Q_0 + (1-\theta)\,\overline{Q} = Q_A + Q_{B0},\ \theta Q_1 + (1-\theta)\,\overline{Q} = Q_A + Q_R. \end{aligned} \tag{2}$$

The right-hand side of the first line of function (1) captures the welfare generated in the σ non-windy periods. The first two terms in the square brackets show the utility from electricity consumption of the shares θ and $1-\theta$ of individuals who consume Q_0 in the non-windy state of nature and $\overline{Q}$ time-invariantly. The remaining two terms contain the variable costs and environmental damage of generating electricity Q_A and Q_{B0}. Similarly, the second line captures the welfare from electricity consumption in the $1-\sigma$ windy periods. Then, only the use of the base-load technology causes variable costs. The third line shows the fixed costs of building up the base-load, peak-load and RE capacities. Finally, the first line of eq. (2) contains the capacity constraints of electricity generation, while the second line states that consumption must equal output at each point in time in both windy and non-windy periods.

In optimum, a technology may be used in only one of the two states of nature, but if it is employed in a period, then always at full capacity. Leaving some capacity completely idle in all states of nature would be a waste of resources. Thus, capacity constraints are binding when technologies are used, i.e., $Q_A = K_A$, $Q_{B0} = K_B$ and $Q_R = K_R$. Plugging these constraints into the second line of eq. (2) gives consumption levels Q_0 and Q_1 as functions of capacities K_A, K_B and K_R and of consumption level $\overline{Q}$:

$$Q_0 = \frac{1}{\theta}\left[K_A + K_B - (1-\theta)\,\overline{Q}\right] \text{ and } Q_1 {=} \frac{1}{\theta}\left[K_A + K_R - (1-\theta)\,\overline{Q}\right] \tag{3}$$

Taking account of the binding capacity constraints and the resulting consumption levels (3), maximising welfare (1) yields the first-order conditions[9]

$$\frac{\partial W}{\partial \overline{Q}} = (1-\theta)\left[U'(\overline{Q}) - \sigma U'(Q_0) - (1-\sigma)\,U'(Q_1)\right] = 0, \tag{4}$$

$$\frac{\partial W}{\partial K_R} = (1-\sigma)\,U'(Q_1) - g(K_R;\alpha) = 0, \tag{5}$$

$$\frac{\partial W}{\partial K_A} = \sigma U'(Q_0) + (1-\sigma)\,U'(Q_1) - (c_A + \delta_A) - F_A = 0, \tag{6}$$

$$\frac{\partial W}{\partial K_B} = \sigma\left[U'(Q_0) - (c_B + \delta_B)\right] - F_B = 0. \tag{7}$$

The interpretation of these conditions is straightforward. Condition (4) means that the marginal utility $U'(\overline{Q})$ of individuals with time-invariant consumption has to be equal to the weighted marginal utilities $\sigma U'(Q_0) + (1-\sigma)\,U'(Q_1)$ of those with time-variant consumption, with weights given by the total length of non-windy and windy periods. This condition guarantees that consumption is efficiently allocated between these two groups of consumers.

The remaining three conditions (5), (6) and (7) ensure socially optimal capacity and output levels. In the case of the peak-load technology, the social costs of marginally increasing capacity and thus electricity generation at each point in time in the non-windy periods, i.e., $\sigma\,(c_B + \delta_B) + F_B$, have to equal the marginal utility of electricity consumption in these periods, i.e., $\sigma U'(Q_0)$. Similarly, the marginal benefit in the windy periods, i.e., $(1-\sigma)\,U'(Q_1)$, has to match the cost of marginally increasing RE capacity and thus electricity generation in these periods, i.e., $g(K_R;\alpha)$. As the base-load technology is employed at each point in time, its marginal social costs of capacity and electricity

[9]The second-order conditions are satisfied.

generation, i.e., $c_A + \delta_A + F_A$, needs to be equal to the marginal utility across non-windy and windy periods, i.e., $\sigma U'(Q_0) + (1-\sigma)\,U'(Q_1)$.

Rearranging the first-order conditions gives

$$U'(\overline{Q}) = c_A + \delta_A + F_A, \tag{8}$$

$$U'(Q_0) = c_B + \delta_B + \frac{F_B}{\sigma}, \tag{9}$$

$$U'(Q_1) = \frac{1}{1-\sigma}\left[c_A + \delta_A + F_A - \sigma\left(c_B + \delta_B + \frac{F_B}{\sigma}\right)\right], \tag{10}$$

$$c_A + \delta_A + F_A = \sigma\left(c_B + \delta_B + \frac{F_B}{\sigma}\right) + g(K_R;\alpha). \tag{11}$$

These alternative characterisations provide some additional insights and prove to be convenient for the following comparative statics. Condition (11) characterises the efficient choice of technology for any given output level. To understand this condition, recall that marginally increasing electricity generation with the base-load technology induces social generation and capacity costs of $c_A + \delta_A + F_A$. To keep total electricity output constant, both peak-load and RE generators need to marginally cut their output at each point in time at which these technologies are employed. The reduction in peak-load and RE generation and capacity costs amount to $\sigma(c_B + \delta_B) + F_B + g(K_R;\alpha)$. In social optimum, these cost savings equal the additional cost of generating base-load electricity, as stated in condition (11).

This condition implies that the cost parameters of the base-load and peak-load technologies fix the RE capacity cost at the margin. They also fully determine the shadow prices $U'(Q_0)$, $U'(Q_1)$ and $U'(\overline{Q})$ of consumption and thus the individual consumption levels Q_0, Q_1 and $\overline{Q}$, as shown in conditions (8), (9) and (10). These model properties simplify the otherwise unwieldy comparative-statics analysis below.[10]

3.2 RE Capacity Costs and Consumer Flexibility

Having derived the optimality conditions above, the impact of a decline in RE capacity costs (i.e., an increase of the cost parameter α) and of the growth of consumer share θ on the socially optimal outcome can be analysed. For brevity, the θ individuals whose electricity consumption is time-variant are referred to as flexible consumers, the remaining $1-\theta$ are referred to as inflexible ones. Let us start with some preliminary considerations. Conditions (8) to (10) directly imply lemma 1.

Lemma 1. *Independence of Individual Consumption Levels.*
In the socially optimal outcome, individual consumption levels Q_0, $Q_1$and $\overline{Q}$ are inde-

[10]These conditions also show that the costs of electricity generation varies widely between the technologies in social optimum, simply reflecting the fact that these technologies are imperfect substitutes. As Joskow (2011) stresses, comparing costs of intermittent and dispatchable technologies is of limited meaning. The same is true for comparing costs of dispatchable base-load and peak-load technologies, as highlighted by Borenstein (2012).

pendent of RE capacity cost parameter α and the share θ of flexible consumers (i.e., $dQ_i/d\alpha = d\overline{Q}/d\alpha = dQ_i/d\theta = d\overline{Q}/d\theta = 0$, $i = 0, 1$), and so are the shadow prices $U'(Q_0)$, $U'(Q_1)$ and $U'(\overline{Q})$.

The proofs of all lemmas, propositions and corollaries are relegated to the appendix. As lemma 1 clarifies, a decline in RE capacity costs or an increase in the share of flexible consumers does not shape the optimal outcome through its impact on individual consumption levels of the two consumer types. Such changes can thus only influence the optimal allocation through its effect on the pattern of electricity generation and aggregate consumer behaviour. To confirm this notion, let us first explore the role of RE capacity costs. Recall that an increase in cost parameter α reduces the RE capacity cost at the margin, i.e., $\partial g(k;\alpha)/\partial\alpha = \partial H(\alpha)/\partial\alpha < 0$, as outlined in section 2.

Lemma 2. *Threshold Values of RE Capacity Cost Parameter α.*
(i) For RE capacity cost parameter α, threshold levels $\underline{\alpha}$ and $\overline{\alpha}$ exist such that (a) $K_A > 0$ and $K_B = 0$ if $\alpha = \underline{\alpha}$, *(b)* $K_A > 0$ and $K_B > 0$ *if $\alpha \in (\underline{\alpha}, \overline{\alpha})$, and (c)* $K_A = 0$ and $K_B > 0$ if $\alpha = \overline{\alpha}$.
(ii) Capacity, production and individual consumption levels are ranked as follows: for all $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, $Q_{B0} = K_B < Q_R = K_R$ and $Q_0 < \overline{Q} < Q_1$.

The first part of lemma 2 establishes that there indeed exists a range of parameter values of α so that the capacities of all technologies are positive in the socially optimal outcome. The intuition of lemma 2's conclusions is best explained after, and in conjunction with, proposition 1.

Proposition 1. *Impact of a Decline in RE Capacity Costs.*
Consider the case with $\alpha \in [\underline{\alpha}, \overline{\alpha}]$. *As RE capacity costs decline (i.e., as parameter α increases from $\underline{\alpha}$ to $\overline{\alpha}$), the socially optimal capacity, consumption and environmental damage levels adjust as follow:*
(i) RE capacity K_R increases. Formally, $dK_R/d\alpha > 0$.
(ii) Base-load capacity K_A decreases by the same amount as RE capacity K_R increases. Formally, $dK_A/d\alpha = -dK_R/d\alpha < 0$.
(iii) Peak-load capacity K_B increases by the same amount as RE capacity K_R increases. Formally, $dK_B/d\alpha = dK_R/d\alpha > 0$.
(iv) Aggregate electricity consumption remains constant in each state of nature, and so does total electricity consumption across the two states of nature. More precisely, $d(K_A + K_B)/d\alpha = d(K_A + K_R)/d\alpha = 0$ and $d[\sigma(K_A + K_B) + (1-\sigma)(K_A + K_R)]/d\alpha = 0$.
(v) Total environmental damage D, with $D = \delta_A K_A + \sigma\delta_B K_B$, will decrease (increase) if, and only if, the pollution parameter δ_A of the base-load technology is greater (smaller) than the threshold level $\sigma\delta_B$. Formally, $dD/d\alpha \lesseqgtr 0 \Leftrightarrow \delta_A \gtreqless \sigma\delta_B$.

The comparative-statics results in proposition 1 are straightforward. A decline in RE capacity costs raises RE capacity and electricity generation, crowding out base-load capacity and power by the very same amount in the optimal solution. The associated decline in electricity generation in the non-windy state of nature is, in turn, fully compensated by the induced increase in peak-load capacity and electricity. The fact that base-load capacity declines by the same amount as RE and peak-load capacities increase directly follows from lemma 1. For given consumer share θ, individual and aggregate consumption levels stay the same across the two states of nature, simply reflecting that capacity and generation costs do not change at the margin in either state of nature in optimum. As RE capacity costs decline, RE capacity has to increase to restore its initial cost level at the margin. Base-load and peak-load capacities adjust accordingly to maintain the unchanged optimal consumption levels. In social optimum, only the capacity composition adjusts in response to declining RE costs, but not aggregate electricity generation.

The environmental implications of a decline in RE capacity are ambiguous. Dirty base-load electricity is replaced with clean RE electricity in the windy state of nature, but with potentially even dirtier peak-load electricity in the non-windy state of nature. Total environmental damage will only fall if the peak-load technology is not too dirty relative to the base-load technology (i.e., $\delta_B < \delta_A/\sigma$). Otherwise, total environmental damage increases.[11] In this case, cost-saving considerations are the key driver for employing more RE technology, and not the fact that RE is cleaner. With RE costs falling, any amount of electricity can be produced at lower overall costs by replacing base-load capacity with RE and peak-load capacities, even if the impact on the environment is negative, as implied by condition (11) and the corresponding discussion above.

The comparative-statics analysis above already indicates that all technologies are employed only for a bounded interval of α values. For $\alpha = \overline{\alpha}$, RE costs are so low that base-load capacity is just about to be completely crowded out. By contrast, for $\alpha = \underline{\alpha}$, base-load electricity alone is still so prominent that the shadow value $U'(Q_0)$, with $Q_0 = (1/\theta)\left[K_A - (1-\theta)\,\overline{Q}\right]$, just equals the marginal social generation and capacity costs of the peak-load technology, i.e., $c_B + \delta_B + (F_B/\sigma)$. At this point, employing the peak-load technology becomes just viable in optimum, and only for $\alpha \in (\underline{\alpha}, \overline{\alpha})$ capacities of all technologies will be positive. Not surprisingly, for the whole interval $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, a flexible individual always consumes more electricity than an inflexible individual in the windy state of nature (i.e., $Q_1 > \overline{Q}$), and less in the non-windy state (i.e., $Q_0 < \overline{Q}$). Since both the consumption of inflexible consumers and the amount of base-load electricity are state-independent, peak-load capacity and electricity generation can only fall short of RE capacity and energy generation (i.e., $Q_{B0} = K_B < Q_R = K_R$).

As the next proposition establishes, an increase in consumer flexibility, which can be enabled through the spread of smart meters, leads to effects that are in contrast to those

[11] In a similar vein, Holland et al. (2022) argue that lower RE capital costs can in general lead to more or less emissions. In the current analysis, the conditions for these outcomes to occur in social optimum are specified.

explained above.

Proposition 2. *The Impact of an Increase in Consumer Flexibility.*
As the share θ of flexible consumers increases, the socially optimal capacity, consumption and environmental damage levels adjust as follow:
(i) RE capacity K_R remains constant. Formally, $dK_R/d\theta = 0$.
(ii) Base-load capacity K_A increases. Formally, $dK_A/d\theta > 0$.
(iii) Peak-load capacity K_B decreases. Formally, $dK_B/d\theta < 0$.
(iv) Aggregate electricity consumption decreases in the non-windy state, while it increases in the windy state. Formally, $d\left(K_A + K_B\right)/d\theta < 0$ and $d\left(K_A + K_R\right)/d\theta > 0$.
(v) Total electricity consumption across the two states of nature will increase (decrease) if the marginal utility, or demand, function is convex (concave). Formally,
$d\left[\sigma\left(K_A + K_B\right) + (1-\sigma)\left(K_A + K_R\right)\right]/d\theta \gtreqless 0$ if $U'''(Q) \gtreqless 0$.
(vi) Total environmental damage $D = \delta_A K_A + \sigma\delta_B K_B$ will decrease (increase) if, and only if, the pollution parameter δ_A of the base-load technology is smaller (greater) than the threshold level $\sigma\delta_B\left(Q_1 - Q_0\right)/\left(Q_1 - \overline{Q}\right)$. Formally, $dD/d\theta \lesseqgtr 0 \Leftrightarrow \delta_A \lesseqgtr \sigma\delta_B(Q_1 - Q_0)/(Q_1 - \overline{Q})$.

A flexible response of consumers to changing supply situations is often seen as a prerequisite for a more widespread use of intermittent RE technologies. Indeed, an increase in the share θ of flexible households shifts socially optimal electricity consumption and production from the non-windy state of nature to the windy one, as expected. However, this shift leaves the optimal RE capacity unaffected in the current model. Instead, it should be achieved by employing more base-load and less peak-load capacity, enabling an overall less expensive electricity generation.[12] Thereby, the technology mix changes without affecting social generation and capacity costs at the margin.

This reasoning, which underpins the conclusions in parts (i) to (iv) of proposition 2, clearly follows again from condition (11). Just assume that instead of base-load capacity, RE capacity would be increased as consumer share θ grows. Such an adjustment would drive up RE costs and bring condition (11) out of balance. The technology choice would not be optimal anymore, as any amount of electricity could be produced at lower social costs by using more base-load capacity and less peak-load and RE capacities.[13]

Total electricity consumption across the two states of nature rises (falls) in response to a higher share θ if the marginal utility function is convex (concave), as stated in part

[12]This conclusion underlines the importance of distinguishing between base-load and peak-load technologies, since the adjustment would obviously be different in a model with only one conventional technology (see Ambec and Crampes, 2021).

[13]Analysing competitive electricity markets in which stochastic demand and supply are partly correlated with each other and can lead to outage, Chao (2011) conducts simulations that yield a similar result: moving all customers from time-invariant to real-time prices reduces (increases) electricity generation with a conventional peak-load (base-load) technology, despite the presence of RE. However, Chao's (2011) and the current model are not directly comparable. In the current, simpler model, the impact of marginal changes in the share of flexible consumers on capacities can be determined analytically and explained without relying on simulations.

(v) of proposition 2. To understand this conclusion, let us take a linear marginal utility, or demand, function as benchmark. In this benchmark, the 'new' flexible individuals consume as much more electricity in the windy periods as they consume less in the non-windy periods, compared to their consumption as inflexible consumers, thus leaving their total consumption unaltered. With a convex utility function instead of a linear one, and starting from the inflexible consumption level $\overline{Q}$, the shadow value $U'(Q)$ decreases less rapidly as Q increases, and increases more rapidly as Q decreases. As a result, the optimal additional consumption of the 'new' flexible individuals in the windy periods is higher, and the optimal reduction in their consumption in the non-windy periods is curbed, compared to the benchmark case of a linear marginal utility curve. Consequently, overall electricity consumption increases. For the case of concave utility functions, this reasoning can simply be reversed, leading to the conclusion that overall consumption decreases.

