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# Efficient taxation of sugar-sweetened beverages and missing markets for sugar content

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## Abstract

This paper identifies missing markets for the sugar content of sugar-sweetened beverages (SSBs) as a novel foundation of soft drink taxation. If the social marginal value of sugar content is negative, then missing price signals imply an inefficiently high sugar content. Efficiency is restored with a tax on the sugar content per unit of the SSB, augmented by a subsidy on the SSB. In an empirical calibration to the UK, the optimal SSB subsidy is small, whereas the optimal sugar content tax is £0.38 per liter and, thus, one and a half to two times larger than the tax rates implemented by the UK's soft drink levy.

*Keywords:* Obesity; sugar-sweetened beverages; sugar content; soft drink levy

*JEL classification:* D50; H21; I18

## 1. Introduction

Obesity has reached epidemic proportions globally, with at least 2.8 million people dying each year as a result of being overweight or obese (World Health Organization, 2022). Obesity and being overweight are caused to a large extent by overconsumption of sugar, in particular sugar-sweetened beverages (SSBs). Therefore, World Health Organization (2017) recommends taxing SSBs and, according to Allcott et al. (2019a), by 2019, already 39 countries worldwide had introduced soft drink taxes, in addition to a number of cities and counties in the United States. Many governments tax SSBs using a tax rate applied to each volume unit (e.g., ounce or liter) of the SSB. But very recently, taxes on the sugar content of SSBs have become more and more popular. In 2018, for instance, the UK introduced a soft drink levy with a rate of £0.18 per liter on SSBs with 5–8 gram sugar per 100 ml and £0.24 per liter on SSBs with more than 8 gram sugar per 100 ml. Soft drink taxes with a similar rate structure have been implemented in Chile since 2014 and in

Portugal since 2017 (see Griffith et al., 2019). In 2018, France also reformed its soft drink tax such that the tax rate is differentiated according to the sugar content of SSBs (see Kurz and König, 2021).

The present paper provides a new economic foundation for taxes on SSBs, in particular taxes on the sugar content of SSBs. We abstract from those externalities and internalities that have previously been used to justify sugar taxation; for a survey, see Allcott et al. (2019a) and Griffith et al. (2020). Instead, we identify a novel sugar content externality not identified so far in the literature. Key to our argument is that, in practice, markets for sugar content may be absent, so competitive prices do not reflect the full social marginal benefits and costs of sugar content. If the social marginal value of sugar content (i.e., the difference between marginal consumption benefits and marginal health costs of sugar content in the social optimum) is negative, then the unregulated laissez-faire economy yields an inefficiently low SSB price and an inefficiently high sugar content. The market failure can be corrected with the help of a tax on the sugar content per unit of the SSB. Because the sugar content tax applies to each unit of the SSB, tax payments increase with the quantity of the SSB. This leads to an unintended distortion of the SSB quantity, which has to be corrected by an additional subsidy on each volume unit of the SSB. In a calibration to the UK, the optimal SSB subsidy turns out to be small, whereas the optimal sugar content tax is £0.38 per liter and, thus, one and a half to two times larger than the above-mentioned tax rates implemented by the UK's soft drink levy.

These results are derived in a general equilibrium model with sugar production, SSB production, and SSB consumption. We consider a single SSB that can be interpreted as a representative or average SSB. This SSB is produced by a representative firm and consumed by a representative household. Each unit of the SSB contains a certain amount of sugar that explicitly enters the analysis as a production factor. The embodied sugar per unit of SSB output, called sugar content, is a product characteristic that can be varied in the SSB production process. The consumer has preferences regarding the quantity and the sugar content of the SSB, and her health is harmed by the sugar intake stemming from SSB consumption. Within this framework, we first derive the Pareto optimum and show that, in the efficient allocation, the social marginal value of sugar content equals the difference between the marginal consumption benefits and the marginal health costs of sugar content, and is reflected by the shadow price of sugar content.

The efficient solution is then compared with the market outcome. In order to model the market economy, we make use of the indirect market approach first considered in Lancaster (1966) and Rosen (1974). Accordingly, the market price of the SSB is a function of the embodied sugar content, and the (implicit) market price of sugar content equals the derivative of this price function. If all markets work smoothly, market prices reflect the social marginal values

(shadow prices) of the traded goods, inclusive of the sugar content, and the laissez-faire market economy implements the efficient allocation. However, if the indirect market for sugar content is missing, then the market price of sugar content is zero and does not reflect the shadow price of sugar content. The SSB producer's choice of sugar content then exerts an externality on the consumers and the laissez-faire economy cannot decentralize the efficient allocation. If the social marginal value of sugar content is negative, the SSB price is inefficiently low and the sugar content inefficiently high.

Next, we show that this market failure can be corrected by a variety of tax policy options. First, a yearly or one-time charge (license) on the sugar content in the formulation of the SSB directly replaces the missing price of sugar content and thereby restores efficiency. Second, efficiency is also attained by a tax on sugar content per unit of the SSB (or, equivalently, a sugar input tax), combined with a subsidy on each volume unit of the SSB. The subsidy is needed because the sugar content tax falls on each unit of the SSB and, thereby, distorts the SSB quantity. Interestingly, the tax–subsidy combination is revenue neutral. Hence, if both instruments are levied on SSB producers, net tax payments are zero, which may increase the producers' acceptability of sugar taxation. If the SSB subsidy is granted to consumers, we obtain a deposit–refund system that can easily be incorporated in existing deposit–refund systems for SSB containers.

In order to estimate the empirical significance of the tax–subsidy solution, we calibrate our model to the UK, where in 2018 the government introduced the above-mentioned soft drink levy. We choose the model parameters such that the laissez-faire allocation reproduced UK data from 2015, when the soft drink levy was neither introduced nor announced. The calibrated model parameters are then used for computing the efficient allocation as well as the optimal tax and subsidy rates. It turns out that the optimal SSB subsidy is around half a pence and, thus, rather small. Hence, it can be either completely ignored or incorporated by a small surcharge of, say, £0.01 per liter in the deposit–refund system that the UK government plans to introduce in 2025.<sup>1</sup> In contrast, the sugar content tax may be substantial. Evaluated at the average sugar content of SSBs in the year 2015, it amounts to £0.38 per liter and, thus, is roughly one and a half to two times larger than the tax rates of £0.24 and £0.18 per liter implemented by the UK's soft drink levy. In a sensitivity analysis, we show that the SSB subsidy remains small and that our estimate of £0.38 per liter is likely to be a lower bound for the optimal sugar content tax.