The impact of a larger share θ of flexible consumers on total environmental damage is ambiguous, since there are again opposing effects on pollution at work. More base-load electricity raises pollution, while less peak-load capacity reduces pollution. In contrast to the conclusion of proposition 1, total environmental damage will now decrease only if the peak-load technology is sufficiently dirty compared to the base-load technology (i.e., $\delta_B > \delta_A(Q_1 - \overline{Q})/[\sigma(Q_1 - Q_0)]$). Otherwise, total environmental damage increases. In fact, for equally polluting conventional technologies (i.e., $\delta_A = \delta_B$), total environmental damage decreases (increases) under the same condition under which total electricity consumption decreases (increases). This is stated in the corollary 1, which also further highlights the potentially contrasting effects of a decline in RE capacity costs and an increase in consumer flexibility on total environmental damage.

Corollary 1. *Environmental Damage.*
(i) For $\delta_A < \sigma\delta_B$, total environmental damage D increases as RE capacity costs decline, and it decreases as consumer share θ grows. For $\sigma\delta_B \leq \delta_A \leq \sigma\delta_B(Q_1 - Q_0)/(Q_1 - \overline{Q})$, total damage D decreases as RE capacity costs decline and consumer share θ increases. Finally, for $\sigma\delta_B(Q_1 - Q_0)/(Q_1 - \overline{Q}) < \delta_A$, total damage D decreases as RE capacity costs decline, and it increases with consumer share θ.
(ii) Consider the case in which base-load and peak-load technologies are equally polluting (i.e., $\delta_A = \delta_B$). Then, total environmental damage decreases as RE capacity costs decline. Formally, $dD/d\alpha < 0$. By contrast, total environmental damage decreases (increases) as consumer share θ grows if the marginal utility function is concave (convex). Alternatively, $dD/d\theta \lesseqgtr 0$ if $U'''(Q) \lesseqgtr 0$.

As corollary 1 points out, neither a decline in RE costs nor an increase in the share of flexible consumers necessarily goes hand in hand with a decrease in total environmental damage in social optimum. In fact, only for specific parameter constellations do both a lower RE cost and a higher consumer flexibility reduce overall pollution.

4 Environmental Policy in a Liberalised Market

Having characterised the socially optimal outcome and how it changes in response to declining RE capacity costs and increasing consumer flexibility, let us next determine the SPN equilibrium in a liberalised electricity market and the optimal environmental policy.

4.1 Market Equilibrium

Solving the model by means of backward induction, the interactions in the electricity markets in the fourth stage are analysed first. This subsection then explores the RE capacity choices, or RE market entry decisions, in the third stage and afterwards the monopolist's capacity choices in the second stage. Finally, the government's policy choices in the first stage are characterised in subsection 4.2.

Retail and Wholesale Markets

In the fourth stage, energy suppliers, retailers and households interact in the retail and wholesale markets. In the retail market, flexible households face real-time prices p_0 and p_1 in the non-windy periods and the windy ones, respectively, while inflexible households pay the time-invariant price $\overline{p}$ irrespective of the state of nature. With individuals maximising the utility from electricity consumption net of payments, individual instantaneous inverse demands are given by the marginal utility function:

$$p_0 = U'(Q_0), \quad p_1 = U'(Q_1), \quad \overline{p} = U'(\overline{Q}), \tag{12}$$

where $U'(Q_0)$ and $U'(Q_1)$ capture the inverse demands of the flexible consumers in the non-windy state and the windy one, and $U'(\overline{Q})$ stands for the inverse demand of the inflexible consumers.

Retailers compete for final customers in Bertrand fashion. As they have no costs other than wholesale electricity costs, retail prices p_0 and p_1 coincide with the wholesale prices in the non-windy and windy states of nature. (Thus, there is no separate notation for wholesale prices.) In equilibrium, retail firms are also indifferent between selling to flexible and inflexible customers. This requires that the time-invariant retail price $\overline{p}$ equals the average wholesale price, yielding the arbitrage condition $\overline{p} = \sigma p_0 + (1-\sigma)\, p_1$ or, plugging in demand (12),

$$U'(\overline{Q}) = \sigma U'(Q_0) + (1-\sigma)\, U'(Q_1). \tag{13}$$

In the wholesale market, the aggregate demands of retail firms are $\theta Q_0 + (1-\theta)\, \overline{Q}$ and $\theta Q_1 + (1-\theta)\, \overline{Q}$ in the non-windy state and the windy one, which are simply the sums of the state-dependent demands of the θ flexible individuals and the invariant demand of the $1-\theta$ inflexible individuals. Retail firms purchase their electricity in state-contingent markets for the windy state of nature and the non-windy one.

In the windy state of nature, profit-maximising RE generators choose to produce at full capacity and supply $Q_R = K_R$ as long as price p_1 is non-negative (which is the case in equilibrium), since the marginal cost is zero at this stage and investment costs are sunk. Similarly, the monopolist employs the base-load technology at full capacity and supplies $Q_A = K_A$ across both states of nature if the marginal revenues exceed the marginal generation costs and emission taxes at this output level. This is the case in equilibrium, since a profit-maximising monopolist on its own would never build up capacities that lay completely idle, and a welfare-maximising government would never incentivise such a socially suboptimal strategy. In the same vein, the monopolist fully uses its peak-load capacity and supplies $Q_{B0} = K_B$, but only in the non-windy state of nature. As this technology exhibits higher costs than the base-load technology when employed permanently, the monopolist on its own never uses the peak-load technology in both states of nature, but only in the state of nature in which electricity is scarcer. Moreover, the government would always face incentives to prevent the monopolist from doing otherwise by levying a prohibitive emission tax t_{B1}. To summarise, decision paths that do not lead to $Q_A = K_A$, $Q_{B0} = K_B$, $Q_{B1} = 0$ and $Q_R = K_R$ are inconsistent with an SPN equilibrium.

Thus, instantaneous aggregate supply is $K_A + K_B$ in the non-windy state of nature and $K_A + K_R$ in the windy one. Then, the market-clearing conditions are

$$\theta Q_0 + (1-\theta)\,\overline{Q} = K_A + K_B, \tag{14}$$

$$\theta Q_1 + (1-\theta)\,\overline{Q} = K_A + K_R. \tag{15}$$

RE Capacity

In the third stage, the potential RE generators decide whether or not to enter the market. Facing no costs other than their investment, they do so as long as revenue $(1-\sigma)\,p_1$ in the fourth stage weakly exceeds capacity cost $g(k;\alpha)$. Using inverse demand $U'(Q_1) = p_1$, the resulting zero-profit condition of the marginal RE generator is

$$\pi_R(K_R;\alpha) = (1-\sigma)\,U'(Q_1) - g(K_R;\alpha) = 0, \tag{16}$$

where $\pi_R(K_R;\alpha)$ stands for the profit of the marginal RE firm in the market.

Base-load and Peak-load Capacities

In the second stage, the monopolist chooses the base-load and peak-load capacities K_A and K_B. As the firm anticipates the impact of the capacity choices on the decisions in the ensuing stages, inverse demands $p_0 = U'(Q_0)$ and $p_1 = U'(Q_1)$ and outputs $Q_A = K_A$

and $Q_{B0} = K_B$ can already be plugged into the profit function of the monopolist, yielding

$$\begin{aligned}\pi_M = \sigma \left[U'(Q_0)\left(K_A + K_B\right) - \left(c_A + t_{A0}\right) K_A - \left(c_B + t_{B0}\right) K_B\right] \\ + (1-\sigma)\left[U'(Q_1) K_A - \left(c_A + t_{A1}\right) K_A\right] \\ - \left(F_A + \tau_A\right) K_A - \left(F_B + \tau_B\right) K_B,\end{aligned} \tag{17}$$

which includes the technology-specific capacity taxes τ_A and τ_B and technology- and state-of-nature-specific emission taxes t_{A0}, t_{A1} and t_{B0}. The first line on the right-hand side captures the monopolist's revenue net of the variable production costs (including the technology- and state-dependent emission taxes) that accrue in the σ non-windy periods when both base-load and peak-load power stations run at full capacity. The second line is the counterpart for the windy periods, in which only the base-load technology is used, again at full capacity. Finally, the third line contains the capacity costs and taxes.

The first of the two first-order conditions for the profit-maximising capacities is

$$\begin{aligned}\frac{d\pi_M}{dK_A} = \sigma[U'(Q_0) + \underbrace{U''(Q_0)\frac{dQ_0}{dK_A}\left(K_A + K_B\right)}_{\text{own-market effect } \Lambda_{A0}:=} - \left(c_A + t_{A0}\right)] \\ + (1-\sigma)\left[U'(Q_1) + \underbrace{U''(Q_1)\frac{dQ_1}{dK_A} K_A}_{\text{own-market eff. } \Lambda_{A1}:=} - \left(c_A + t_{A1}\right)\right] - \left(F_A + \tau_A\right) \\ + \underbrace{[\sigma \underbrace{U''(Q_0)\frac{dQ_0}{dK_R}\left(K_A + K_B\right)}_{\text{cross-market effect } \Psi_{R0}:=} + (1-\sigma)\underbrace{U''(Q_1)\frac{dQ_1}{dK_R} K_A}_{\text{own-market eff. } \Lambda_{R1}:=}]\frac{dK_R}{dK_A}}_{\text{strategic investment effect}} = 0,\end{aligned} \tag{18}$$

where the signs of the derivatives on the right-hand side are as follows:

$$\frac{dQ_0}{dK_A} = \frac{dQ_1}{dK_A} > 0, \quad \frac{dQ_0}{dK_R} \leq 0, \quad \frac{dQ_1}{dK_R} > 0, \quad \frac{dK_R}{dK_A} \in (-1, 0)\,. \tag{19}$$

The first and second line on the right-hand side of the first-order condition (18) imply the standard conclusion that marginal revenues equal marginal costs including the emission taxes in optimum. Only, the terms are weighted according to the duration of the two states of nature, and the marginal cost and tax of building up base-load capacity are added. The second terms in the square brackets in the first and second line show the indirect effects of an increase in capacity on the monopolist's revenues through price changes that occur in the markets in which output rises, referred to, for brevity, as *own-market effects* Λ_{A0} and Λ_{A1}. Not surprisingly, an increase in base-load capacity K_A raises the quantities Q_0 and Q_1 that are traded in the market equilibrium in the fourth stage (i.e., $dQ_i/dK_A > 0$, $i = 0, 1$) and depresses the corresponding prices p_0 and p_1 (i.e., $U''(Q_j)\,(dQ_j/dK_A) < 0$), since it directly increases the supply in both states of nature. Thus, the own-market effects Λ_{A0} and Λ_{A1} are negative. [The results of the bulky comparative statics on the relationships between the capacities and the equilibrium quantities, and between the RE capacity on the one hand and the base-load and peak-load capacities on the other, are provided in the appendix, with eqs. (19) above and (21) below just summarising the signs. See eqs. (A.7) to (A.15) in the appendix.]

The third line of the first-order condition (18) as a whole captures the effect of a higher base-load capacity on the monopolist's revenues through its impact on RE capacity, referred to as *strategic investment effect* in the following. The term outside the square brackets is straightforward. An increase of base-load capacity and thus supply in the windy periods depresses price p_1. This in turn discourages RE firms from entering the market. That is, capacities K_R and K_A are strategic substitutes ($dK_R/dK_A < 0$).

A change in RE capacity, in turn, leads to two opposing effects on the monopolist's revenues, as shown by the terms in the square brackets of the third line. An increase in RE capacity K_R raises the RE supply and thus quantity Q_1 traded in windy periods, thereby depressing price p_1 (i.e., $U''(Q_1)\,(dQ_1/dK_R) < 0$) and the monopolist's revenues that accrue in these periods. This negative *own-market effect* Λ_{R1}, included in the second term in the square brackets in the third line, is opposed by a positive *cross-market effect* Ψ_{R0}, included in the first term. A lower price p_1 in windy periods means that the time-invariant price $\overline{p}$ also falls. This, in turn, boosts demand of inflexible consumers in the non-windy periods, which drives up overall demand $\theta Q_0 + (1-\theta)\,\overline{Q}$ and price p_0 (i.e., $U''(Q_0)\,(dQ_0/dK_R) > 0$), thereby inevitably crowding out some consumption of flexible households (i.e., $dQ_0/dK_R < 0$). Higher overall demand and price raise the monopolist's revenue in the non-windy state of nature (i.e., $\Psi_{R0} > 0$).

Overall, the strategic investment effect is positive (negative), and the monopolist strategically overinvest (underinvest) in base-load capacity K_A, if the weighted own-market effect dominates (is dominated by) the weighted cross-market effect, with weights being again σ and $1-\sigma$. Then, with base-load capacity K_A depressing RE capacity K_R, the positive effect of less RE capacity on the monopolist's revenue in the windy periods more than (less than) compensates for the negative impact of less RE capacity on the revenue in the non-windy ones (i.e., $(1-\sigma)\,\Lambda_{R1}\,(dK_R/dK_A) > (<) |\sigma\Psi_{R0}\,(dK_R/dK_A)|$). As explored in sections 5 and 6, the overall sign of the strategic investment effect is systematically related to the RE capacity costs and the share of flexible consumers.

The second first-order condition is given by

$$\begin{aligned}\frac{d\pi_M}{dK_B} = \sigma[U'(Q_0) + &\underbrace{U''(Q_0)\frac{dQ_0}{dK_B}(K_A+K_B)}_{\text{own-market effect }\Lambda_{B0}:=} - (c_B + t_{B0})] \\ &+ (1-\sigma)\underbrace{U''(Q_1)\frac{dQ_1}{dK_B}K_A}_{\text{cross-market eff. }\Psi_{B1}:=} - (F_B+\tau_B) \qquad (20)\\ &+ \left[\sigma U''(Q_0)\frac{dQ_0}{dK_R}(K_A+K_B) + (1-\sigma)\,U''(Q_1)\frac{dQ_1}{dK_R}K_A\right]\frac{dK_R}{dK_B} = 0,\end{aligned}$$

where the missing signs of the derivatives on the right-hand side are as follows:

$$\frac{dQ_0}{dK_B} > 0, \quad \frac{dQ_1}{dK_B} \leq 0, \quad \frac{dK_R}{dK_B} \in [0, 1)\,. \tag{21}$$

As already mentioned, the details of the derivatives (19) and (21) are presented in the appendix. The first line of the second-order condition (20) is the counterpart to the first line of condition (18). Thus, it needs no further explanation, and neither does the term $(F_B + \tau_B)$ in the second line.

The first term of the second line contains the *cross-market effect* Ψ_{B1}, whose explanation is in line with that of the previous cross-market effect. An increase in peak-load capacity K_B and the corresponding output Q_{B0} reduces the state-dependent price p_0 and thus also the time-invariant price $\overline{p}$. This leads to a higher demand from inflexible customers in the windy periods, pushing up overall demand $\theta Q_1 + (1-\theta)\,\overline{Q}$ and price p_1 (i.e., $U''(Q_1)\,(dQ_1/dK_B) > 0$), now inevitably crowding out some consumption of flexible households in the windy periods (i.e., $dQ_1/dK_B < 0$). Higher overall demand and price improve the monopolist's revenue that accrues in the windy periods (i.e., $\Psi_{B1} > 0$). This positive effect on its profit incentivises the monopolist to overinvest in peak-load capacity and oversupply peak-load electricity. As the previous cross-market effect, this one also crucially hinges on the presence of inflexible customers. Without them (i.e., for $\theta = 1$), the link between the markets in the non-windy and windy states of nature breaks down. Then, both cross-market effects vanish (i.e., $\Psi_{B1} = \Psi_{R0} = 0$ because $dQ_1/dK_B = dQ_0/dK_R = 0$).

The third line captures the impact of peak-load capacity on revenues through its effect on RE capacity, and is thus the counterpart of the third line of the first-order condition (18). This effect is again referred to as *strategic investment effect*. The terms in the square brackets are the same as those in the third line of the first-order condition (18), since they both capture the same relationship between RE capacity and the monopolist's revenues. However, while an increase in base-load capacity reduces the mass of RE firms entering the market, an increase in peak-load capacity has the opposite effect. As it raises price p_1 through the cross-market effect (as long as there are some inflexible consumers; i.e., for $\theta < 1$), it attracts more RE capacity.[14] So while *base-load and RE capacities* are *strategic substitutes*, *peak-load and RE capacities* are *strategic complements*. Hence, while the overall strategic investment effect can again be positive or negative, it has for sure the opposite sign of its counterpart above. That is, whenever there is an incentive to strategically overinvest (underinvest) in base-load capacity, there is also an incentive to strategically underinvest (overinvest) in peak-load capacity.

[14] Again, for $\theta = 1$, there is no cross-market effect and thus no impact of base-load capacity on RE capacity (i.e., $dK_R/dK_B = 0$ for $\theta = 1$).

4.2 Optimal Emission and Capacity Taxes

In the first stage, the government sets the emission and capacity taxes such that welfare (1), which is equivalent to the sum of consumer surplus and profits net of environmental damage, is maximised. To explore the optimal policies, let us define the total base-load and peak-load tax burdens T_A and T_B as the sums of emission and capacity taxes per unit of output: $T_A = \sigma t_{A0} + (1-\sigma)\, t_{A1} + \tau_A$ and $T_B = t_{B0} + (\tau_B/\sigma)$. Then, a closer look at the first-order conditions (18) and (20) reveals that the optimal capacity choices K_A and K_B depend only on these total burdens T_A and T_B, and not on how the total tax burdens are exactly apportioned to the individual components, either t_{A0}, t_{A1} and τ_A or t_{B0} and τ_B. However, to facilitate the explanation of the comparative statics in the following sections, the total tax burdens are allocated such that the individual components address specific causes of market failure. More specifically, the emission taxes t_{A0}, t_{A1} and t_{B0} tackle the environmental externality caused by the corresponding technologies and the issue of market power in the corresponding states of nature. The capacity taxes deal with the distortive strategic investment incentives.

Then, comparing the first-order conditions (4) to (7) with the equilibrium conditions (13), (16), (18) and (20) yields a set of optimal taxes:

$$t_{A0} = \delta_A + \underbrace{U''(Q_0)\frac{dQ_0}{dK_A}\,(K_A + K_B)}_{\text{own-market effect } \Lambda_{A0}:=}, \tag{22}$$

$$t_{A1} = \delta_A + \underbrace{U''(Q_1)\frac{dQ_1}{dK_A}K_A}_{\text{own-market eff. } \Lambda_{A1}:=}, \tag{23}$$

$$t_A = \sigma t_{A0} + (1-\sigma)\, t_{A1}, \tag{24}$$

$$t_{B0} = \delta_B + \underbrace{U''(Q_0)\frac{dQ_0}{dK_B}\,(K_A + K_B)}_{\text{own-market effect } \Lambda_{B0}:=} + \frac{1-\sigma}{\sigma}\underbrace{U''(Q_1)\frac{dQ_1}{dK_B}K_A}_{\text{cross-market eff. } \Psi_{B1}:=}, \tag{25}$$

$$\tau_A = [\underbrace{\sigma U''(Q_0)\frac{dQ_0}{dK_R}\,(K_A + K_B)}_{\text{cross-market effect } \Psi_{R0}:=} + (1-\sigma)\underbrace{U''(Q_1)\frac{dQ_1}{dK_R}K_A}_{\text{own-market eff. } \Lambda_{R1}:=}]\frac{dK_R}{dK_A}, \tag{26}$$

$$\tau_B = [\overbrace{\sigma\, U''(Q_0)\frac{dQ_0}{dK_R}\,(K_A + K_B)} + (1-\sigma)\overbrace{U''(Q_1)\frac{dQ_1}{dK_R}K_A}]\frac{dK_R}{dK_B}, \tag{27}$$

with the signs of the derivatives again given by eqs. (19) and (21).

Technology- and state-dependent emission taxes t_{A0} and t_{A1} show the traditional characteristics of environmental taxes under imperfect competition. They are equal to marginal environmental damage δ_A corrected for what are labelled above the own-market effects Λ_{A0} and Λ_{A1}, respectively, and thus underinternalise the environmental damage as usual under imperfect competition (i.e., $t_{A0}, t_{A1} < \delta_A$). Instead of levying technology- and state-dependent emission taxes t_{A0} and t_{A1}, the government can simply impose the technology-dependent tax t_A, irrespective of the state of nature, as implied by the discussion above. Emission tax t_A is simply the average of the state-dependent ones weighted according to the duration of the non-windy and windy periods.

Emission tax t_{B0} takes account of the cross-market effect Ψ_{B1} in addition to the negative own-market effect Λ_{B0}. As the cross-market effect is positive and incentivises the monopolist to increase peak-load power generation (see discussion above), it raises the tax and thus counteracts the underinternalisation of environmental damage caused by the own-market effect, as further discussed below. The tax formulas (22) to (27) do not include emission tax t_{B1}. Such a tax might be necessary to discourage the monopolist from employing the peak-load technology in windy periods and just needs to be 'sufficiently' high such that using peak-load technology in windy states is prohibitive.

Capacity taxes τ_A and τ_B eliminate the incentives to strategically over- or underinvest in base-load and peak-load capacities, respectively. The preliminary characterisation of these taxes in lemma 3 follows directly from our discussion of these strategic investment incentives in subsection 4.1.

Lemma 3. *Capacity Taxes and Subsidies.*
Assume that there are some inflexible consumers. Then, both capacity taxes τ_A and τ_B can be positive or negative. Whenever one of them is positive, the other one is negative, and vice versa. More precisely, for $\theta < 1$,

$$\tau_A \gtreqless 0 \Leftrightarrow K_A \gtreqless \sigma \frac{1-\theta}{\theta} \frac{U''(Q_0)}{U''(\overline{Q})} K_B \Leftrightarrow \tau_B \lesseqgtr 0. \tag{28}$$

Interestingly, when the capacity of one of the two conventional technologies should be subsidised, the capacity of the other one should be taxed. This issue is picked up below. In any case, capacity costs F_A and F_B are assumed to be sufficiently high so that they exceed any optimal subsidies $-\tau_A$ and $-\tau_B$ that are characterised by the tax formulas (26) and (27). In other words, the constraints $\tau_A > -F_A$ and $\tau_B > -F_B$ are assumed to be non-binding for the government when it chooses its welfare-maximising taxes, which is a fairly innocent assumption.[15]

Then, an SPN equilibrium is characterised by the emission and capacity taxes (22) to (27) in addition to the equilibrium conditions (13), (16), (18) and (20). With the taxes outlined above, the government can induce socially optimal output, consumption and capacity levels, which were characterised by conditions (8) to (11) and explored in section 3.

Before the comparative-statics properties of the environmental policy is analysed in the next section, this section concludes with two remarks that relate the current results to those in the literature. First, capacities are taxed or subsidised in the current context to counteract a conventional incumbent's incentives to prevent or foster market entry

[15]Obviously, if these constraints were not satisfied, the monopolist would build up as much capacity as possible without ever intending to employ all this capacity.

of RE providers. Explicitly differentiating between base-load and peak-load technologies shows that these incentives turn out to be fairly complex, as further explored in the next sections. The motivation for capacity taxes and subsidies in this paper is very different from the alternative justifications for these policy instruments in the literature on electricity markets or RE. These justifications include providing capacity payments to reduce the risk of blackouts in the presence of stochastic demand (e.g., Fabra, 2018) and employing specifically RE capacity subsidies to replace only imperfectly available emission taxes in second-best settings (e.g., Helm and Mier, 2021) or to attract internationally mobile green capital (e.g., Eichner and Runkel, 2014).[16]

Second, there are important differences between the implications of variations in supply and in demand. In the current setting, pollution and market power cause inefficiencies, but variations in supply over different states of nature themselves do not. In particular, variations in supply do not distort the time-invariant retail price $\overline{p} = U'(\overline{Q})$ (see optimality condition (4) and equilibrium condition (13)). By contrast, variations in demand usually do distort the price-invariant retail price, as shown in Borenstein and Holland (2005). Abstracting from pollution, they show that even a competitive market equilibrium is not second-best when demand varies across time and some consumers are charged a time-invariant price.[17]

5 Environmental Policy and RE Capacity Costs

Let us now analyse how the socially optimal emission and capacity taxes adjust to a changing environment. In this section, the effects of declining RE capacity costs on these taxes are explored. Propositions 3 to 5 cover the case in which at least some consumers are on time-invariant prices (i.e., $\theta < 1$). Afterwards, proposition 6 analyses how the results change if all consumers are on real-time prices (i.e., $\theta = 1$). Let us start with considering the impact of RE costs on emission taxes in the case of $\theta < 1$.

Proposition 3. *Emission Taxes and RE Capacity Costs for $\theta < 1$.*
(i) As RE capacity costs decline (i.e., as parameter α increases from $\underline{\alpha}$ to $\overline{\alpha}$), emission tax t_{A0} remains unchanged, while emission taxes t_{A1} and t_A strictly increase proportionally to each other. By contrast, emission tax t_{B0} strictly decreases as RE capacity costs fall. Formally, $dt_{A0}/d\alpha = 0$, $dt_{A1}/d\alpha > 0$, $dt_A/d\alpha = (1-\sigma)\, dt_{A1}/d\alpha > 0$ and $dt_{B0}/d\alpha < 0$.
(ii) All emission taxes underinternalise environmental damage with the exception of emission tax t_{A1}, which fully internalises environmental damage, but only when the cost pa-

[16]Green subsidies are also discussed as a means to address inefficiencies due to technological spillovers (e.g., Fischer and Newell, 2008; Fischer et al., 2017).

[17]As explored in Borenstein and Holland (2005), the time-invariant market price equals the quantity-weighted average real-time price, while the second-best time-invariant price, which minimises the dead-weight loss of time-invariant pricing, equals the average real-time price with the weights given by the slopes of the demand curves. Without variations in demand across time, as in the current paper, the equilibrium price coincides with its second-best value. However, even with variations in demand, a second-best outcome can be achieved if two-part tariffs are allowed, as shown by Joskow and Tirole (2006).

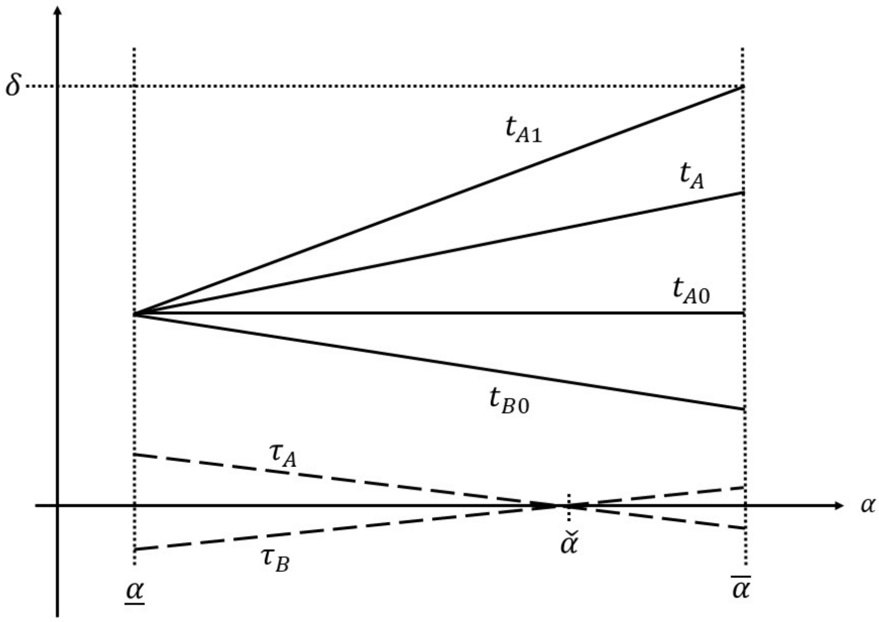

Figure 1: RE Capacity Costs and Taxes, $\theta < 1$

rameter α reaches its upper bound $\overline{\alpha}$. Formally, $t_{A0}, t_A < \delta_A$ and $t_{B0} < \delta_B$ for $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, $t_{A1} < \delta_A$ for $\alpha \in [\underline{\alpha}, \overline{\alpha})$, and $t_{A1} = \delta_A$ for $\alpha = \overline{\alpha}$.

The conclusions of proposition 3 are intuitive. Recall that the socially optimal consumption, output and capacity levels are decentralised in equilibrium. Then, a decline in RE capacity costs changes neither the consumption levels nor the monopolist's competitive position in the non-windy state of nature and its overall output $K_A + K_B$ (see lemma 1 and proposition 1). The own-market effect Λ_{A0} thus stays the same in the SPN equilibrium with its socially optimal taxes, and so does emission tax t_{A0} (see eq. (22)). By contrast, as RE capacity costs fall and RE firms penetrate the market in ever larger numbers, growing supply of RE makes the electricity market in the windy state of nature increasingly competitive. With the monopolist's residual demand declining in windy periods, the base-load capacity K_A is continuously crowded out. As a result, the absolute value $|\Lambda_{A1}|$ of the own-market effect shrinks, and tax t_{A1} increases (see eq. (23)). Ultimately, for $\alpha = \overline{\alpha}$, as base-load capacity K_A falls to zero, the own-market effect Λ_{A1} vanishes and the emission tax t_{A1} thus equals marginal environmental damage δ_A. With tax t_{A0} being constant, any rise in tax t_{A1} by Δt_{A1} is translated into a rise in tax t_A by $(1 - \sigma)\,\Delta t_{A1}$, simply by construction of tax t_A (see eq. (24)). These relationships between emission taxes and RE capacity costs are illustrated in figure 1.

In contrast to emission taxes t_{A0}, t_{A1} and t_A, tax t_{B0} decreases as RE capacity costs fall, which is also depicted in figure 1. This decline results since while the home market effect Λ_{B0} remains unaltered, as does its counterpart Λ_{A0}, the cross-market effect Ψ_{B1} weakens (compare eqs. (22) and (25)). Recall that the latter effect incentivises the monopolist to increase peak-load generation in the non-windy periods to push up demand of inflexible consumers and thus price p_1 in the windy periods. This incentive to distort the market outcome drives up emission tax t_{B0}. However, the strength of the underpinning cross-market effect Ψ_{B1} fades away as base-load capacity K_A is crowded out, causing the optimal emission tax t_{B0} to decline in line with RE costs.

In any case, and although the monopolist faces fringe RE competitors, the second-best emission taxes underinternalise environmental damage with the exception of tax t_{A1}. But even this tax only fully internalises environmental damage when base-load capacity is just about to be completely crowded out. In the case of emission tax t_{B0}, underinternalisation results despite the positive cross-market effect Ψ_{B1} because the negative own-market effect Λ_{A0} is simply stronger. This in turn follows from the fact that the direct negative impact of peak-load capacity on the price in non-windy periods, when this capacity is employed, is unsurprisingly more pronounced than its indirect positive impact on the price in non-windy periods, when this capacity is not employed (i.e., $|U''(Q_0)\,(dQ_0/dK_B)| > U''(Q_1)\,(dQ_1/dK_B)$).

Having discussed some basic comparative-statics features, the next proposition explores the ranking of the emission taxes for $\theta < 1$. To have a meaningful comparison, the environmental damages of the two fossil-fuel based technologies are assumed to be identical in proposition 4.

Proposition 4. *Ranking of Emission Taxes for $\theta < 1$.*
Assume that technologies A and B are equally damaging (i.e., $\delta_A = \delta_B$).
(i) If demand is strictly convex (i.e., $U'''(Q) > 0$), then the emission taxes will be ranked as follows: $t_{B0} \leq t_{A0} < t_A < t_{A1}$ for all $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, with *$t_{B0} = t_{A0}$ for $\alpha = \underline{\alpha}$ and $t_{B0} < t_{A0}$ for $\alpha \in (\underline{\alpha}, \overline{\alpha}]$.*
(ii) If demand is linear (i.e., $U'''(Q) = 0$), then all emission taxes will coincide for $\alpha = \underline{\alpha}$ and the ranking in part (i) will be maintained for $\alpha \in (\underline{\alpha}, \overline{\alpha}]$. That is, $t_{B0} = t_{A0} = t_A = t_{A1}$ for $\alpha = \underline{\alpha}$ and $t_{B0} < t_{A0} < t_A < t_{A1}$ for $\alpha \in (\underline{\alpha}, \overline{\alpha}]$.
(iii) If demand is strictly concave (i.e., $U'''(Q) < 0$), then critical values $\tilde{\alpha}$ and $\hat{\alpha}$, with $\underline{\alpha} < \tilde{\alpha} < \hat{\alpha} < \overline{\alpha}$, will exist such that $t_{B0} \gtreqless t_A \Leftrightarrow \alpha \lesseqgtr \tilde{\alpha}$ and $t_{A0} \gtreqless t_A \gtreqless t_{A1} \Leftrightarrow \alpha \lesseqgtr \hat{\alpha}$. Again, $t_{B0} = t_{A0}$ for $\alpha = \underline{\alpha}$ and $t_{B0} < t_{A0}$ for $\alpha \in (\underline{\alpha}, \overline{\alpha}]$.

To understand proposition 4, let us consider the case in which the demand function is linear (i.e., $U'''(Q) = 0$) as a starting point. This is the case that is illustrated in figure 1.[18] Clearly, at $\alpha = \underline{\alpha}$ and thus $K_B = 0$, when the monopolist is just about to employ the peak-load technology, the own-market effects Λ_{A0} and Λ_{A1} and thus emission taxes t_{A0} and t_{A1} coincide, as eqs. (22) and (23) for $K_B = 0$ in conjunction with eq. (19) reveal.[19]

[18]The $H(\alpha)$-function is also assumed to be linear. Otherwise, the relationships in figure 1 would not be linear.