<sup>1</sup>See the government press release, "Deposit Return Scheme for drinks containers moves a step closer", <https://www.gov.uk/government/news/deposit-return-scheme-for-drinks-containers-moves-a-step-closer>.

Finally, we extend the analysis into three directions in order to further prove the robustness of our results. First, we investigate the second-best sugar content tax rate per unit of the SSB when this instrument is the only one available. While the complexity of our theoretical model prevents us from deriving analytical results, in the calibration we show that the second-best sugar content tax rate is only marginally different from its first-best level. Second, we introduce an internality caused by a present bias of the consumer. In this extension, it turns out that the combination of a sugar content tax per unit of the SSB and a subsidy on the SSB quantity remains largely unchanged, both in the theoretical model as well as in the empirical calibration. Third, we extend our theoretical model to the case with several SSBs and show that the policy implications remain qualitatively unchanged, except that each policy instrument is now SSB-specific.

The market failure and the need for the corrective policy identified in this paper crucially depends on: (i) the assumption of a missing market for sugar content; and (ii) the negative sign of the social marginal value of sugar content in the social optimum (shadow price of sugar content), implying a negative sign of the sugar content externality.<sup>2</sup> With respect to condition (i), notice that a missing market for sugar content implies a zero market price of sugar content, and this is consistent with the empirical evidence on the so-called uniform product pricing, according to which an SSB and its diet or zero-sugar variant are commonly sold at the same price (e.g., McMillan, 2007; Bollinger and Sexton, 2018).<sup>3</sup> To the best of our knowledge, there is no empirical study investigating directly whether condition (ii) is satisfied. But the Global BMI Mortality Collaboration (2016) finds that, in terms of increased mortality, health costs are rapidly and convexly increasing in the body mass index that is determined, among others, by sugar consumption. Hence, the social marginal value of the sugar content of SSBs is likely to be negative. This conclusion is supported by the empirical calibration of our model to the UK's soft drink levy, which finds a negative shadow price of sugar content.

Our analysis contributes to the literature on sin taxation, in general, and sugar taxation, in particular. In this literature, sin or SSB taxes are usually justified by standard externality and internality arguments. The

<sup>2</sup>With a positive sign of the shadow price of sugar content, the sugar content externality is positive and we still have market failure if the market for sugar content is absent. But the direction of the inefficiency under laissez-faire and the signs of the optimal regulatory policy instruments are then reversed.

<sup>3</sup>Chen and Cui (2013) present a theoretical model to show that consumers' concern for peer-induced price fairness might explain uniform product pricing. Other explanations may refer to imperfect or asymmetric information. As the main aim of our analysis is to investigate the policy implications of missing markets, we simply take a zero price for sugar content as given without providing an explanation for it.

externality argument is mainly associated with the moral hazard problem in health insurance markets that leads to excessive sugar consumption, while the internality problem refers to behavioral consumers who may have present-biased preferences and self-control problems that also induce a too high sugar intake. Excellent surveys on this literature are given in Allcott et al. (2019a), Grummon et al. (2019), and Griffith et al. (2020). Original contributions can be found in Gruber and Koszegi (2001), O'Donoghue and Rabin (2003, 2006), Schroeter et al. (2008), Cremer et al. (2012, 2016), Allcott et al. (2019b), Fahri and Gabaix (2020), Kalamov and Runkel (2020, 2022), and Arnabal (2021), to name only a few.<sup>4</sup> Our approach has several important differences from this literature. First, moral hazard effects on consumption due to health-care insurance represent “only” a second-best argument for sugar taxation, as such effects would vanish if we abolish health insurance or if insurers have full information. In contrast, the tax–subsidy policy derived in our paper implements the first-best (Pareto) optimum. Second, the internality approach is paternalistic, while the optimal policy derived in our paper presupposes fully rational consumers and, correspondingly, provides a non-paternalistic foundation of sugar taxation.<sup>5</sup> Third, and perhaps most important, all above-mentioned articles do not explicitly model the sugar content of SSBs and, thus, do not derive the results that we obtain in our general equilibrium model with an endogenously determined sugar content. Important exceptions are Calcott and Petkov (2016), Réquillart et al. (2016), Cremer et al. (2019), and Calcott (2022), who consider endogenous product characteristics of sin goods in different frameworks. But they focus on the implications of internalities, externalities, and imperfect competition for the optimal regulation of the product design and, in contrast to our paper, they assume that a market with an implicit price for the product characteristics exists. Hence, they do not derive any of the results that we obtain in the case of missing markets for sugar content.

<sup>4</sup>We here only refer to theoretical papers related to the justification of sin taxation, while ignoring the works on the incidence of sin taxes (see, e.g., Kotakorpi, 2008; Bonnet and Réquillart, 2013; Dragone et al., 2016) and empirical studies on the effects of SSB taxes (see, e.g., Harding and Lovenheim, 2017; Cawley et al., 2019; Dubois et al., 2020; Aguilar et al., 2021; Dickson et al., 2023).

<sup>5</sup>There is a controversial debate in the literature about the suitability of the internality foundation of sin taxation. For example, Whitman and Rizzo (2015) criticize that the rationality axioms adopted by behavioral paternalism are not justified and that there is no evidence that policymakers can be expected to make better decisions than consumers, while the idea of libertarian paternalism or nudging discussed in, for example, Loewenstein and Chater (2017) basically allows an internality foundation of sin taxation. Our analysis in the present paper is not indented to make the case for one or the other position in this discussion. Instead, we would like to emphasize the complementary nature of both kinds of foundations.

The paper is organized as follows. Section 2 outlines the model. In Section 3, we derive the properties of the efficient allocation. In Section 4, we analyze the competitive economy with indirect markets for sugar content. In Section 5, we characterize the laissez-faire economy with missing markets for sugar content. In Section 6, we derive corrective tax–subsidy schemes. Sections 7 and 8 contain the empirical calibration and extensions, respectively. We conclude in Section 9.