[19]The argument above hinges on the result that a change in base-load capacity increases consumption levels of flexible consumers in the non-windy and windy state of nature by the same amount (i.e., $dQ_0/dK_A = dQ_1/dK_A > 0$). This result is not surprising, since the base-load technology is equally employed across both states of nature.

Since tax t_{A1} increases with parameter α, while tax t_{A0} remains constant, tax t_{A1} exceeds t_{A0} for all $\alpha \in (\underline{\alpha}, \overline{\alpha}]$. By construction, tax t_A lies in between its components t_{A0} and t_{A1}, and thus coincides with them when they are identical.

Emission tax t_{B0} also coincides with the other emission taxes for $\alpha = \underline{\alpha}$. The reason for this outcome is as follows: On the one hand, the positive cross-market effect Ψ_{B1} raises tax t_{B0} compared to the constant emission tax t_{A0}. On the other hand, the negative own-market effect Λ_{B0} is stronger than its counterpart Λ_{A0} (i.e., $\Lambda_{B0} < \Lambda_{A0}$), which lowers tax t_{B0} compared to tax t_{A0}. To understand the difference in relative strengths of the own-market effects, recall that an increase in base-load capacity K_A drives up output in both the non-windy and windy periods. The ensuing fall in real-time price p_1 in the windy periods also lowers time-invariant price $\overline{p}$ and thus raises the demand of the inflexible consumers. This in turn puts upward pressure on real-time price p_0 in the non-windy state of nature, thus depressing consumption Q_0 of flexible consumers in the windy periods. This negative effect is absent when peak-load capacity K_B is increased, implying $dQ_0/dK_B > dQ_0/dK_A$ and thus, for linear demand and $\alpha = \underline{\alpha}$, $\Lambda_{B0} < \Lambda_{A0}$.

In any case, the two opposing effects on the magnitude of emission tax t_{B0} compared to t_{A0} (i.e., $\Psi_{B1} > 0$ versus $\Lambda_{B0} < \Lambda_{A0}$) exactly offset each other at $\alpha = \underline{\alpha}$. Hence, tax t_{B0} coincides with tax t_{A0}, which in turn is identical to taxes t_{A1} and t_A at this point. As tax t_{B0} decreases with parameter α, this tax falls short of all the other taxes for $\alpha \in (\underline{\alpha}, \overline{\alpha}]$.

The unambiguous ranking of the emission taxes for $\alpha \in (\underline{\alpha}, \overline{\alpha}]$ in the case of a linear demand function basically carries over to the case of strictly convex demand functions. Only, with strictly convex demand, taxes t_{A1} and t_A already strictly exceed taxes t_{A0} and t_{B0} for $\alpha = \underline{\alpha}$. To understand this difference, note that in the case of strictly convex demand, the effect of quantity on the real-time price is stronger in the non-windy state of nature than in the windy state (i.e., $|U''(Q_0)| > |U''(Q_1)|$ for $Q_0 < Q_1$). By contrast, this effect is the same in the case of a linear demand function. Therefore, with strictly convex demand, the negative own-market effect Λ_{A1} becomes relatively weaker, while the negative own-market effect Λ_{A0} becomes relatively stronger. Hence, tax t_{A1} rises relative to tax t_{A0}, which still coincides with tax t_{B0}.[20] Thus, the emission taxes diverge from the outset, with the ranking $t_{B0} = t_{A0} < t_A < t_{A1}$ already being valid for $\alpha = \underline{\alpha}$. Again, tax t_A simply lies between taxes t_{A0} and t_{A1} by construction.

Only if demand is strictly concave, the ranking changes for sufficiently high RE capacity costs (i.e., for $\alpha \leq \hat{\alpha}$). With strictly concave demand, the arguments about the relative strengths of the own-market effects and cross-market effect in the case of strictly convex demand can simply be reversed. Initially, emission tax t_{A0} then exceeds t_{A1}. Also, emission tax t_{B0} is greater than tax t_A at the beginning, since tax t_{B0} coincides with t_{A0} for $\alpha = \underline{\alpha}$, while tax t_A falls short of t_{A0} by construction. However, the initial tax levels do not alter the comparative statics outlined in proposition 3. As emission tax t_{A1}

[20] Regarding tax t_{B0}, not only the own-market effect Λ_{B0} is affected (although to a different extent than its counterpart Λ_{A0}), but also the positive cross-market effect Ψ_{B0} is relatively weakened, putting downward pressure on tax t_{B0}.

increases, tax t_{A0} stays constant, and tax t_{B0} decreases, the ranking $t_{B0} < t_{A0} < t_A < t_{A1}$ is eventually restored, first regarding to emission taxes t_A and t_{B0}, and then regarding to the remaining taxes t_{A0} and t_{A1}.

For $\delta_A = \delta_B$, the ranking of the emission taxes is exactly inverse to the ranking of the internalisation gaps, i.e., the difference between the environmental damages and the corresponding taxes. Once δ_B exceeds δ_A, the tax t_{B0} shifts upwards in parallel fashion relative to the other emission taxes. This changes the tax ranking. However, proposition 4 still continues to correctly reflect the ranking of the internalisation gaps even for $\delta_A < \delta_B$.

Having explored the effect of RE capacity costs on the emission taxes, let us next turn to the response of the capacity taxes and the total base-load and peak-load tax burdens. Proposition 5 states the key results, again for $\theta < 1$.

Proposition 5. *Capacity Taxes, Total Tax Burdens and RE Capacity Cost for $\theta < 1$.*
(i) As RE capacity costs decline, capacity tax τ_A strictly decreases from a positive to a negative value, while capacity tax τ_B strictly increases from a negative to a positive value. More precisely, $d\tau_A/d\alpha < 0$ and $d\tau_B/d\alpha > 0$, with $\tau_A \gtreqless 0 \Leftrightarrow \alpha \lesseqgtr \check{\alpha} \Leftrightarrow \tau_B \lesseqgtr 0$ and $\check{\alpha} \in (\underline{\alpha}, \overline{\alpha})$.
(ii) As RE capacity costs decline, total tax burden $T_A = t_A + \tau_A$ strictly increases, while total tax burden $T_B = t_{B0} + (\tau_B/\sigma)$ strictly decreases. In any case, these total tax burdens per output unit fall short of environmental damage. Formally, $dT_A/d\alpha > 0$, with $T_A < \delta_A$, and $dT_B/d\alpha < 0$, with $T_B < \delta_B$.

From the monopolist's perspective, crowding out RE capacity is a double-edged sword, as explored in section 4 and reflected in the policy conclusions in part (i) of proposition 5. On the one hand, it has a positive impact on the monopolist's profit that accrues in the windy periods, since a lower RE supply increases the monopolist's residual demand in the windy state of nature and thus real-time price p_1. On the other hand, a lower RE capacity has a negative impact on the monopolist's profit in the non-windy state, since a lower RE supply in the windy periods increases the time-invariant price $\overline{p}$ and thus reduces the demand in the non-windy state and real-time price p_0. If RE capacity costs are sufficiently high (i.e., $\alpha \leq \check{\alpha}$) and the monopolist therefore has a substantial market share in the windy periods, the positive effect of lower RE supply will dominate the negative effect. In this case, the monopolist faces an incentive to crowd out RE capacity. It does so by means of (i) strategically overinvesting in base-load capacity to increase supply in windy periods and (ii) strategically underinvesting in peak-load capacity to raise the time-invariant price $\overline{p}$ for inflexible consumer and thus to lower demand in the windy periods. Both measures depress the profits of RE firms and thus crowd out RE capacity. To counteract the strategic investment incentives of the monopolist, base-load capacity needs to be taxed and peak-load capacity to be subsidised.

As RE capacity costs decrease, RE capacity increases, while base-load capacity falls. From the perspective of the monopolist, the market for electricity in the windy state of nature becomes less important as its market share plummets with the rise of RE capacity, while the market for electricity in the non-windy state gains in relative importance. Consequently, the strategic investment incentives of the monopolist first become weaker and then reverse. If RE capacity costs are sufficiently low (i.e. $\alpha > \check{\alpha}$), crowding in RE capacity will be beneficial to the monopolist. Then, a higher RE supply in the windy periods reduces the time-invariant price $\overline{p}$ and thus increases the demand of inflexible consumers in the non-windy periods, driving up real-time price p_0 and thus the monopolist's profit in the non-windy periods. While additional RE capacity still lowers real-time price p_1 and thus the monopolist's profit in the windy periods, this negative effect is not dominant anymore, since the monopolist's market share in the windy state of nature is too small for this market to be decisive. Hence, the monopolist reverses its strategy: it (i) underinvests in base-load capacity to reduce its supply in the windy periods and (ii) overinvests in peak-load capacity to reduce the time-invariant price $\overline{p}$ and thus to boost the demand of inflexible consumers in the windy periods. As both measures improve the profits of RE firms, they attract additional RE capacity. To counteract the reversed strategic investment incentives of the monopolist, base-load capacity needs to be subsidised and peak-load capacity to be taxed. The tax on base-load (peak-load) capacity monotonically moves from a positive (negative) to a negative (positive) value as RE capacity costs decline, as illustrated in figure 1.

Interestingly, the qualitative impact of declining RE costs on capacity taxes is the opposite of their effect on emission taxes: while emission tax t_A increases, capacity tax τ_A declines. Also, while emission tax t_{B0} declines, capacity tax τ_B increases. Analysing the total tax burdens shows that the effects on emission taxes trump those on capacity taxes. This result confirms the notion that changes in emission taxes, which tackle the fundamental externality, are expected to be more prominent than those of capacity taxes, which tackle the strategic incentives to manipulate RE entries. Intuitively, the own-market and cross-market effects that influence emission taxes are very similar to those that drive capacity taxes. However, in the case of capacity taxes, all effects are cushioned, since they operate only indirectly through the impact of the monopolist's capacity choices on RE capacity (recall that $dK_R/dK_A \in (-1, 0)$ and $dK_R/dK_B \in [0, 1)$, as stated in eqs. (19) and (21) above and, more precisely, in eqs. (A.13) and (A.14) in the appendix).

In any case, considering emission and capacity taxes together, the overall tax burdens per output unit are smaller than the corresponding marginal environmental damages. The optimal policy thus continues to underinternalise environmental damage even if capacity taxes in response to strategic investment effects are taken into account.

While most of the above conclusions remain valid if all consumers are flexible (i.e., $\theta = 1$), some need to be amended, as stated in proposition 6 and illustrated in figure 2.

Proposition 6. *Consumer Flexibility and Impact of RE Capacity Costs.*
Consider the case in which all consumers are on real-time prices (i.e., $\theta = 1$).
(i) Emission tax t_{B0} coincides with tax t_{A0}, and capacity tax τ_B is equal to zero. Changes

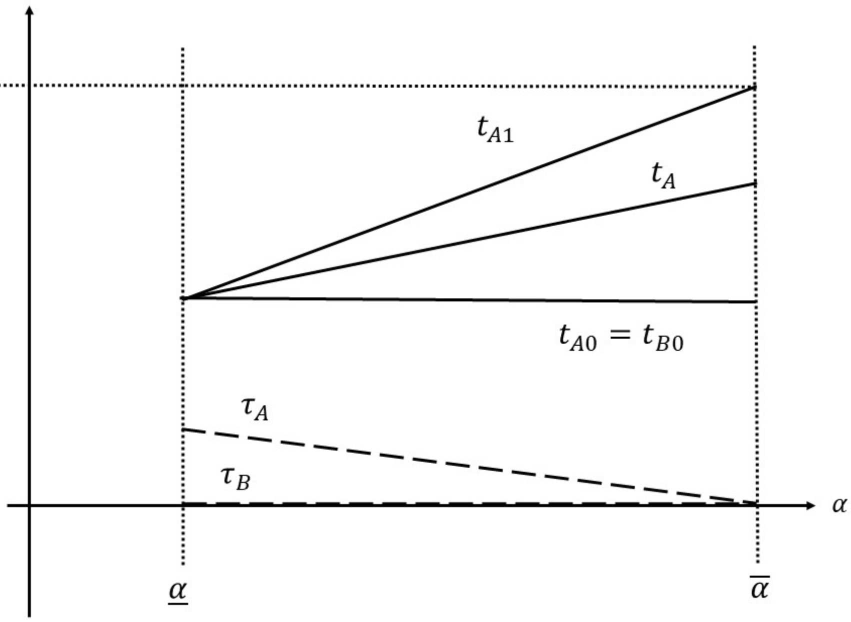

Figure 2: RE Capacity Costs and Taxes, $\theta = 1$

in RE capacity costs leave both tax t_{B0} and tax τ_B, and thus total tax burden T_B, unaffected. Formally, for all $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, $dt_{B0}/d\alpha = d\tau_B/d\alpha = dT_B/d\alpha = 0$, with $T_B = t_{B0} = t_{A0}$ and $\tau_B = 0$.
(ii) As RE capacity costs decline, capacity tax τ_A strictly decreases from a positive value to zero. Formally, $d\pi_A/d\alpha < 0$, with $\tau_A > 0 \Leftrightarrow \alpha \in [\underline{\alpha}, \overline{\alpha})$ and $\tau_A = 0 \Leftrightarrow \alpha = \overline{\alpha}$.
(iii) All other results of propositions 3 to 5 still hold.

If all consumer are on real-time prices, the link between markets in the windy state of nature and the non-windy state is severed. Hence, all cross-market effects and all effects that hinge on cross-market effects vanish. Consequently, the monopolist's incentive to underinvest, or overinvest, in peak-load technology disappears, and so does thus capacity tax τ_B. The total tax burden T_B simply consists of the emission tax t_{B0}, and the emission taxes t_{B0} and t_{A0} are identical. Finally, the capacity tax τ_A still decreases with RE capacity costs, but remains non-negative. That is, without inflexible consumers, there is no reason left to subsidise either base-load or peak-load capacity in the current model.

Overall, the impact of declining RE capacity costs on taxes is mixed. Regarding base-load electricity, emission tax t_A and total tax burden T_A strictly increase, thus moving closer to full internalisation of environmental damage. By contrast, emission tax and total tax burden of peak-load electricity move in the opposite direction. However, the decline of tax t_{B0} and total tax burden T_B does not occur once all consumers are flexible. In this sense, consumer flexibility supports the suggestion that taxes on conventional electricity should rather increase as RE capacity costs decline.

6 Environmental Policy and Consumer Flexibility

Proposition 6 already gives a taste of the importance of consumer flexibility. Let us now examine the effect of consumer flexibility on emission and capacity taxes more comprehensively. This analysis requires an assumption about the fourth derivative of the utility function (i.e., the third derivative of the inverse demand function). The following one proves to be both helpful and fairly innocent.

Assumption 2. *Utility Function.*
Let us assume that $|U''(Q)|$ is log-concave in Q or, equivalently, that inequality $U''''(Q) \geq [U'''(Q)]^2 / U''(Q)$ is satisfied.

This assumption allows for a range of convex and concave inverse demand functions including linear, power and exponential ones.[21] It is assumed to be fulfilled in propositions 7 to 10.

Proposition 7. *Emission Taxes and Consumer Flexibility.*
(i) As the share θ of flexible consumers grows, emission taxes t_{A0} and t_{B0} strictly increase and, if demand is strictly convex, so does emission tax t_A. Formally, $dt_{B0}/d\theta > 0$, $dt_{A0}/d\theta > 0$ and, if $U'''(Q) > 0$, $dt_A/d\theta > 0$.
(ii) In the case of a linear demand function, a rise in share θ leaves emission tax t_A unaffected and raises tax t_{A0} by the same amount by which it lowers tax t_{A1}. Formally, if $U'''(Q) = 0$, then $dt_A/d\theta = 0$ and $dt_{A0}/d\theta = -dt_{A1}/d\theta > 0$.

As consumers become more flexible, overall demand shifts from the more expensive non-windy periods to the less expensive windy periods. The monopolist's position becomes weaker in the non-windy state of nature and stronger in the windy one, with overall conventional capacity $K_A + K_B$ decreasing but base-load capacity K_A increasing. (Recall that the decentralised, socially optimal RE capacity and output remain unchanged; see proposition 2.) As a result, the absolute value $|\Lambda_{A0}|$ of the negative own-market effect falls, while the absolute value $|\Lambda_{A1}|$ rises, thus driving emission tax t_{A0} up and tax t_{A1} down (see eqs. (22) and (23)). In the case of a linear demand function (i.e., $U''(Q_0) = U''(Q_1)$), these two opposing effects cancel each other out such that the overall emission tax t_A remains unchanged as the share θ grows. With a convex demand function (i.e., $|U''(Q_0)| > |U''(Q_1)|$), the increase in tax t_{A0} gains prominence relative to the decline in tax t_{A1}, and emission tax t_A then increases (see eqs. (22) to (24)), as illustrated in figure 3. Also, the positive impact of capacity K_A on consumption levels Q_0 and Q_1 (i.e., $dQ_0/dK_A = dQ_1/dK_A > 0$), which is constant in the case of linear demand, shrinks as

[21] Simple examples include the linear function $U'(Q) = \gamma_0 - \gamma_1 Q$, the power function $U'(Q) = \gamma_2 (\gamma_3 - Q)^{\mu_1}$, $\gamma_3 > Q$, and the exponential function $U'(Q) = \gamma_4 e^{-\mu_2 Q}$, where γ_0, γ_1, γ_2, γ_3, γ_4, μ_1 and μ_2 are positive parameters. See Cowan (2004) for a discussion on the use of the concept of log-concavity to characterise demand functions when conducting comparative-statics analysis in the context of models of imperfect competition. In the current analysis, this concept is applied to characterise the slope of the demand curve.