## 2. Model

On the production side of the economy, we consider a representative sugar firm and a representative SSB producer. The intermediate good sugar is produced in quantity  $z^s$  with the help of labor input in quantity  $\ell_z^d$  according to the convex technology<sup>6</sup>

$$z^s \leq Z(\ell_z^d), \quad (1)$$

with  $Z_\ell > 0$ . The SSB is produced in quantity  $x^s$  with two types of ingredients, which are embodied in the output. One ingredient is sugar, which is employed in quantity  $z^d$ . The other ingredient is health-neutral and itself generated from  $\ell_x^d$  units of labor. In order to focus on sugar as the unhealthy ingredient, we do not explicitly model the production of the health-neutral ingredient and assume that it is already integrated into the production function of the SSB. Formally, the SSB production technology is given by<sup>7</sup>

$$x^s \leq X(\ell_x^d, z^d), \quad (2)$$

with  $X_\ell, X_z > 0$ . The technology (2) allows for varying the input mix or, more generally, the formulation of the SSB, as measured by the share of sugar per unit of the SSB, i.e.,

$$q^s := \frac{z^d}{x^s}. \quad (3)$$

<sup>6</sup>We use the convention that lowercase letters represent variables or parameters. The superscripts  $s$  and  $d$  attached to them indicate quantities supplied and demanded, respectively, and a subscript attached to them refers to the sector to which the variable or parameter belongs. Uppercase letters are reserved to denote functions and subscripts attached to them indicate derivatives.

<sup>7</sup>An explicit modeling of the second ingredient would require us to introduce the technology  $w = W(\ell_x^d)$  with  $W_\ell > 0$ , where  $w$  may be interpreted as water input. The SSB production function can then be written as  $\tilde{X}(w, z^d)$ . Replacing water input  $w$  by the water production function  $W(\ell_x^d)$  gives the integrated production function  $\tilde{X}[W(\ell_x^d), z^d] =: X(\ell_x^d, z^d)$ . Our main results will remain unchanged, if we assume a separate water sector producing water from labor according to the function  $W$  and delivering its output to the SSB production sector. We can also generalize our results to the case where the SSB production needs a further separate labor input that is not used for water generation. Such generalizations would increase the complexity of our formal analysis without providing any further insights.

The SSB's sugar content defined in equation (3) is an intrinsic product characteristic chosen by the SSB producer. In the following, we refer to  $q^s$  as the “supplied” sugar content.

On the consumption side of the economy, we consider a representative consumer. This consumer supplies  $\ell^s$  units of labor and consumes  $x^d$  units of the SSB with the “demanded” sugar content  $q^d$ . The consumer's health status is decreasing in her total sugar intake  $z := x^d q^d$  and represented by the health function  $h = H(z)$  with  $H_z < 0$ . The total utility of consumer  $i$  is specified by the quasi-concave utility function

$$u = U(x^d, q^d, \ell^s, h) = U[x^d, q^d, \ell^s, H(x^d q^d)], \quad (4)$$

with  $U_x, U_q, U_h > 0$ , and  $U_\ell < 0$ . The model is closed by the resource constraints

$$\ell^s \geq \ell_z^d + \ell_x^d, \quad (5)$$

$$z^s \geq z^d, \quad (6)$$

$$x^s \geq x^d, \quad (7)$$

$$q^s = q^d. \quad (8)$$

Inequalities (5) and (6) represent the resource constraints of labor and sugar, respectively. In each inequality, the left-hand side captures the quantity supplied and the right-hand side the quantity demanded. The constraints (7) and (8) show the transactions between the SSB producer and the consumer. Accordingly, the SSB producer offers the bundle  $(x^s, q^s)$  to the consumer who demands the bundle  $(x^d, q^d)$  from the SSB producer.

### 3. Pareto efficiency

In this section, we focus on the Pareto efficient allocation in the economy described above. Consider a social planner who maximizes the consumer's utility (4), subject to the technologies (1)–(3) and the resource constraints (5)–(8). The Lagrangian and the full set of first-order conditions to this maximization problem are given in the Appendix. In an interior solution, it holds that  $x^s = x^d =: x$ ,  $q^s = q^d =: q$ ,  $z^s = z^d =: z$ , and  $\ell = \ell_z + \ell_x$ , with  $\ell := \ell^s$ ,  $\ell_z := \ell_z^d$ , and  $\ell_x := \ell_x^d$ . The first-order conditions can be rearranged to the conditions listed in Column 1 of Table 1. The Lagrange multipliers  $\lambda_z$ ,  $\lambda_x$ ,  $\lambda_q$ , and  $\lambda_\ell$  represent shadow prices of sugar, the quantity of the SSB, the sugar content of the SSB, and labor, respectively. Because the Pareto optimum determines only relative shadow prices, we choose labor as the numéraire and divide all shadow prices by the shadow price of labor. In order to ease notation in the theoretical analysis, we set  $\lambda_\ell = 1$ . From Column 1,



**Table 1.** Conditions for Pareto efficiency and market equilibrium

		Pareto efficiency	Indirect market	Regulated market
		1	2	3
Sugar	1	$\frac{1}{Z_\ell} = \frac{\lambda_z}{\lambda_\ell}$	$\frac{1}{Z_\ell} = \frac{p_z}{p_\ell}$	$\frac{1}{Z_\ell} = \frac{p_z - \tau_z^s}{p_\ell}$
Producer	2	$\frac{1}{X_\ell} = \frac{\lambda_x}{\lambda_\ell} - \frac{q}{x} \frac{\lambda_q}{\lambda_\ell}$	$\frac{1}{X_\ell} = \frac{P(q)}{p_\ell} - \frac{q}{x} \frac{xP_q(q)}{p_\ell}$	$\frac{1}{X_\ell} = \frac{p_x - \tau_x^s}{p_\ell} + \frac{q}{x} \frac{\tau_q}{p_\ell}$
	3	$\frac{X_z}{X_\ell} = \frac{\lambda_z}{\lambda_\ell} - \frac{1}{x} \frac{\lambda_q}{\lambda_\ell}$	$\frac{X_z}{X_\ell} = \frac{p_z}{p_\ell} - \frac{1}{x} \frac{xP_q(q)}{p_\ell}$	$\frac{X_z}{X_\ell} = \frac{p_z + \tau_z^d}{p_\ell} + \frac{1}{x} \frac{\tau_q + \tau_{xq}x}{p_\ell}$
Consumer	4	$-\frac{U_x + qU_hH_z}{U_\ell} = \frac{\lambda_x}{\lambda_\ell}$	$-\frac{U_x + qU_hH_z}{U_\ell} = \frac{P(q)}{p_\ell}$	$-\frac{U_x + qU_hH_z}{U_\ell} = \frac{p_x + \tau_x^d}{p_\ell}$
	5	$-\frac{U_q + xU_hH_z}{U_\ell} = \frac{\lambda_q}{\lambda_\ell}$	$-\frac{U_q + xU_hH_z}{U_\ell} = \frac{xP_q(q)}{p_\ell}$	—