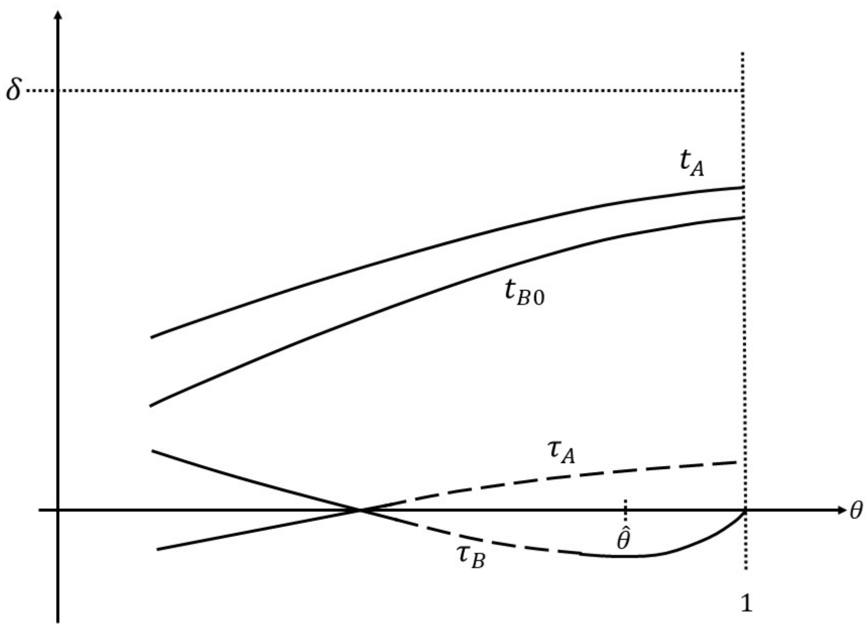

Figure 3: Consumer Flexibility and Taxes

share θ grows in the case of convex demand, thereby further pushing up both taxes t_{A0} and t_{A1} and thus overall emission tax t_A.

If share θ increases, the negative own-market effect Λ_{B0} becomes weaker, as does its counterpart Λ_{A0}, thus pushing up emission tax t_{B0} (see eq. (25)). Despite an increasing base-load capacity K_A, the positive cross-market effect Ψ_{B1} also ultimately weakens as share θ grows, which counteracts the increase in tax t_{B0}. After all, for $\theta = 1$, the link between the markets in the two states of nature is severed (i.e., $dQ_1/dK_B = 0$), and the emission-tax increasing cross-market effects Ψ_{B1} completely disappears. However, and not surprisingly, the direct own-market effect is not only stronger than the corresponding indirect cross-market effect, as already discussed in section 5, but changes in the own-market effect in response to a higher share θ also systematically dominate those in the cross-market effect. Hence, emission tax t_{B0} rises with share θ, as depicted in figure 3.

Having analysed the effect of consumer flexibility on emission taxes, let us explore how capacity taxes and total tax burdens vary with share θ.

Proposition 8. *Capacity Tax, Total Tax Burden and Consumer Flexibility.*
(i) Consider a rise in consumer share θ. Then, capacity tax τ_A will strictly increase if it is non-positive. Once capacity tax τ_A is positive, it remains positive as the share θ grows further. Formally, $d\tau_A/d\theta > 0$ if $\tau_A \leq 0$. Also, if $\tau_A \geq 0$ for any $\tilde{\theta}$, then $\tau_A > 0$ for all $\theta > \tilde{\theta}$.
(ii) Total tax burden T_A will strictly increase with the consumer share θ if demand is weakly convex. Formally, $dT_A/d\theta > 0$ if $U'''(Q) \geq 0$.

To understand proposition 8, consider first the case in which all consumers are on real-time prices (i.e., $\theta = 1$). In this case, the cross-market effect Ψ_{R0} disappears, since the link between the markets in the two states of nature is broken (i.e., $dQ_0/dK_R = 0$). Then, being determined only by the negative own-market effect Λ_{R1} and the negative interaction between capacities K_R and K_A, capacity tax τ_A is positive for sure (i.e., $(1-\sigma)\,\Lambda_{R1}\,(dK_R/dK_A) > 0$, see eq. (26)). Simply, without a cross-market effect, the incentive to underinvest in base-load capacity K_A, which is discussed in section 4, vanishes. Hence, a positive capacity tax τ_A is needed to combat the then remaining incentive to overinvest in base-load capacity as the monopolist aims at crowding out RE capacity and thus defending its profit in the windy state of nature.

By contrast, for sufficiently low values of share θ, the incentive to underinvest in base-load capacity dominates, and a capacity subsidy is required to eliminate this incentive (i.e., $\tau_A < 0$). In this case, the monopolist's profits predominantly accrue in the non-windy periods, since aggregate capacity $K_A + K_B$ is large relative to base-load capacity K_A, as implied by the comparative statics in section 3 (see proposition 2). Then, underinvesting in base-load capacity to crowd in RE capacity and thus increase the price p_0 in the non-windy periods is optimal for the monopolist, as explored in section 3.

Overall, the government moves from subsidising to taxing base-load capacity as consumers become more flexible. Capacity tax τ_A strictly increases with consumer share θ until this tax is positive and then remains positive as the share of flexible consumers further grows. Since emission tax t_A will be non-decreasing in share θ if demand is convex, and since capacity tax τ_A tends to increase with share θ, it is not surprising that total tax burden T_A goes up as consumers become more flexible.

As the analysis in the previous sections has revealed, the strategic incentive to invest in peak-load capacity is of the opposite sign to the strategic incentive to invest in base-load technology for $\theta < 1$, and so are the optimal taxes to counteract these incentives (see lemma 3). Hence, for sufficiently low values of share θ, capacity tax τ_B is positive. It decreases as consumers become more flexible and, once it has turned negative, remains negative as consumer share θ further increases. Only, when share θ converges towards one, the cross-market effects vanish, and so does the strategic interaction between RE and peak-load capacities, which depends on cross-market effects (i.e., $dK_R/dK_B = 0$). Thus, any incentives to strategically invest in peak-load capacity fade away (see eq. 27)) and, once consumer flexibility exceeds a critical value $\hat{\theta}$, capacity tax τ_B increases to zero (compare with proposition 6), as stated in the first part of the next proposition.

Proposition 9. *Capacity tax, Total Tax Burden and Consumer Flexibility Cont'd.*
(i) Consider a rise in consumer share θ, with $\theta < 1$, and assume that $\alpha \in (\underline{\alpha}, \overline{\alpha})$. Then, capacity tax τ_B will strictly decrease if it is non-negative. Once the share θ is sufficiently large so that the capacity tax τ_B is negative, the tax τ_B remains negative as the share θ grows further as long as $\theta < 1$. The capacity tax τ_B is zero for $\theta = 1$. Moreover, there exists a critical value $\hat{\theta}$, with $\hat{\theta} < 1$ and $\tau_B|_{\theta=\hat{\theta}} < 0$, such that the tax τ_B will increase if the

share θ is greater than $\hat{\theta}$. Formally, for $\theta < 1$, $d\tau_B/d\theta < 0$ if $\tau_B \geq 0$. Then, $d\tau_B/d\theta > 0$ if $\theta \in \left(\hat{\theta}, 1\right]$.
(ii) Total tax burden T_B strictly increases with share θ. Formally, $dT_B/d\theta > 0$.

While emission tax t_{B0} increases with the share θ of flexible consumers, capacity tax τ_B does so only for sufficiently large levels of flexibility. As in the case of declining RE capacity costs, however, the change in the emission tax dominates any potential opposite change in the capacity tax for the very same reason that is explored after proposition 5. Hence, the total tax burden T_B always rises in response to growing consumer flexibility.

Propositions 8 and 9 characterise the relationships between capacity taxes and consumer flexibility, but also leave some ambiguity about the complete shape of these relationships. This is illustrated in figure 3, where the solid parts of the τ_A- and τ_B-curve indicate the sections for which the signs of the slopes, and not only the signs of the taxes, are unambiguously determined. Proposition 10 fills the gaps for the case of a linear demand function. Then, there is (i) a monotone relationship between capacity tax τ_A and consumer share θ and (ii) a unique turning point in the relationship between tax τ_B and share θ, as depicted by the broken lines of the τ_A- and τ_B-curve in figure 3.

Proposition 10. *Linear Demand Specification.*
Consider the case of a linear demand function (i.e. $U'''(Q) = 0$). Then, capacity tax τ_A strictly increases with consumer share θ. Capacity tax τ_B decreases (increases) with consumer share θ if, and only if, consumer share θ is smaller (greater) than the critical value $\hat{\theta}$. Formally, $d\tau_B/d\theta \lesseqgtr 0 \Leftrightarrow \theta \lesseqgtr \hat{\theta}$ and $d\tau_A/d\theta > 0$.

7 Putting the Pieces Together - A Conclusion

We can now put the pieces together and look at the overall picture. This paper considers an electricity market with a monopolist employing conventional fossil-fuel technologies to generate electricity and a competitive fringe providing RE. The government implements emission and capacity taxes to address the environmental externality, market power and distortive strategic investment incentives.

The initial suggestion that a decline in RE capacity costs and an increase in consumer flexibility intensifies the competition between the monopolist and the RE firms and thus raises taxes towards the level of full internalisation of the environmental externality finds some support. As consumers become more flexible, the total tax burdens T_A and T_B on base-load and peak-load electricity rise, and the corresponding key emission taxes t_A and t_{B0} edge closer towards their Pigouvian tax levels.[22] In the same vein does the total burden T_A on base-load electricity and the corresponding emission tax t_A increase as RE capacity costs fall. Tax t_{A1} actually reaches the environmental damage level δ_A, but only

[22]With the qualification that these results will hold if demand is convex and the absolute value of the slope of demand is log-concave.

when the RE capacity costs are so low that base-load capacity is anyway about to be completely crowded out (i.e., for $\alpha = \overline{\alpha}$).

However, the results are not quite consistent. As RE capacity costs decrease, the total tax burden T_B on peak-load electricity and the corresponding emission tax t_{B0} will remain constant only if all consumer are flexible. Otherwise, they will fall. The inconsistencies arise since a fall in RE capacity costs and an increase in consumer flexibility very differently affect the monopolist's market power across the windy and non-windy states of nature. For instance, a decline in RE capacity costs crowds out conventional base-load capacity and electricity generation but leaves consumption of conventional electricity in the non-windy state unchanged, while an increase in consumer flexibility crowds in conventional base-load capacity and electricity generation but reduces consumption of conventional electricity in the non-windy state.

The monopolist's different competitive challenges across the states of nature also affect the magnitude of the emission taxes. The emission taxes levied on conventional base-load generation, which immediately competes with RE, will be closer to their Pigouvian level than the emission tax on peak-load generation if demand is weakly convex, or if demand is concave and the RE capacity costs are sufficiently low.

The need for capacity taxes to counteract the monopolist's strategic investment incentives further complicates the picture. The monopolist overinvests (underinvests) in base-load capacity and underinvests (overinvests) in peak-load capacity to crowd out (in) RE capacity. Hence, the taxes τ_A and τ_B on base-load and peak-load capacities always show opposite signs (unless both are zero). If RE costs decline (consumer flexibility increases), then the tax on base-load capacity goes from being positive (negative) to being negative (positive), while the tax on peak-load capacity moves in the opposite direction. These taxes disappear in the boundary case in which consumers are fully flexible and the base-load technology is about to be completely crowded out of the market. In any case, the emission taxes drive the overall tax burden, and not the capacity taxes, since the former ones systematically dominate the latter.

The complexity of the socially optimal capacity tax scheme raises the question whether a more straightforward policy instrument can achieve the same outcome. Indeed, a feed-in tariff can replace the capacity taxes in the current context without affecting the magnitude of the emission taxes, which would simply stay the same. If the government guarantees the RE providers an electricity price, or feed-in tariff, that equals the socially optimal shadow value of electricity in the windy state of nature irrespective of the market price, then fringe firms will obviously build up the socially optimal RE capacity. The monopolist is no longer able to manipulate their choices. The feed-in tariff completely eliminates the monopolist's strategic investment incentives.[23]

[23]This argument in favour of feed-in tariffs differs from the justification for these tariffs that are discussed in the literature on electricity markets, such as, for instance, using them to replace emission taxes when these taxes are not fully available (e.g., Abrell et al., 2019), to facilitate market entry of RE producers when entry costs are lumpy (e.g., Antoniou and Strausz, 2016), and to achieve the optimal

Appendix

Proof of Lemma 1:

Lemma 1 follows directly from the rearranged first-order conditions (8) to (10).

Proof of Lemma 2 and Proposition 1:

Let us start with proving proposition 1, assuming that all technologies are at least 'almost' employed; i.e., $\alpha \in [\underline{\alpha}, \overline{\alpha}]$ (see below). Conducting standard comparative statistics by using the rearranged first-order conditions (8) to (11) yields

$$\frac{dK_R}{d\alpha} = -\frac{dK_A}{d\alpha} = \frac{dK_B}{d\alpha} = -\frac{\partial g(K_R;\alpha)/\partial\alpha}{\partial g(K_R;\alpha)/\partial K_R} = -\frac{H'(\alpha)}{\hat{h}} > 0, \tag{A.1}$$

which proves parts (i) to (iii) and directly implies part (iv). Since $g(K_R;\alpha)$ is twice-continuously differentiable in K_R and α, the capacities K_R, K_A and K_B are twice-continuously differentiable functions of the cost parameter α.

Part (v) of proposition 1 follows from

$$\frac{dD}{d\alpha} = \delta_A \frac{dK_A}{d\alpha} + \sigma\delta_B \frac{dK_B}{d\alpha} = -(\delta_A - \sigma\delta_B)\frac{dK_B}{d\alpha} \lesseqgtr 0 \Leftrightarrow \delta_A \gtreqless \sigma\delta_B, \tag{A.2}$$

where expression (A.1) is used.

Next, let us prove part (i) of lemma 2. Recall that the inequalities $U'(N) < \left[\overline{h} + H(\alpha^{max})\right]/(1-\sigma) \leq c_A + \delta_A$ and $H(\alpha^{min})/(1-\sigma) > c_A + \delta_A + F_A$ are assumed to be satisfied (see section 2). Also, $c_A + \delta_A < U'(Q_1) < c_A + \delta_A + F_A$ holds. This relationship follows from $U'(Q_1) = \frac{1}{1-\sigma}\left[c_A + \delta_A + F_A - \sigma\left(c_B + \delta_B + F_B/\sigma\right)\right] > c_A + \delta_A \Leftrightarrow c_A + \delta_A + F_A/\sigma > c_B + \delta_B + F_B/\sigma$, where the first equality states first-order condition (10) and the last inequality is satisfied under part (vii) of assumption 1, and $U'(Q_1) = \frac{1}{1-\sigma}\left[c_A + \delta_A + F_A - \sigma\left(c_B + \delta_B + F_B/\sigma\right)\right] < c_A+\delta_A+F_A \Leftrightarrow c_A+\delta_A+F_A < c_B+\delta_B+F_B/\sigma$, where the last inequality is satisfied under part (vi) of assumption 1.

These features imply that $\left[\overline{h} + H(\alpha^{max})\right]/(1-\sigma) < U'(Q_1) < H(\alpha^{min})/(1-\sigma)$. Since $g(0;\alpha^{min}) = H(\alpha^{min})$ and $g(N;\alpha^{max}) = \overline{h} + H(\alpha^{max})$, with $H'(\alpha) < 0$ and $\partial g(K_R;\alpha^{max})/\partial K_R > 0$, there exists a critical value $\overline{\alpha}$, with $\alpha^{min} < \overline{\alpha} < \alpha^{max}$, such that $g(\theta Q_1 + (1-\theta)\overline{Q};\overline{\alpha})/(1-\sigma) = U'(Q_1)$ by means of a continuity argument. Then, $Q_R = K_R = \theta Q_1 + (1-\theta)\overline{Q}$ follows from first-order condition (5). Hence, for $\alpha = \overline{\alpha}$, the constraints $\theta Q_1 + (1-\theta)\overline{Q} = Q_A + Q_R$ and $\theta Q_0 + (1-\theta)\overline{Q} = Q_A + Q_B$ imply $Q_A = K_A = 0$ and $Q_B = K_B = \theta Q_0 + (1-\theta)\overline{Q} > 0$, with all first-order conditions satisfied. Moreover, there also exists a critical value $\underline{\alpha}$, with $\alpha^{min} < \underline{\alpha} < \overline{\alpha}$, such that $g(\theta(Q_1 - Q_0);\underline{\alpha})/(1-\sigma)$=$U(Q_1)$ by means of a continuity argument, where

level and distribution of RE investment when economies of scale are present (e.g., Garcia et al., 2012). See Couture and Gagnon (2010) for an overview of different designs of feed-in tariffs and their impact on reducing the risks of RE investment.