Row 1 of Table 1, we then infer that the shadow price of sugar is positive (i.e.,  $\lambda_z > 0$ ). According to Column 1, Row 4 of Table 1, the SSB shadow price  $\lambda_x$  reflects the social marginal value of the SSB quantity defined as  $SMV_x := -(U_x + qU_hH_z)/U_\ell$ . This expression can be positive or negative, depending on the relation between the marginal consumption benefits  $U_x > 0$  and the marginal health costs  $qU_hH_z < 0$  of the SSB quantity. Analogously, from Column 1, Row 5 of Table 1, we see that the sugar content shadow price  $\lambda_q$  equals the social marginal value of the SSB's sugar content given by  $SMV_q := -(U_q + xU_hH_z)/U_\ell$ . This expression can be positive or negative, depending on the relation between the marginal consumption benefits  $U_q > 0$  and the marginal health costs  $xU_hH_z < 0$  of sugar content. We suppose that for the SSB quantity the marginal social value is positive, implying a positive shadow price  $\lambda_x = SMV_x > 0$ , while for the sugar content the marginal health costs are so high that the social marginal value of sugar content is negative, implying a negative shadow price  $\lambda_q = SMV_q < 0$ . Roughly speaking, we thus assume that from a welfare point of view the SSB itself is a good, whereas its sugar content is a bad. This assumption will be confirmed by our empirical calibration in Section 7.

In order to further characterize the Pareto optimum, we eliminate the shadow prices from the conditions in Column 1 of Table 1. From Rows 1, 3, and 5, we obtain

$$\frac{1}{Z_\ell} + \frac{1}{x} \underbrace{\frac{U_q + xU_hH_z}{U_\ell}}_{-SMV_q} = \frac{X_z}{X_\ell}, \quad (9)$$

while Rows 2, 4, and 5 imply

$$\frac{1}{X_\ell} = \underbrace{-\frac{U_x + qU_hH_z}{U_\ell}}_{SMV_x} + \frac{q}{x} \underbrace{\frac{U_q + xU_hH_z}{U_\ell}}_{-SMV_q}. \quad (10)$$

Equations (9) and (10) represent the efficient allocation rules for sugar and the SSB quantity, respectively. In order to understand the rule for sugar, suppose the social planner keeps constant the SSB quantity  $x$  and increases the sugar quantity  $z$ . Equation (9) then requires that, in the Pareto optimum, the additional labor costs of sugar production ( $1/Z_\ell$ ) plus the loss in consumer utility due to an increase in sugar content  $q = z/x$ , measured by the social marginal value for sugar content per SSB unit in absolute terms ( $-\text{SMV}_q/x$ ), equals the SSB production benefits in terms of saved labor input ( $X_z/X_\ell$ ). For interpreting the rule of the SSB quantity, suppose the social planner keeps constant the amount of sugar  $z$  and increases the SSB quantity  $x$ . Equation (10) then requires that the additional SSB production costs ( $1/X_\ell$ ) equal the increase in consumer utility due to both a rise in the SSB quantity, measured by the social marginal value of the SSB quantity ( $\text{SMV}_x$ ), and the fall in the sugar content  $q = z/x$ , measured by the quality-weighted social marginal value of sugar content per SSB unit in absolute terms ( $-q \text{SMV}_q/x$ ).

#### 4. Indirect market for sugar content

Next we consider markets and investigate their potential to decentralize the efficient allocation by prices. As a benchmark, we consider a full set of perfectly competitive markets. Labor is supplied by the consumer and demanded by the sugar sector and the SSB sector at price  $p_\ell$ . Sugar is sold by the sugar sector to the SSB sector at price  $p_z$ . On the market of the SSB, there is a hedonic price function of the SSB with an implicit price for sugar content. This indirect market approach goes back to Lancaster (1966) and Rosen (1974). In our context, the sugar content is an intrinsic attribute of the SSB and we suppose the SSB producer and the consumer are aware that changes in this attribute have an impact on the SSB price. Formally, imagine a Walrasian auctioneer who announces the SSB price as a function  $p_x = P(q)$  of the sugar content supplied or demanded. In determining their decisions, the SSB producer and the consumer take this function into consideration. Hence, even though there is no explicit price for sugar content, the price system comprises an implicit price represented by the derivative  $P_q(q)$ . A market equilibrium is attained if the price function is such that the market for the SSB is cleared and the sugar content demanded by the consumer equals the sugar content supplied by the SSB producer.

The sugar sector chooses labor input and sugar output in order to maximize its profit subject to the sugar technology. The associated profit maximization problem is

$$\max_{\ell_z^d, z^s} \pi_z = p_z z^s - p_\ell \ell_z^d \quad \text{s.t.} \quad (1), \quad (11)$$

where profit  $\pi_z$  equals revenues from selling sugar less labor costs. The SSB sector sets its inputs and outputs in order to maximize its profit subject to the SSB production technology and the definition of the supplied sugar content. Its maximization problem is

$$\max_{\ell_x^d, z^d, x^s, q^s} \pi_x = P(q^s)x^s - p_\ell \ell_x^d - p_z z^d \text{ s.t. (2) and (3),} \quad (12)$$

with profit  $\pi_x$  equal to revenues from selling the SSB, including an implicit price for the supplied sugar content, less costs for the inputs labor and sugar. Finally, the consumer chooses SSB consumption and labor supply in order to maximize her utility subject to her budget constraint. The maximization problem can be written as

$$\max_{x^d, q^d, \ell^s} (4) \text{ s.t. } p_\ell \ell^s + \pi \geq P(q^d)x^d. \quad (13)$$

The consumer's income consists of labor income and profit income, where  $\pi := \pi_z + \pi_x$  is total profit in the economy. The consumer takes the profit income as given and uses her total income to finance her expenditures for the SSB, including an implicit payment for the demanded sugar content. The market economy is closed by the constraints (5)–(8), which are now interpreted as market clearing conditions.

Prices  $p_\ell, p_z$ , the price function  $p_x = P(\cdot)$ , and the allocation resulting from solving (11)–(13) constitute a competitive equilibrium, if the market clearing conditions (5)–(8) are satisfied as equalities. The Lagrangians and the full set of first-order conditions to (11)–(13) are derived in the Appendix. Eliminating the Lagrange multipliers from the first-order conditions and focusing again on an interior solution  $x^s = x^d =: x$ ,  $q^s = q^d =: q$ ,  $z^s = z^d =: z$ , and  $\ell = \ell_z + \ell_x$ , with  $\ell := \ell^s$ ,  $\ell_z := \ell_z^d$ , and  $\ell_x := \ell_x^d$ , we obtain the equilibrium conditions in Column 2 of Table 1. As the market equilibrium determines only relative prices, we divide all prices by the price of labor. For the ease of notation, we set  $p_\ell = 1$  in the theoretical analysis. Comparing Columns 1 and 2 of Table 1 then immediately implies the following.

**Proposition 1 (Efficiency of indirect market for sugar content).** *Suppose all markets work smoothly. Then, the competitive market economy with market prices  $p_\ell = \lambda_\ell = 1$ ,  $p_z = \lambda_z$ ,  $p_x = P(q) = \lambda_x$ , and  $P_q(q) = \lambda_q/x$  decentralizes the efficient allocation, where the shadow prices  $\lambda_\ell$ ,  $\lambda_z$ ,  $\lambda_x$ , and  $\lambda_q$  as well as the quantity  $x$  and sugar content  $q$  of the SSB are from the social optimum.*

Proposition 1 shows that with a full set of frictionless markets, the competitive equilibrium implements the efficient allocation, if the market prices of labor, sugar, and the SSB, i.e.,  $p_\ell$ ,  $p_z$ , and  $p_x = P(q)$ , equal the respective shadow prices from the Pareto optimum (i.e.,  $\lambda_\ell = 1$ ,  $\lambda_z$ , and  $\lambda_x$ ),

and if the implicit price of sugar content,  $P_q(q)$ , reflects the SSB-weighted shadow price of sugar content from the social optimum (i.e.,  $\lambda_q/x$ ). Such a price system covers the social marginal value of all traded goods, including sugar content as a bad, so producers of sugar and the SSB as well as the consumer receive the right price signals in order to choose the efficient allocation in the competitive market economy.

## 5. Missing market for sugar content

As argued in Section 1, phenomena such as uniform product pricing imply equal prices for an SSB and its zero-sugar or diet variant, and provide evidence that markets for sugar content may be absent in practice. In that case, the SSB producer does not receive price signals for sugar content and ignores the effect of its sugar content choice on the consumer, resulting in a sugar content externality. In our model, the missing market for sugar content formally ensues by assuming that the implicit market price for sugar content is zero (i.e.,  $P_q(q) \equiv 0$ ). The market price of the SSB quantity is then independent of the SSB's sugar content and simply given by  $p_x$ . Even though there are no price signals for sugar content and the SSB producer ignores the effect of sugar content on the SSB price, the SSB producer still implicitly determines the sugar content  $q^s$  by choosing sugar input  $z^d$  and SSB output  $x^s$ . The consumer takes the sugar content determined by the SSB producer as given. Formally, the condition in Column 2, Row 5 of Table 1 then vanishes.

Setting  $P_q(q) \equiv 0$  in Column 2 of Table 1 and comparing the resulting conditions with the efficiency conditions in Column 1 of Table 1 immediately yields the following.

**Proposition 2 (Inefficiency of missing market for sugar content).** *Suppose there is no market for sugar content (i.e.,  $P_q(q) \equiv 0$ ). Then, the competitive market economy does not decentralize the efficient allocation.*

In order to attain efficiency, the price that the SSB producer receives for the sugar content in the market economy should reflect the social marginal value of sugar content  $SMV_q$  represented by the corresponding shadow price  $\lambda_q$  from the social optimum. But if the market for sugar content is missing, the market price of sugar content is zero and the producer does not receive the right price signal when setting the sugar content in her production. This also distorts the input and output decisions of the sugar and SSB production sectors as well as the decisions of the consumer, and implies that the competitive market economy is not capable of decentralizing the efficient allocation.

We can further elaborate on the market failure identified in Proposition 2 by deriving allocation rules for sugar and the SSB quantity in the market equilibrium, comparable to the allocation rules (9) and (10) characterizing the

Pareto optimum. For this purpose, set the implicit market price for the SSB's sugar content  $P_q(q) \equiv 0$  in Column 2 of Table 1. Inserting Row 1 into Row 3 and Row 4 into Row 2, it is straightforward to show that

$$\frac{1}{Z_\ell} = \frac{X_z}{X_\ell}, \quad (14)$$

$$\frac{1}{X_\ell} = -\frac{U_x + qU_h H_z}{U_\ell}. \quad (15)$$

Comparing these rules with the allocation rules (9) and (10) of the efficient allocation, it becomes visible that – due to the missing price signal for sugar content – the rules in the competitive market economy do not reflect the social marginal value of the sugar content; that is, the expression  $SMV_q = -(U_q + xU_h H_z)/U_\ell$  is missing in the allocation rules (14) and (15). As consequence, if this social marginal value of sugar content is negative, we expect an inefficiently low SSB price  $p_x$  and an inefficiently high sugar content  $q$  in the competitive market economy without a market for sugar content.

In order to prove this assertion and to investigate the inefficiency properties of the other variables in the unregulated market economy, tractability requires that we introduce some mild simplifications regarding the production technologies  $Z$  and  $X$ . The Appendix proves the following.