$0 < \theta(Q_1 - Q_0) < \theta Q_1 + (1-\theta)\overline{Q}$. Then, $Q_R = K_R = \theta(Q_1 - Q_0)$ follows from first-order condition (5). Hence, for $\alpha = \underline{\alpha}$, the constraints $\theta Q_1 + (1-\theta)\,\overline{Q} = Q_A + Q_R$ and $\theta Q_0 + (1-\theta)\,\overline{Q} = Q_A + Q_B$ imply $Q_A = K_A = \theta Q_0 + (1-\theta)\,\overline{Q} > 0$ and $Q_B = K_B = 0$, again with all first-order conditions satisfied. Then, for $\alpha \in (\underline{\alpha}, \overline{\alpha})$, $K_A, K_B > 0$ by means of a continuity argument. First-order conditions (4) to (7) or, alternatively, (8) to (11) are satisfied for all $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, and the comparative-statics results are as described in proposition 1. (The comparative statics for $\alpha \notin [\underline{\alpha}, \overline{\alpha}]$ can be obtained from the author upon request.)

Finally, let us prove part (ii) of lemma 2, using the rearranged first-order conditions (8) to (10). Since $U''(Q) < 0$, the relationship $Q_0 < \overline{Q} < Q_1$ follows from $U'(Q_1) < c_A + \delta_A + F_A = U'(\overline{Q})$, where the inequality is proven above, and $U'(\overline{Q}) = c_A + \delta_A + F_A < c_B + \delta_B + F_B < c_B + \delta_B + F_B/\sigma = U'(Q_0)$, where part (vi) of assumption 1 is used. As clarified above, for $\alpha = \underline{\alpha}$, $K_R = \theta\,(Q_1 - Q_0) > 0 = K_B$. Then, expression (A.1) implies that $K_R > K_B$ for all $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, with $K_R - K_B = \theta\,(Q_1 - Q_0) > 0$.

Proof of Proposition 2:

As previously, let us focus on the case with $\alpha \in [\underline{\alpha}, \overline{\alpha}]$. Conducting standard comparative statistics by using conditions (8) to (11) leads again to some very simple expressions:

$$\frac{dK_A}{d\theta} = Q_1 - \overline{Q} > 0, \ \frac{dK_B}{d\theta} = -\left(Q_1 - Q_0\right) < 0, \ \frac{dK_R}{d\theta} = 0, \tag{A.3}$$

where the inequality signs follow from part (ii) of lemma 2. Eq. (A.3) implies

$$\frac{d\left(K_A + K_B\right)}{d\theta} = -\left(\overline{Q} - Q_0\right) < 0, \ \frac{d\left(K_A + K_R\right)}{d\theta} = Q_1 - \overline{Q} > 0. \tag{A.4}$$

Expressions (A.3) and (A.4) prove parts (i) to (iv) of proposition 2 and yield

$$\frac{d\left[\sigma\left(K_A + K_B\right) + (1-\sigma)\left(K_A + K_R\right)\right]}{d\theta} = \sigma Q_0 + (1-\sigma)\,Q_1 - \overline{Q}. \tag{A.5}$$

Jensen's inequality gives us $\sigma Q_0 + (1-\sigma)\,Q_1 - \overline{Q} > (=, <)\, 0$ if the marginal utility, or inverse demand, curve $U'(Q)$ is convex (linear, concave), implying part (v).[24]

Part (vi) of proposition 2 follows from

$$\begin{aligned} \frac{dD}{d\theta} &= \delta_A \frac{dK_A}{d\theta} + \sigma\delta_B \frac{dK_B}{d\theta} = \delta_A\left(Q_1 - \overline{Q}\right) - \sigma\delta_B\left(Q_1 - Q_0\right) \lesseqgtr 0 \\ &\Leftrightarrow \delta_A \lesseqgtr \sigma\delta_B \frac{Q_1 - Q_0}{Q_1 - \overline{Q}}, \end{aligned} \tag{A.6}$$

[24]Let us interpret quantity as a function of the shadow value: $Q_0 = U'^{-1}(s_0)$, $\overline{Q} = U'^{-1}(\overline{s})$ and $Q_1 = U'^{-1}(s_1)$, with $s_0 = U'(Q_0)$, $s_1 = U'(Q_1)$ and $\overline{s} = \sigma s_0 + (1-\sigma)\,s_1$. Then, $\sigma Q_0 + (1-\sigma)\,Q_1 \geq \overline{Q} \Leftrightarrow \sigma U'^{-1}(s_0) + (1-\sigma)\,U'^{-1}(s_1) \geq U'^{-1}(\sigma s_0 + (1-\sigma)s_1)$, where the last inequality is Jensen's inequality for $U'^{-1}(s)$ being convex in s (and thus $U'(Q)$ being convex in Q).

where expression (A.3) is used.

Proof of Corollary 1:

Part (i) and the first statement of part (ii) follow directly from propositions 1 and 2. It remains to explore the sign of $dD/d\theta$. For $\delta_A = \delta_B$, $dD/d\theta = \delta_A \left[\sigma Q_0 + (1-\sigma) Q_1 - \overline{Q}\right]$. The terms in the square brackets are identical to those on the right-hand side of eq. (A.5), and so is the sign of these terms (see discussion in the proof of proposition 2), which proves the second statement of part (ii) of corollary 1.

Comparative Statics - Relationships between Consumption and Capacities

To determine the signs of the derivatives (19) and (21), let us first use conditions (13), (14) and (15), which characterise the market equilibrium in the fourth stage, to show how the demand levels vary with base-load, peak-load and RE capacity. The comparative-statics analysis gives

$$\frac{dQ_0}{dK_A} = \frac{dQ_1}{dK_A} = \frac{U''(\overline{Q})}{\Omega} > 0, \tag{A.7}$$

$$\frac{dQ_0}{dK_B} = \frac{\theta U''(\overline{Q}) + (1-\theta)(1-\sigma) U''(Q_1)}{\theta\Omega} > 0, \tag{A.8}$$

$$\frac{dQ_1}{dK_B} = -\frac{\sigma(1-\theta) U''(Q_0)}{\theta\Omega} \leq 0, \tag{A.9}$$

$$\frac{dQ_0}{dK_R} = -\frac{(1-\theta)(1-\sigma) U''(Q_1)}{\theta\Omega} \leq 0, \tag{A.10}$$

$$\frac{dQ_1}{dK_R} = \frac{\theta U''(\overline{Q}) + \sigma(1-\theta) U''(Q_0)}{\theta\Omega} > 0, \tag{A.11}$$

where the inequality signs follow from $U''(Q) < 0$ and

$$\Omega = \theta U''(\overline{Q}) + (1-\theta)\left[\sigma U''(Q_0) + (1-\sigma) U''(Q_1)\right] < 0. \tag{A.12}$$

(This comparative-statics analysis also leads to $d\overline{Q}/dK_j > 0$, $j = A, B, R$, but the detailed expressions are omitted because this result is not explicitly referred to in the further analysis.)

The signs of dK_R/dK_A and dK_R/dK_B remain to be explored. Totally differentiating zero-profit condition (16), which characterises the market-entry equilibrium in the third stage, and using eqs. (A.7), (A.9), (A.11) and $\partial g(K_R;\alpha)/\partial K_R = \widehat{h}$ to rearrange the resulting terms give

$$\frac{dK_R}{dK_A} = -\frac{(1-\sigma) U''(Q_1)(dQ_1/dK_A)}{(1-\sigma) U''(Q_1)(dQ_1/dK_R) - \widehat{h}} = -\frac{(1-\sigma) U''(\overline{Q}) U''(Q_1)}{\Psi} \in (-1, 0)\,, \tag{A.13}$$

and

$$\begin{aligned}\frac{dK_R}{dK_B} &= -\frac{(1-\sigma)\,U''(Q_1)\,(dQ_1/dK_B)}{(1-\sigma)\,U''(Q_1)\,(dQ_1/dK_R)-\widehat{h}} \\ &= \frac{\sigma\,(1-\sigma)\,(1-\theta)\,U''(Q_0)U''(Q_1)}{\theta\Psi}\in[0,1)\,,\end{aligned} \tag{A.14}$$

where the signs and ranges of values follow from $U''(Q)<0$, $\Omega<0$ (see eq. (A.12)) and

$$\Psi=(1-\sigma)\,U''(Q_1)\left[U''(\overline{Q})+\sigma\frac{1-\theta}{\theta}U''(Q_0)\right]-\widehat{h}\Omega>0. \tag{A.15}$$

Proof of Lemma 3:

Plugging eqs. (A.10) and (A.11) into eq. (26) yields, after some rearrangements,

$$\begin{aligned}\tau_A &= (1-\sigma)\,U''(Q_1)\frac{U''(\overline{Q})K_A-\sigma\,[(1-\theta)\,/\theta]\,U''(Q_0)K_B}{\Omega}\frac{dK_R}{dK_A}\gtreqless 0 \\ &\Leftrightarrow K_A\gtreqless\sigma\frac{1-\theta}{\theta}\frac{U''(Q_0)}{U''(\overline{Q})}K_B,\end{aligned} \tag{A.16}$$

where $\Omega<0$, $dK_R/dK_A<0$ (see eqs. (A.12) and (A.13)) and $U''(Q)<0$ were used.

Then, eqs. (26), (27), (A.13), (A.14) and (A.16) imply, for $\theta<1$,

$$\tau_B=\tau_A\frac{dK_R/dK_B}{dK_R/dK_A}\lesseqgtr 0\Leftrightarrow K_A\gtreqless\sigma\frac{1-\theta}{\theta}\frac{U''(Q_0)}{U''(\overline{Q})}K_B. \tag{A.17}$$

Proof of Proposition 3:

(i) Lemma 1 directly implies that the second derivatives $U''(Q_0)<0$, $U''(Q_1)<0$ and $U''(\overline{Q})<0$ are not affected by an increase in parameter α, and thus neither are the derivatives $dQ_0/dK_A>0$, $dQ_1/dK_A>0$, $dQ_0/dK_B>0$ and $dQ_1/dK_B\leq 0$ (with $dQ_1/dK_B<0$ if $\theta<1$), as eqs. (A.7) to (A.9) and (A.12) reveal. Also, proposition 1 states that $dK_A/d\alpha<0$, $dK_B/d\alpha>0$ and $d\,(K_A+K_B)\,/d\alpha=0$ (see eq. (A.1)). Thus, differentiating eqs. (22) to (25) with respect to parameter α yields

$$\frac{dt_{A0}}{d\alpha}=0,\ \frac{dt_{A1}}{d\alpha}=U''(Q_1)\frac{dQ_1}{dK_A}\frac{dK_A}{d\alpha}>0,\ \frac{dt_A}{d\alpha}=(1-\sigma)\,\frac{dt_{A1}}{d\alpha}>0 \tag{A.18}$$

and, for $\theta<0$,

$$\frac{dt_{B0}}{d\alpha}=\frac{1-\sigma}{\sigma}U''(Q_1)\frac{dQ_1}{dK_B}\frac{dK_A}{d\alpha}<0. \tag{A.19}$$

(ii) Eq. (22) reveals that $t_{A0}<\delta_A$, since $U''(Q)<0$, $dQ_0/dK_A>0$ (see eq. (A.7)) and $K_A+K_B>0$ for $\alpha\in[\underline{\alpha},\overline{\alpha}]$ (see lemma 2). Similarly, eq. (23) implies that $t_{A1}<\delta_A$ for $\alpha\in[\underline{\alpha},\overline{\alpha})$, since $U''(Q_1)<0$, $dQ_1/dK_A>0$ and, for $\alpha\in[\underline{\alpha},\overline{\alpha})$, $K_A>0$. However, for $\alpha = \overline{\alpha}$, $K_A = 0$ (see lemma 2) and thus $t_{A1} = \delta_A$. Combining these results gives $t_A = \sigma t_{A0} + (1-\sigma)\, t_{A1} < \delta_A$ (see eq. (24)).

Plugging eqs. (A.8) and (A.9) into eq. (25) yields, after some rearrangements,

$$t_{B0} = \delta_B + \frac{U''(\overline{Q})U''(Q_0)K_A + \left[U''(\overline{Q})U''(Q_0) + (1-\sigma)\,\frac{1-\theta}{\theta}U''(Q_0)U''(Q_1)\right] K_B}{\Omega} < \delta_B, \tag{A.20}$$

since $U''(Q) < 0$ and $\Omega < 0$ (see eq. (A.12)).

Proof of Proposition 4:

Comparing taxes t_{A0} and t_{B0} yields, after some rearrangements,

$$t_{A0} \geq t_{B0} \Leftrightarrow (1-\theta)\, K_B \geq 0, \tag{A.21}$$

where eqs. (22), (A.7), (A.12) and (A.20) are used. Since $K_B = 0$ for $\alpha = \underline{\alpha}$ and $K_B > 0$ for $\alpha \in (\underline{\alpha}, \overline{\alpha}]$, $t_{A0} = t_{B0}$ for $\alpha = \underline{\alpha}$ and $t_{A0} > t_{B0}$ for $\alpha \in (\underline{\alpha}, \overline{\alpha}]$ and $\theta < 1$.

Next, let us compare taxes t_{A0} and t_{A1}:

$$t_{A1} \gtreqless t_{A0} \Leftrightarrow -U''(Q_0)K_B - \left[U''(Q_0) - U''(Q_1)\right] K_A \gtreqless 0, \tag{A.22}$$

where eqs. (22), (23), (A.7) and (A.12) are used. Since $K_A > 0$ and $K_B = 0$ for $\alpha = \underline{\alpha}$, eq. (A.22) yields, for $\alpha = \underline{\alpha}$, $t_{A0} \lesseqgtr t_{A1} \Leftrightarrow -U''(Q_1) \lesseqgtr -U''(Q_0)$. Thus, as $Q_0 < Q_1$ holds, $t_{A0} < t_{A1}$ ($t_{A0} = t_{A1}$, $t_{A0} > t_{A1}$) results for $\alpha = \underline{\alpha}$ if inverse demand $U'(Q)$ is strictly convex (linear, strictly concave). Also, recall that $dt_{A0}/d\alpha = 0$ and $dt_{A1}/d\alpha > 0$, with $t_{A0} < \delta_A$ for all $\alpha \in [\underline{\alpha}, \overline{\alpha}]$ and $t_{A1} = \delta_A$ for $\alpha = \overline{\alpha}$ (see proposition 3), and that $t_A = \sigma t_{A0} + (1-\sigma)\, t_{A1}$ (see eq. (24)). Hence, if inverse demand $U'(Q)$ is linear, then $t_{A0} = t_A = t_{A1}$ for $\alpha = \underline{\alpha}$ and $t_{A0} < t_A < t_{A1}$ for $\alpha \in (\underline{\alpha}, \overline{\alpha}]$. Also, if inverse demand $U'(Q)$ is strictly convex, then $t_{A0} < t_A < t_{A1}$ for $\alpha \in [\underline{\alpha}, \overline{\alpha}]$. By contrast, if inverse demand $U'(Q)$ is strictly concave, then $t_{A0} > t_{A1}$ for $\alpha = \underline{\alpha}$, $t_{A0} < \delta_A = t_{A1}$ for $\alpha = \overline{\alpha}$, $dt_{A0}/d\alpha = 0$ and $dt_{A1}/d\alpha > 0$ imply that, by means of continuity, a critical value $\hat{\alpha}$, with $\underline{\alpha} < \hat{\alpha} < \overline{\alpha}$, exists such that $t_{A0} \gtreqless t_A \gtreqless t_{A1} \Leftrightarrow \alpha \lesseqgtr \hat{\alpha}$. This concludes the proof of the rankings of the taxes t_{A0}, t_{A1} and t_A in parts (i) to (iii) of proposition 4.

Combining the comparisons between the taxes taxes t_{A0} and t_{B0} and between taxes t_{A0} and t_{A1} gives the complete ranking of parts (i) and (ii) of proposition 4. Moreover, if demand is strictly concave and $\theta < 1$ holds, then $t_{A0} = t_{B0}$ and $t_{A0} > t_A > t_{A1}$ for $\alpha = \underline{\alpha}$ as well as $t_{A0} > t_{B0}$ for $\alpha \in (\underline{\alpha}, \overline{\alpha}]$ and $t_{A0} \leq t_A \leq t_{A1}$ for $\alpha \in [\hat{\alpha}, \overline{\alpha}]$ imply that $t_A < t_{B0}$ for $\alpha = \underline{\alpha}$ as well as $t_A > t_{B0}$ for $\alpha \in [\hat{\alpha}, \overline{\alpha}]$. Hence, since $dt_A/d\alpha > 0$ and $dt_{B0}/d\alpha < 0$, a critical value $\tilde{\alpha}$, with $\tilde{\alpha} < \hat{\alpha}$, exists by means of continuity such that $t_{B0} \gtreqless t_A \Leftrightarrow \alpha \lesseqgtr \tilde{\alpha}$, as stated in part (iii) of proposition 4.