**Proposition 3 (Allocation in economy with missing market for sugar content).** *Suppose there is no market for sugar content (i.e.,  $P_q(q) \equiv 0$ ). Assume technologies  $Z$  and  $X$  in (1) and (2) are linear homogeneous. Then, in the competitive market equilibrium*

- (i) *the SSB sugar content  $q$  is inefficiently high, the SSB price  $p_x$  is inefficiently low, and the sugar prize  $p_z$  is efficient;*
- (ii) *the SSB quantity  $x$  and the sugar quantity  $z$  may be inefficiently low or high.*

Part (i) of Proposition 3 confirms our intuition that in the market economy the SSB price  $p_x$  is inefficiently low, while the sugar content  $q$  is inefficiently high. The reason for this is that the sugar content reduces the consumer's utility, indeed, but this negative effect is not reflected by the price system. The sugar price  $p_z$  is solely technology-driven and thereby efficient, as Proposition 3 proceeds on the assumption of linear homogeneous production technologies. While the efficiency of the sugar prize  $p_z$  will certainly change if we deviate from the assumption of linear homogeneous technologies, intuitively the results of an inefficiently low SSB price  $p_x$  and an inefficiently

high sugar content  $q$  are expected to hold also under more general assumptions regarding production technologies.

At first glance, the inefficiency of the sugar content  $q = z/x$  might suggest that the sugar quantity  $z$  is inefficiently high and the SSB quantity  $x$  is inefficiently low. However, part (ii) shows that this is not true in general. This is because, due to the general equilibrium nature of our model, the efficiency properties of the sugar quantity  $z$  and the SSB quantity  $x$  largely depend on the consumer's consumption and labor supply decision. To see this, remember first that – according to part (i) of Proposition 3 – the transition from the efficient allocation to the market allocation is accompanied by a drop in the SSB price  $p_x$  and an increase in the sugar content  $q$ . The fall in the SSB price  $p_x$  triggers a substitution effect as well as an income effect (real income goes up). The increase in the sugar content  $q$  causes a further substitution effect on the consumer's decision. The interaction of these substitution and income effects is complicated and renders the efficiency properties of sugar and the SSB quantity in the market economy ambiguous.

In order to understand the interplay of these effects, in the proof of Proposition 3 contained in the Appendix, we run numerical simulations with a CES production function in the SSB sector and a CES utility function, where  $1/(1 + \rho)$  with  $\rho \geq -1$  is the substitution elasticity between the arguments of the utility function. We start with an example where all arguments in the utility function are complements ( $\rho = 1$ ) and show that the SSB quantity  $x$  is inefficiently high. In this case, all three effects – the substitution and income effects of the fall in  $p_x$  as well as the substitution effect of the increase in  $q$  – increase SSB demand  $x$  directly, and this increase dominates the fall in the SSB demand  $x$  caused indirectly by an increase in health  $h$ . The inefficiently high value of  $x$  also translates into an inefficiently high sugar quantity  $z$  in this case. If we turn to substitutes by lowering  $\rho$ , the substitution and income effects of the fall in  $p_x$  still exert an upward pressure on the SSB demand  $x$ , but the substitution effect via the increase in  $q$  now lowers  $x$  (instead of raising  $x$  as in the case of complements). If this latter effect is strong enough, then SSB demand  $x$  becomes inefficiently low in the competitive equilibrium. The change in  $x$  may leave the sugar quantity  $z$  still inefficiently high – if we lower the substitution parameter only moderately to, say,  $\rho \approx 0$  – or may render also sugar quantity  $z$  inefficiently low – if we reduce the substitution parameter substantially to, for example,  $\rho = -0.7$ .

## 6. Regulated markets

Having shown that the laissez-faire economy without markets for sugar content does not provide the right price signals for implementing the efficient allocation, we now turn to the question of how the government may regulate

the market participants in order to correct the market failure. We focus on tax instruments levied on sugar demand and supply, the SSB demand and supply, the supplied sugar content as well as the supplied sugar content per unit of the SSB, and investigate which combinations of these taxes restore efficiency. In contrast to Proposition 3, we return to general technologies and preferences.

Denoting the tax rate levied on each unit of sugar supply by  $\tau_z^s$ , the profit maximization problem of the sugar sector changes to

$$\max_{\ell_z^d, z^s} \pi_z = (p_z - \tau_z^s)z^s - p_\ell \ell_z^d \quad \text{s.t.} \quad (1). \quad (16)$$

In the absence of a market price for sugar content, the profit maximization problem of the SSB sector can now be rewritten as

$$\begin{aligned} \max_{\ell_x^d, z^d, x^s, q^s} \pi_x &= (p_x - \tau_x^s)x^s - \tau_q q^s - p_\ell \ell_x^d - (p_z + \tau_z^d)z^d - \tau_{xq}x^s q^s \\ &\text{s.t. (2) and (3).} \end{aligned} \quad (17)$$

The SSB producer has to pay an SSB tax at rate  $\tau_x^s$ ,<sup>8</sup> a sugar content tax at rate  $\tau_q$ , a sugar input tax at rate  $\tau_z^d$ , and a sugar content tax per unit of the SSB at rate  $\tau_{xq}$ . Turning to the household sector, the consumer's utility maximization problem becomes

$$\max_{x^d, q^d, \ell^s} (4) \quad \text{s.t.} \quad p_\ell \ell^s + \pi + \psi \geq (p_x + \tau_x^d)x^d. \quad (18)$$

The consumer's expenditures now comprise the SSB tax payments  $\tau_x^d x^d$ . Her income additionally contains the total tax revenues  $\psi = \tau_z^s z^s + \tau_z^d z^d + \tau_x^s x^s + \tau_x^d x^d + \tau_q q^s + \tau_{xq} x^s q^s$ , which are transferred lump-sum and taken as given by the consumer. In the competitive equilibrium, the market clearing conditions (5)–(8) are satisfied with equality.

The full set of first-order conditions to the maximization problems (16)–(18) are given in the Appendix. In the regulated market equilibrium, we again obtain  $x^s = x^d =: x$ ,  $q^s = q^d =: q$ ,  $z^s = z^d =: z$ , and  $\ell = \ell_z + \ell_x$ , with  $\ell := \ell^s$ ,  $\ell_z := \ell_z^d$ , and  $\ell_x := \ell_x^d$ . Eliminating the Lagrange multipliers from the first-order conditions, the Appendix derives the conditions listed in Column 3 of Table 1. Notice that the regulated market does not encompass a condition comparable to the condition in Column 2, Row 5 of Table 1, as the consumer takes as given the sugar content. By comparing Column 3 with the efficient

<sup>8</sup>This is a unit tax on the SSB quantity. If the SSB quantity is taxed by an ad valorem tax, all our subsequent results remain unchanged, except for dividing the optimal tax rate by the SSB price  $p_x$ .

allocation in Column 1 of Table 1, it is straightforward to prove the following result.

**Proposition 4 (Optimal regulation).** *Suppose there is no market for sugar content (i.e.,  $P_q(q) \equiv 0$ ). Then, the regulated market economy with prices and tax rates satisfying  $p_\ell = \lambda_\ell = 1$ ,  $p_x = \lambda_x - \tau_x^d$ ,  $p_z = \lambda_z + \tau_z^s$ , and*

$$\tau_z^s + \tau_z^d + \frac{1}{x}\tau_q + \tau_{xq} = -\frac{1}{x}\lambda_q, \quad -\tau_x^s - \tau_x^d + \frac{q}{x}\tau_q = -\frac{q}{x}\lambda_q, \quad (19)$$

*decentralizes the efficient allocation, where the shadow prices  $\lambda_\ell$ ,  $\lambda_z$ ,  $\lambda_x$ , and  $\lambda_q$  as well as the quantity  $x$  and sugar content  $q$  of the SSB are from the social optimum.*

The policy identified in Proposition 4 can equivalently be obtained if we derive the allocation rules for sugar and the SSB quantity in the regulated market economy. Using  $p_\ell = 1$  in the conditions listed in Column 3 of Table 1, it is straightforward to show that

$$\frac{1}{Z_\ell} + \tau_z^s + \tau_z^d + \frac{1}{x}\tau_q + \tau_{xq} = \frac{X_z}{X_\ell}, \quad (20)$$

$$\frac{1}{X_\ell} = -\frac{U_x + qU_hH_z}{U_\ell} - \tau_x^s - \tau_x^d + \frac{q}{x}\tau_q. \quad (21)$$

Comparing these equations with the allocation rules (9) and (10) of the Pareto optimum reveals that the market equilibrium is efficient if

$$\begin{aligned} \tau_z^s + \tau_z^d + \frac{1}{x}\tau_q + \tau_{xq} &= \frac{1}{x} \frac{U_q + xU_hH_z}{U_\ell}, \\ -\tau_x^s - \tau_x^d + \frac{q}{x}\tau_q &= \frac{q}{x} \frac{U_q + xU_hH_z}{U_\ell}, \end{aligned} \quad (22)$$

where all functions and variables are evaluated at the Pareto-efficient allocation. Recalling from Column 1, Row 5 of Table 1 that  $\lambda_q = -(U_q + xU_hH_z)/U_\ell$ , we infer that the tax policies given in equations (19) and (22) are perfectly equivalent.

Proposition 4 offers ample opportunities for correcting the market failure caused by the missing market for sugar content. The most obvious policy would be a direct tax on the sugar content chosen by the SSB producer. To see this, set all taxes but  $\tau_q$  equal to zero. The conditions (19) or, equivalently, (22) then simplify to

$$\tau_q = \frac{U_q + xU_hH_z}{U_\ell} > 0. \quad (23)$$

Hence, we can correct the market failure by directly taxing the SSB producer's choice of the sugar content, where the tax rate in equation (23) reflects the



social marginal value or, equivalently, the shadow price of sugar content from the social optimum in absolute terms, that is,  $-\lambda_q = -\text{SMV}_q = (U_q + xU_h H_z)/U_\ell > 0$ , which is not reflected by the price system in the absence of taxation. The sugar content tax in equation (23) thus simply replaces the missing market price of the sugar content by a regulatory instrument.

The policy in equation (23) is a tax on the SSB producer's product design. It can be implemented, for instance, as a yearly or even one-time charge (license) that depends on sugar content, but such a policy seems to be uncommon in practice. An alternative would be to tax the sugar content per unit of the SSB at rate  $\tau_{xq}$ , as implemented in the UK, for example. But according to our analysis, this tax alone is not sufficient to restore efficiency, as the second condition in (19) and (22) is violated, when setting all other tax rates to zero. Instead, we have to regulate also the SSB quantity, either on the demand or the supply side. Formally, equations (19) and (22) are satisfied if  $\tau_z^s = \tau_z^d = \tau_q = 0$  and

$$\tau_{xq} = \frac{1}{x} \frac{U_q + xU_h H_z}{U_\ell} > 0, \quad \tau_x^s + \tau_x^d = -\frac{q}{x} \frac{U_q + xU_h H_z}{U_\ell} < 0. \quad (24)$$

The government has to supplement the tax on the sugar content per unit of SSB by a subsidy on each unit of the SSB, where the tax and subsidy rates again reflect the social marginal value of sugar content from the social optimum in absolute terms, that is,  $-\lambda_q = -\text{SMV}_q = (U_q + xU_h H_z)/U_\ell > 0$ . The intuition is that the tax base of the tax  $\tau_{xq}$  equals  $xq$ , so  $\tau_{xq}$  is not solely targeted at the sugar content  $q$ , but also at the SSB quantity  $x$ . The SSB quantity is thus distorted and has to be corrected by an additional subsidy, at either the supplied or demanded SSB quantity.