Proof of Proposition 5:

(i) Since $K_A = 0$ for $\alpha = \overline{\alpha}$ and $K_B = 0$ for $\alpha = \underline{\alpha}$, eq. (28) directly implies that $\tau_A > 0$ and $\tau_B < 0$ for $\alpha = \underline{\alpha}$, and that $\tau_A < 0$ and $\tau_B > 0$ for $\alpha = \overline{\alpha}$, if $\theta < 1$.

Differentiating eq. (26) with respect to parameter α gives

$$\frac{d\tau_A}{d\alpha} = (1-\sigma)\, U''(Q_1) \frac{dQ_1}{dK_R} \frac{dK_R}{dK_A} \frac{dK_A}{d\alpha} < 0, \tag{A.23}$$

since $U''(Q_0) < 0$, $U''(Q_1) < 0$, $dQ_0/dK_R < 0$ (if $\theta < 1$), $dQ_1/dK_R > 0$, $dK_R/dK_A < 0$ and $(K_A + K_B)$ are all unaffected by a change in α (see discussion at the beginning of the proof of proposition 3 and eqs. (A.10) to (A.13), and recall the technology assumptions $\partial^2 g(K_R;\alpha)/\partial K_R^2 = 0$ and $\partial^2 g(K_R;\alpha)/\partial K_R \partial\alpha = 0$ discussed in section 2), and since $dK_A/d\alpha < 0$ (see proposition 1 and eq. (A.1)).

Similarly, differentiating eq. (27) with respect to parameter α yields

$$\frac{d\tau_B}{d\alpha} = (1-\sigma)\, U''(Q_1) \frac{dQ_1}{dK_R} \frac{dK_R}{dK_B} \frac{dK_A}{d\alpha} > 0, \tag{A.24}$$

where $dK_R/dK_B > 0$ if $\theta < 1$ (see eq. (A.14)) is additionally used.

Since $d\tau_A/d\alpha < 0$ and, if $\theta < 1$, $d\tau_B/d\alpha > 0$ for $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, and since, if $\theta < 1$, $\tau_A > 0 > \tau_B$ for $\alpha = \underline{\alpha}$ and $\tau_A < 0 < \tau_B$ for $\alpha = \overline{\alpha}$ follow from our discussion above, a unique threshold value $\check{\alpha}$, with $\check{\alpha} \in (\underline{\alpha}, \overline{\alpha})$, exists such that $\tau_A \gtreqless 0 \Leftrightarrow \alpha \lesseqgtr \check{\alpha} \Leftrightarrow \tau_B \lesseqgtr 0$.

(ii) Differentiating total tax burdens $T_A = t_A + \tau_A$ and $T_B = t_{B0} + (\tau_B/\sigma)$ with respect to α gives

$$\frac{dT_A}{d\alpha} = (1-\sigma)\, U''(Q_1) \left(\frac{dQ_1}{dK_A} + \frac{dQ_1}{dK_R} \frac{dK_R}{dK_A} \right) \frac{dK_A}{d\alpha} > 0, \tag{A.25}$$

$$\frac{dT_B}{d\alpha} = \frac{(1-\sigma)}{\sigma} U''(Q_1) \left(\frac{dQ_1}{dK_B} + \frac{dQ_1}{dK_R} \frac{dK_R}{dK_B} \right) \frac{dK_A}{d\alpha} < 0, \tag{A.26}$$

where eqs. (A.18), (A.19), (A.23) and (A.24) are used. The inequality signs follow from $U''(Q) < 0$, $dK_A/d\alpha < 0$ (see eq. (A.1)) and, after rearranging eqs. (A.7), (A.9) and (A.11) to (A.15),

$$\frac{dQ_1}{dK_A} + \frac{dQ_1}{dK_R} \frac{dK_R}{dK_A} = -\frac{U''(\overline{Q})\widehat{h}}{\Psi} > 0, \tag{A.27}$$

$$\frac{dQ_1}{dK_B} + \frac{dQ_1}{dK_R} \frac{dK_R}{dK_B} = \frac{\sigma\,(1-\theta)\, U''(Q_0)\widehat{h}}{\theta\Psi} < 0, \tag{A.28}$$

where $\partial g(K_R;\alpha)/\partial K_R = \widehat{h} > 0$ and $\Psi > 0$ (see eq. (A.15)) are also used.

Finally, $t_A|_{\alpha=\overline{\alpha}} < t_{A1}|_{\alpha=\overline{\alpha}} = \delta_A$ (see proposition 3), $\tau_A|_{\alpha=\overline{\alpha}} < 0$ (see part (i) of this proof) and $dT_A/d\alpha > 0$ imply that $T_A \leq t_A|_{\alpha=\overline{\alpha}} + \tau_A|_{\alpha=\overline{\alpha}} < t_A|_{\alpha=\overline{\alpha}} < \delta_A$. Similarly, $t_{B0}|_{\alpha=\underline{\alpha}} < \delta_B$ (see propositions 3), $\tau_B|_{\alpha=\underline{\alpha}} < 0$ (see part (i) of this proof) and $dT_B/d\alpha < 0$ imply that $T_B \leq t_{B0}|_{\alpha=\underline{\alpha}} + (\tau_B|_{\alpha=\overline{\alpha}}/\sigma) < t_{B0}|_{\alpha=\underline{\alpha}} < \delta_B$.

Proof of Proposition 6:

(i) For $\theta = 1$, eqs. (A.19) and (A.21) imply that $t_{B0} = t_{A0}$ and, because $dQ_1/dK_B = 0$ if $\theta = 1$ (see eq. (A.9)), $dt_{B0}/d\alpha = 0$. Also, $\tau_B = 0$ for $\alpha \in [\underline{\alpha}, \overline{\alpha}]$ and thus $d\tau_B/d\alpha = 0$ follow from eq. (27) with $dK_R/dK_B = 0$ if $\theta = 1$ (see eq. (A.14)). Then, $T_B = t_{B0} + (\tau_B/\sigma) = t_{B0}$ and $dT_B/d\alpha = 0$.

(ii) Eq. (26) implies that $\tau_A = 0$ for $\alpha = \overline{\alpha}$, since $K_A = 0$ for $\alpha = \overline{\alpha}$ (see lemma 2), and since $dQ_0/dK_R = 0$ if $\theta = 1$ (see eq. (A.10)). As $d\tau_A/d\alpha < 0$ irrespective of θ (see eq. (A.23) in connection with (A.1), (A.11) and (A.13)), $\tau_A > 0$ for $\alpha \in [\underline{\alpha}, \overline{\alpha})$.

(iii) See propositions 3 to 5.

Proof of Proposition 7:

(i) Using eqs. (22), (A.4), (A.7) and (A.12) leads to

$$\frac{dt_{A0}}{d\theta} = -U''(Q_0)\frac{dQ_0}{dK_A}\left[\frac{\Upsilon}{\Omega}(K_A + K_B) + \left(\overline{Q} - Q_0\right)\right] > 0, \tag{A.29}$$

where $\Upsilon := \partial\Omega/\partial\theta = U''(\overline{Q}) - \sigma U''(Q_0) - (1-\sigma)\, U''(Q_1)$. The inequality sign follows from the facts that $\Upsilon \leq 0$ if $|U''(Q)|$ is log-concave in Q (assumption 2), a relationship which is shown separately in lemma 4 below, and that $\overline{Q} - Q_0 > 0$, $\Omega < 0$, $dQ_0/dK_A > 0$ and $U''(Q) < 0$ (see lemma 2 and eqs. (A.7) and (A.12)).

Similarly, using eqs. (23), (24), (A.3), (A.7), (A.12) and (A.29) gives

$$\begin{aligned}\frac{dt_A}{d\theta} = \frac{dQ_0}{dK_A}\Big\{&-\frac{\Upsilon}{\Omega}\left[\sigma U''(Q_0)\,(K_A + K_B) + (1-\sigma)\,U''(Q_1)K_A\right]\\ &-\sigma U''(Q_0)\left(\overline{Q} - Q_0\right) - (1-\sigma)\,U''(Q_1)\left(\overline{Q} - Q_1\right)\Big\} > 0,\end{aligned} \tag{A.30}$$

where $dQ_0/dK_A = dQ_1/dK_A$ is taken into account (the derivative $dt_{A1}/d\theta$, which is included in eq. (A.30), is not separately stated). The first line of eq. (A.30) is non-negative, since $\Upsilon \leq 0$ under assumption 2, $\Omega < 0$, $dQ_0/dK_A > 0$ and $U''(Q) < 0$. The sign of the second line is positive if the (inverse) demand function is strictly convex, since then $-\sigma U''(Q_0)\left(\overline{Q} - Q_0\right) > -(1-\sigma)\,U''(Q_1)\left(Q_1 - \overline{Q}\right) > 0$.

In the same fashion, eqs. (25), (A.3), (A.4), (A.8), (A.9) and (A.12) can be used to derive

$$\frac{dt_{B0}}{d\theta} = \underbrace{-\frac{\Upsilon U''(Q_0)U''(\overline{Q})}{\Omega^2}K_A - \frac{U''(Q_0)\left[(1-\sigma)U''(Q_1)\Omega + \theta^2\Upsilon\Gamma_1\right]}{\theta^2\Omega^2}K_B}_{\Gamma_3:=}$$

$$\underbrace{-\frac{U''(Q_0)\Gamma_1\left(\overline{Q}-Q_0\right) + \left[(1-\theta)/\theta\right]U''(Q_1)\Gamma_2\left(Q_1-\overline{Q}\right)}{\Omega}}_{\Gamma_4:=} > 0, \quad \text{(A.31)}$$

where $\Gamma_1 = U''(\overline{Q}) + (1-\sigma)\left[(1-\theta)/\theta\right]U''(Q_1)$ and $\Gamma_2 = (1-\sigma)U''(Q_0)$, with $\Upsilon = \partial\Omega/\partial\theta$ given above. Both lines of eq. (A.31) are positive because $U''(Q) < 0$, $\Gamma_1 < 0$, $\Gamma_2 < 0$, $\Upsilon \leq 0$, $\Omega < 0$ and $Q_0 < \overline{Q} < Q_1$. Hence, $dt_{B0}/d\theta > 0$ results.

(ii) If $U'''(Q) = 0$, then $\Upsilon = 0$ (see above) and the second line of eq. (A.30) yields $-\sigma U''(Q_0)\left(\overline{Q}-Q_0\right) - (1-\sigma)U''(Q_1)\left(\overline{Q}-Q_1\right) = -U''\left[\overline{Q}-\sigma Q_0-(1-\sigma)Q_1\right] = 0$ (see discussion after eq. (A.5)). Hence, $dt_A/d\theta = 0$ (see eq. (A.30)). Since $dt_{A0}/d\theta > 0$ still holds (see eq. (A.29)), $dt_{A1}/d\theta = -dt_{A0}/d\theta$ must also hold (in general, the sign of $dt_{A1}/d\theta$ is ambiguous).

Lemma 4. *Consider* $\Upsilon := U''(\overline{Q}) - \sigma U''(Q_0) - (1-\sigma)U''(Q_1)$. *If* $|U''(Q)|$ *is log-concave in* Q *or, equivalently, if inequality* $U''''(Q) \geq \left[U'''(Q)\right]^2/U''(Q)$ *is satisfied, then* $\Upsilon \leq 0$.

Proof of Lemma 4:

Let us denote the demand function (i.e., the inverse of $U'(Q)$, with $p = U'(Q)$) by $Z(p)$, with $Q = Z(p)$, $Q_0 = Z(p_0)$, $Q_1 = Z(p_1)$ and $\overline{Q} = Z(\overline{p}) = Z(\sigma p_0 + (1-\sigma)p_1)$. Then, Jensen's inequality implies that $\Upsilon = U''(\overline{Q}) - \sigma U''(Q_0) - (1-\sigma)U''(Q_1) = U''\left(Z(\sigma p_0 + (1-\sigma)p_1)\right) - \sigma U''\left(Z(p_0)\right) - (1-\sigma)U''\left(Z(p_1)\right) \leq 0$ if, and only if, U'' is convex in price p. With $\partial Z(p)/\partial p = 1/U''(Q) < 0$, differentiating U'' twice gives $dU''/dp = \left(\partial U''/\partial Z\right)\left(\partial Z/\partial p\right) = U'''(Q)/U''(Q)$ and

$$\frac{d^2U''}{dp^2} = \frac{\partial\left[U'''/U''\right]}{\partial Z}\frac{\partial Z}{\partial p} = \frac{U''(Q)U''''(Q) - \left[U'''(Q)\right]^2}{\left[U''(Q)\right]^3} \geq 0 \Leftrightarrow U''''(Q) \geq \frac{\left[U'''(Q)\right]^2}{U''(Q)}, \quad \text{(A.32)}$$

where the last inequality provides the condition for U'' being convex in p and thus, as stated in lemma 4, $\Upsilon \leq 0$.

It remains to show that this condition is equivalent to the twice-continuously differentiable function $|U''(Q)|$ being log concave in Q. Differentiating $\log|U''(Q)|$ with respect to Q twice gives $d\log|U''(Q)|/dQ = -U'''(Q)/|U''(Q)| = U'''(Q)/U''(Q)$ and

$$\frac{d^2\log|U''(Q)|}{dQ^2} = \frac{U''(Q)U''''(Q) - \left[U'''(Q)\right]^2}{\left[U''(Q)\right]^2} \leq 0 \Leftrightarrow U''''(Q) \geq \frac{\left[U'''(Q)\right]^2}{U''(Q)}, \quad \text{(A.33)}$$

where the last inequality provides the condition for $\log|U''(Q)|$ being log-concave in Q and is identical to the condition in eq. (A.32), thus proving lemma 4.

Proof of Proposition 8:

(i) Plugging eq. (A.13) into eq. (A.16) gives τ_A as a function of the endogenous variables K_A and K_B and of parameter θ. (Recall that the socially optimal capacity K_R, which is decentralised through the tax system, is independent of share θ, and so are the derivatives $U''(Q_0)$, $U''(Q_1)$ and $U''(\overline{Q})$, as stated in lemma 1 and proposition 2.) Then, the derivative of τ_A with respect to θ can be decomposed into three elements:

$$\frac{d\tau_A}{d\theta} = \frac{\partial\tau_A}{\partial\theta} + \frac{\partial\tau_A}{\partial K_A}\frac{dK_A}{d\theta} + \frac{\partial\tau_A}{\partial K_B}\frac{dK_B}{d\theta}. \tag{A.34}$$

Using eqs. (A.3), (A.13) and (A.16) enables us to show that the second term and the third term on the right-hand side of eq. (A.34) are positive and non-negative, respectively:

$$\frac{\partial\tau_A}{\partial K_A}\frac{dK_A}{d\theta} = -\frac{\left[(1-\sigma)\,U''(Q_1)U''(\overline{Q})\right]^2}{\Omega\Psi}\left(Q_1-\overline{Q}\right) > 0, \tag{A.35}$$

$$\frac{\partial\tau_A}{\partial K_B}\frac{dK_B}{d\theta} = -\frac{\sigma\,(1-\theta)\,[(1-\sigma)\,U''(Q_1)]^2\,U''(Q_0)U''(\overline{Q})}{\theta\Omega\Psi}\,(Q_1-Q_0) \geq 0, \tag{A.36}$$

where the inequality signs follow from $\Omega < 0$, $\Psi > 0$ (see Eqs. (A.12) and (A.15)), $U''(Q) < 0$ and $Q_1 > \overline{Q} > Q_0$ (see lemma 2).

Calculating the first term on the right-hand side of eq. (A.34) leads to

$$\begin{aligned}\frac{\partial\tau_A}{\partial\theta} = \frac{-U''(\overline{Q})\,[(1-\sigma)\,U''(Q_1)]^2}{\Omega^2\Psi^2}&\left\{-\Upsilon\left[U''(\overline{Q})K_A - \sigma\frac{1-\theta}{\theta}U''(Q_0)K_B\right]\right.\\ &\times\left[(1-\sigma)\,U''(Q_1)\left(U''(\overline{Q})+\sigma\frac{1-\theta}{\theta}U''(Q_0)\right)-2\widehat{h}\Omega\right]\\ &+\left[\frac{\sigma}{\theta^2}U''(Q_0)\Omega K_B\left[(1-\sigma)\,U''(Q_1)U''(\overline{Q})-\widehat{h}\Omega\right]\right]\\ &\left.+\frac{\sigma\,(1-\sigma)}{\theta^2}U''(Q_0)U''(Q_1)U''(\overline{Q})\Omega K_A\right\}\end{aligned} \tag{A.37}$$

after some rearrangements. The fraction in the first line outside the curly brackets is positive, and so are the terms in the second, third and fourth line, since $\Omega < 0$, $\Psi > 0$, $U''(Q) < 0$ and $\partial g(K_R;\alpha)/\partial K_R = \widehat{h} > 0$. As $U''(\overline{Q})K_A \gtreqless \sigma\,[(1-\theta)/\theta]\,U''(Q_0)K_B \Leftrightarrow \tau_A \lesseqgtr 0$ (see eq. (A.16), which holds for $\theta \leq 1$) and $\Upsilon \leq 0$ (see lemma 4), the expression after the curly bracket in the first line is non-negative if $\tau_A \leq 0$. Thus, $\partial\tau_A/\partial\theta > 0$ if $\tau_A \leq 0$.

Consequently, $d\tau_A/d\theta > 0$ if $\tau_A \leq 0$, since two terms on the right-hand side of eq. (A.34) are positive and one term is non-negative. Also, if $\tau_A > 0$ for some θ, τ_A cannot become negative as θ increases, since this would require, by means of continuity, $d\tau_A/d\theta < 0$ for $\tau_A = 0$, which would contradict the previous statement.

(ii) Eqs. (A.34) to (A.37) imply that

$$\frac{d\tau_A}{d\theta} > \frac{\left[(1-\sigma)\,U''(Q_1)U''(\overline{Q})\right]^2 \Upsilon K_A}{\Omega^2\Psi^2} \times \left\{(1-\sigma)\,U''(Q_1)\left[U''(\overline{Q})+\sigma\frac{1-\theta}{\theta}U''(Q_0)\right]-2\widehat{h}\Omega\right\}, \quad \text{(A.38)}$$

where the right-hand side contains the only negative term of $\partial\tau_A/\partial\theta$ and $d\tau_A/d\theta$.

Similarly, eqs. (A.7) and (A.30) imply that if inverse demand $U''(Q)$ is convex, then

$$\frac{dt_A}{d\theta} \geq -\frac{U''(\overline{Q})\Upsilon\left[\sigma U''(Q_0)+(1-\sigma)\,U''(Q_1)\right]K_A}{\Omega^2}, \quad \text{(A.39)}$$

where the right-hand side excludes the second line of eq. (A.30), which is non-negative if $U'''(Q) \geq 0$, and a positive term of the first line (see proof of proposition 7). Eqs. (A.38) and (A.39) together yield, after some rearrangements,

$$\begin{aligned}\frac{dT_A}{d\theta} > -\frac{U''(\overline{Q})K_A}{\Omega^2}\Bigg\{&\Upsilon\left[\sigma U''(Q_0)+(1-\sigma)\,U''(Q_1)\right]\\ &-(1-\sigma)\,U''(Q_1)\Upsilon\frac{(1-\sigma)\,U''(Q_1)U''(\overline{Q})}{\Psi}\left(1-\frac{\widehat{h}\Omega}{\Psi}\right)\Bigg\}\\ &\geq -\frac{\sigma U''(Q_0)U''(\overline{Q})\Upsilon K_A}{\Omega^2} \geq 0. \quad \text{(A.40)}\end{aligned}$$

The first inequality sign in the last line might need an explanation: Denote by $\Xi_1 := \left[(1-\sigma)\,U''(Q_1)U''(\overline{Q})\right]/\Psi > 0$ and $\Xi_2 := -\widehat{h}\Omega/\Psi > 0$ the fractions of the second line. As can be easily checked, $\Xi_1+\Xi_2 \leq 1$ (see eq. (A.15)), which implies $\Xi_1\left(1+\Xi_2\right) \leq \left(1-\Xi_2\right)\left(1+\Xi_2\right) = \left(1-\Xi_2^2\right) < 1$. Hence, the second line is greater than, or (if $\Upsilon = 0$) equal to, $-(1-\sigma)\,U''(Q_1)\Upsilon$, which in turn implies the third line. Thus, $dT_A/d\theta > 0$ if $U'''(Q) \geq 0$.

Proof of Proposition 9:

(i) The proof of proposition 9 is analogous to that of proposition 8. Plugging eqs. (A.14) and (A.16) into eq. (A.17) gives τ_B as a function of K_A, K_B and θ. Then, the derivative of τ_B with respect to θ can be decomposed into three elements:

$$\frac{d\tau_B}{d\theta} = \frac{\partial\tau_B}{\partial\theta}+\frac{\partial\tau_B}{\partial K_A}\frac{dK_A}{d\theta}+\frac{\partial\tau_B}{\partial K_B}\frac{dK_B}{d\theta}. \quad \text{(A.41)}$$

Using eqs. (A.3), (A.14), (A.16) and (A.17) enables us to show that the second term and the third term on the right-hand side of eq. (A.41) are non-positive:

$$\frac{\partial \tau_B}{\partial K_A}\frac{dK_A}{d\theta} = \frac{\sigma\,(1-\theta)\left[(1-\sigma)\,U''(Q_1)\right]^2 U''(Q_0)U''(\overline{Q})}{\theta\Omega\Psi}\left(Q_1-\overline{Q}\right) \leq 0, \tag{A.42}$$

$$\frac{\partial \tau_B}{\partial K_B}\frac{dK_B}{d\theta} = \frac{\left[\sigma\,(1-\sigma)\,(1-\theta)\,U''(Q_0)U''(Q_1)\right]^2}{\theta^2\Omega\Psi}\left(Q_1-Q_0\right) \leq 0, \tag{A.43}$$

where the inequality signs follow again from $\Omega < 0$, $\Psi > 0$ (see eqs. (A.12) and (A.15)), $U''(Q) < 0$ and $Q_1 > \overline{Q} > Q_0$ (see lemma 2).

Calculating the first term on the right-hand side of eq. (A.41) gives

$$\begin{aligned}\frac{\partial \tau_B}{\partial \theta} = \frac{\sigma U''(Q_0)\left[(1-\sigma)\,U''(Q_1)\right]^2}{\theta\Omega^2\Psi^2}&\left\{\left[U''(\overline{Q})K_A - \sigma\frac{1-\theta}{\theta}U''(Q_0)K_B\right]\right.\\ &\times\left\{-(1-\theta)\,\Upsilon\left[(1-\sigma)\,U''(Q_1)\left(U''(\overline{Q})+\sigma\frac{1-\theta}{\theta}U''(Q_0)\right)-2\widehat{h}\Omega\right]\right.\\ &\qquad\left.-\frac{\Omega}{\theta}\left[(1-\sigma)\,U''(Q_1)U''(\overline{Q})-\widehat{h}\Omega\right]\right\}\\ &\qquad\qquad\left.+\frac{\sigma\,(1-\theta)}{\theta^2}U''(Q_0)\Psi\Omega K_B\right\}\end{aligned} \tag{A.44}$$

after some rearrangements. The fraction outside the curly brackets on the right-hand side of the first line is negative. The second line is non-negative and the third and fourth line are positive, since $\Omega < 0$, $\Upsilon \leq 0$ (see lemma 4), $\partial g(K_R;\alpha)/\partial K_R = \widehat{h} > 0$ and $U''(Q) < 0$. Since, for $\theta < 1$, $U''(\overline{Q})K_A \gtreqless \sigma\left[(1-\theta)/\theta\right]U''(Q_0)K_B \Leftrightarrow \tau_B \gtreqless 0$, the expression in the square brackets after the curly bracket in the first line is positive if tax τ_B is positive (see lemma 3 and eq. (A.16)). Thus, for $\theta < 1$, $\partial\tau_B/\partial\theta < 0$ if $\tau_B \geq 0$.

Then, for $\theta < 1$, $d\tau_B/d\theta < 0$ if $\tau_B \geq 0$ follows from $(\partial\tau_B/\partial K_A)\,(dK_A/d\theta) < 0$, $(\partial\tau_B/\partial K_B)\,(dK_B/d\theta) < 0$ and $\partial\tau_B/\partial\theta < 0$ (see eqs. (A.42), (A.43) and (A.44)). Also, for $\theta = 1$, $\tau_B = 0$ is implied by eqs. (A.14) and (A.17). Additionally, for $\theta = 1$ and $\alpha \in (\underline{\alpha}, \overline{\alpha})$ at $\theta = 1$ (i.e., $K_A > 0$), $d\tau_B/d\theta > 0$ follows from $(\partial\tau_B/\partial K_A)\,(dK_A/d\theta) = (\partial\tau_B/\partial K_B)\,(dK_B/d\theta) = 0$ and $\partial\tau_B/\partial\theta > 0$ (see again eqs. (A.42), A.43) and (A.44)). Consequently, if $\tau_B < 0$ for some θ, τ_B cannot become positive as θ increases, since this would require, by means of continuity, $d\tau_B/d\theta > 0$ for $\tau_B = 0$ and $\theta < 1$, which would contradict the previous statements. Furthermore, since $d\tau_B/d\theta > 0$ for $\theta = 1$, $d\tau_B/d\theta > 0$ must be satisfied for some interval $\theta \in \left(\hat{\theta}, 1\right]$ by means of continuity.

Note that the lower and upper bounds $\underline{\alpha}$ and $\overline{\alpha}$ are functions of parameter θ. Effectively, K_A has to be 'interior' over the relevant range of values of parameter θ. This is certainly the case if $K_A \geq 0$ holds at the starting point of θ, since $dK_A/d\theta > 0$ results in the decentralised social optimum, as shown in proposition 2. Then, the upward sloping part of the τ_B-θ curve definitely exist, while the downward sloping part will exist if the starting point of θ implies a sufficiently large (small) K_B (K_A).

(ii) Recall that $dt_{B0}/d\theta = \Gamma_3 + \Gamma_4$ (see eq. (A.31)). Then, $dT_B/d\theta = dt_{B0}/d\theta +$

$(1/\sigma)\, d\tau_B/d\theta > 0$ if $\Gamma_4 + (1/\sigma)\left[(\partial\tau_B/\partial K_A)(dK_A/d\theta) + (\partial\tau_B/\partial K_B)(dK_B/d\theta)\right] > 0$ and $\Gamma_3 + (1/\sigma)\,\partial\tau_B/\partial\theta > 0$ (see eqs. (A.31) and (A.41). Let us prove in turn that the latter two inequalities are satisfied. First, rearranging the terms of the first inequality (see eqs. (A.31), (A.42) and (A.43)) gives

$$\Gamma_4 + \frac{1}{\sigma}\left(\frac{\partial\tau_B}{\partial K_A}\frac{dK_A}{d\theta} + \frac{\partial\tau_B}{\partial K_B}\frac{dK_B}{d\theta}\right) = -\frac{(1-\sigma)(1-\theta)\,U''(Q_0)U''(Q_1)}{\theta\Omega}$$
$$\left\{\left(Q_1 - \overline{Q}\right)\left[1 - \frac{(1-\sigma)\,U''(Q_1)\left[U''(\overline{Q}) + \sigma\left[(1-\theta)/\theta\right]U''(Q_0)\right]}{\Psi}\right]\right.$$
$$\left. + \left(\overline{Q} - Q_0\right)\left[1 - \frac{\sigma(1-\sigma)\left[(1-\theta)/\theta\right]U''(Q_0)U''(Q_1)}{\Psi}\right]\right\}$$
$$-\frac{U''(Q_0)U''(\overline{Q})}{\Omega}\left(\overline{Q} - Q_0\right) > 0. \quad \text{(A.45)}$$

This term is indeed positive. The fractions in the square brackets in the second and third line are positive and smaller than one, which follows from the definition of Ψ in eq. (A.15) and the fact that $\Psi > 0$ and $U''(Q) < 0$. Thus, the square brackets are positive and, as $Q_0 < \overline{Q} < Q_1$ also holds (see lemma 2), so are the second line and the third line. With $\Omega < 0$ (see eq. (A.12)), the fourth line and the right-hand side of the first line are positive, too.

Second, using the facts that $\Gamma_3 > -U''(Q_0)\left[(1-\sigma)\,U''(Q_1)\Omega + \theta^2\Upsilon\Gamma_1\right]K_B/\left(\theta^2\Omega^2\right)$ and $\partial\tau_B/\partial\theta > \partial\tau_B/\partial\theta|_{K_A=0}$, which follow from eqs. (A.31) and (A.44), leads to

$$\Gamma_3 + \frac{1}{\sigma}\frac{\partial\tau_B}{\partial\theta} > -\frac{U''(Q_0)K_B}{\Omega^2}\times$$
$$\left\{\Upsilon\left[U''(\overline{Q}) + (1-\sigma)\frac{1-\theta}{\theta}U''(Q_1)\right]\left[1 - \Xi_3\left(1 + \Xi_2\right)\right]\right.$$
$$\left. + \frac{1-\sigma}{\theta^2}U''(Q_1)\Omega\left[1 - \Xi_3\left(1 + \Xi_1 + \Xi_2\right)\right]\right\} > 0 \quad \text{(A.46)}$$

after some rearrangements, with $\Xi_1 = \left[(1-\sigma)\,U''(Q_1)U''(\overline{Q})\right]/\Psi > 0$ and $\Xi_2 = -\widehat{h}\Omega/\Psi > 0$ as defined after eq. (A.40) and $\Xi_3 = \left[\sigma(1-\sigma)(1-\theta)\,U''(Q_0)U''(Q_1)\right]/(\theta\Psi) > 0$. Eq. (A.15) implies that $\Xi_1 + \Xi_2 + \Xi_3 = 1$. Then, $1 - \Xi_3(1+\Xi_2) = \Xi_2^2 + \Xi_1(1+\Xi_2) > 0$ and $1 - \Xi_3(1+\Xi_1+\Xi_2) = (\Xi_1+\Xi_2)^2 > 0$. Thus, as $\Upsilon \leq 0$, $\Omega < 0$ and $U''(Q) < 0$ also hold, $\Gamma_3 + (1/\sigma)\,\partial\tau_B/\partial\theta > 0$ results. Hence, inequalities (A.45) and (A.46) imply $dT_B/d\theta > 0$.

Proof of Proposition 10:

Plugging $U''(Q) = U'' = \text{const.} < 0$ into eqs. (A.35) to (A.37) and (A.42) to (A.44), inserting the resulting terms into eqs. (A.34) and (A.41), and rearranging the equations yield

$$\frac{\partial \tau_A}{\partial \theta} = \frac{\sigma \left[(1-\sigma) U''\right]^2 \left\{\widehat{h} K_B - (1-\sigma)(K_A + K_B) U''\right\}}{\theta^2 \left\{(1-\sigma)\left[1+\sigma(1-\theta)/\theta\right] U'' - \widehat{h}\right\}^2} > 0, \tag{A.47}$$

$$\begin{aligned}\frac{d\tau_B}{d\theta} = {} & \frac{\sigma \left[(1-\sigma) U''\right]^2}{\theta^2 \left\{(1-\sigma)\left[1+\sigma(1-\theta)/\theta\right] U'' - \widehat{h}\right\}^2} \\ & \left\{\left[\theta\left(Q_1 - \overline{Q}\right) + \sigma(1-\theta)(Q_1 - Q_0) + \frac{\sigma}{\theta} K_B\right] \right. \\ & \times (1-\theta)\left[(1-\sigma)\left(1+\sigma\frac{1-\theta}{\theta}\right) U'' - \widehat{h}\right] \\ & \left. + \left(K_A - \sigma\frac{1-\theta}{\theta} K_B\right)\left[\widehat{h} - (1-\sigma) U''\right]\right\}. \end{aligned} \tag{A.48}$$

Since $(\partial\tau_A/\partial K_A)(dK_A/d\theta) > 0$ and $(\partial\tau_A/\partial K_B)(dK_B/d\theta) \geq 0$ follow from eqs. (A.35) and (A.36), and since $\partial\tau_A/\partial\theta > 0$ for $U''' = 0$ follows from eq. (A.47), $d\tau_A/d\theta > 0$ results for $U''' = 0$ (see eq. (A.34)).

The first line on the right-hand side of eq. (A.48) is positive. Then, defining by Γ_5 the expressions in the curly brackets (i.e., the second, third and fourth line of eq. (A.48)) implies that $d\tau_B/d\theta \lesseqqgtr 0 \Leftrightarrow \Gamma_5 \lesseqqgtr 0$. Also, $\Gamma_5 < 0$ if $K_A \leq \sigma\left[(1-\theta)/\theta\right] K_B$ or, equivalently, if $\tau_B \geq 0$ for $\theta < 1$. By contrast, $\Gamma_5 > 0$ if $\theta = 1$. Finally, differentiating Γ_5 yields $d\Gamma_5/\partial\theta > 0$ (where, e.g., $\sigma Q_0 + (1-\sigma) Q_1 - \overline{Q} = 0$ for $U''' = 0$ is used), as can be checked. Hence, by means of continuity, a critical value $\hat{\theta}$, with $\hat{\theta} \in \left(\widetilde{\theta}, 1\right)$ and $\widetilde{\theta} : K_A = \sigma\left[(1-\theta)/\theta\right] K_B$, exists such that $d\tau_B/d\theta \lesseqqgtr 0 \Leftrightarrow \theta \lesseqqgtr \hat{\theta}$.

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