A very similar policy option is obtained if we combine the subsidy on the SSB quantity by a tax on the quantity of sugar. Formally, equations (19) and (22) are also satisfied if the government sets the tax rates  $\tau_q = \tau_{xq} = 0$  and

$$\tau_z^s + \tau_z^d = \frac{1}{x} \frac{U_q + xU_h H_z}{U_\ell} > 0, \quad \tau_x^s + \tau_x^d = -\frac{q}{x} \frac{U_q + xU_h H_z}{U_\ell} < 0. \quad (25)$$

Hence, the government may restore efficiency of the market equilibrium by taxing the quantity of sugar and subsidizing the quantity of the SSB, on either the supply or demand side. The intuition is similar to the intuition of the policy identified in equations (24). The tax on sugar  $z$  is not solely targeted at the sugar content  $q$ , but implicitly also taxes the SSB quantity  $x$ , as overall we have  $z = xq$  units of sugar used in the economy. This unintended distortion has to be corrected by a subsidy on the SSB quantity  $x$ .

Both policy options, equations (24) as well as (25), have an interesting revenue-neutrality property. If only the SSB producer is regulated – that is,  $\tau_x^d = 0$  in equations (24) and  $\tau_z^s = \tau_x^d = 0$  in equations (25) – then the

SSB producer's net tax payments are zero; that is,  $(\tau_x^s + q\tau_{xq})x = 0$  in equations (24) and  $\tau_x^s x + \tau_z^d z = 0$  in equations (25). With taxation solely targeted at the SSB producer, revenue neutrality therefore has the advantage that it may reduce the political resistance of SSB producers against SSB taxation. Alternatively, the tax–subsidy instruments may be spread over two market participants. Under policy (25), the government may tax the sugar industry by  $\tau_z^s > 0$  and subsidize the SSB producer by  $\tau_x^s < 0$  or the consumer by  $\tau_x^d < 0$ . If the government favors the option (24), then it may tax the sugar content per unit of the SSB at rate  $\tau_{xq} > 0$ , to be paid by the SSB producer, and subsidize SSB consumption of the consumer by  $\tau_x^d < 0$ . This latter tax–subsidy combination has the nice property that, particularly for SSBs, it can be interpreted as a deposit–refund system.<sup>9</sup> If the consumer buys a unit of the SSB, the price that the producer charges includes the deposit  $\tau_{xq}q > 0$ , and if the consumer brings back the empty beverage container she gets the refund  $\tau_x^d = -\tau_{xq}q < 0$ . As in practice there are already many deposit–refund systems for beverage containers to which the deposit–refund combination  $(\tau_{xq}q, \tau_x^d)$  can simply be added, we think that this tax–subsidy combination is the most promising policy option in order to correct the market failure, if markets for sugar content of SSBs are missing.

## 7. Empirical calibration

In this section, we empirically calibrate our general equilibrium model in order to compare the results with the existing soft drink levy implemented 2018 in the UK.

### 7.1. General remarks

We choose a simple specification of the model. The sugar production function is assumed to be linear, that is,  $Z(\ell_z) = \ell_z/c_z$  with  $c_z > 0$ , while production in the SSB sector follows the Cobb–Douglas function  $X(\ell_x, z) = \delta \ell_x^\gamma z^{1-\gamma}$  with  $\delta > 0$  and  $\gamma \in ]0, 1[$ . The utility function of the consumer is  $U(x, q, \ell, h) = \{[x(1+q)]^\alpha - 1\}/\alpha + h + \bar{\ell} - \ell$ , where  $1 - \alpha > 0$  is the Arrow–Pratt index of relative risk aversion and  $\bar{\ell}$  is total time endowment. Analogously to the sin taxation literature referred to in Section 1, we consider a quadratic health function  $H(z) = \bar{h} - \beta(c_h/2)z^2$  with  $\bar{h} > 0$ ,  $\beta \in ]0, 1]$ , and  $c_h > 0$ .

<sup>9</sup>Deposit–refund systems have frequently been proposed in efficient waste management; see, for instance, Palmer and Walls (1997), Fullerton and Wolverton (2000), and Eichner and Pethig (2001).

**Table 2.** Conditions for Pareto efficiency and laissez-faire under model specification

		Pareto efficiency	Laissez faire
		1	2
Sugar	1	$c_z = \frac{\lambda_z}{\lambda_\ell}$	$c_z = \frac{p_z}{p_\ell}$
Producer	2	$\frac{1}{\delta\gamma} \left( \frac{\ell_x}{z} \right)^{1-\gamma} = \frac{\lambda_x}{\lambda_\ell} - \frac{q}{x} \frac{\lambda_q}{\lambda_\ell}$	$\frac{1}{\delta\gamma} \left( \frac{\ell_x}{z} \right)^{1-\gamma} = \frac{p_x}{p_\ell}$
	3	$\frac{1-\gamma}{\gamma} \frac{\ell_x}{z} = \frac{\lambda_z}{\lambda_\ell} - \frac{1}{x} \frac{\lambda_q}{\lambda_\ell}$	$\frac{1-\gamma}{\gamma} \frac{\ell_x}{z} = \frac{p_z}{p_\ell}$
Consumer	4	$x^{\alpha-1} (1+q)^\alpha - c_h x q^2 = \frac{\lambda_x}{\lambda_\ell}$	$x^{\alpha-1} (1+q)^\alpha - \beta c_h x q^2 = \frac{p_x}{p_\ell}$
	5	$x^\alpha (1+q)^{\alpha-1} - c_h x^2 q = \frac{\lambda_q}{\lambda_\ell}$	–

We focus on determining the most promising policy option identified in the previous section, that is the policy in equations (24) with  $\tau_x^s = 0$ . The idea of the empirical analysis is to calibrate the laissez-faire solution of our theoretical model to UK data from the year 2015, when the soft drink levy was neither introduced nor announced. We then use the calibrated model parameters for calculating the efficient allocation and, in turn, employ the efficient solution in order to compute the optimal tax rates. Even though we ignore self-control problems in the theoretical analysis, the real-world behavior of SSB consumers is distorted by such problems. Hence, we take  $\beta < 1$  when calibrating the model to the laissez-faire solution, while the efficient solution as well as the optimal tax rates are determined under the assumption  $\beta = 1$ . In this way, we are able to separate the effects of missing markets and self-control problems, and the optimal tax rates still correct solely the missing market for sugar content, as in the theoretical model.

Using the above model specification in Table 1, the first-order conditions for the efficient allocation and the laissez-faire allocation turn into the conditions listed in Table 2.

Adding the technologies  $z = \ell_z / c_z$ ,  $x = \delta \ell_x^\gamma z^{1-\gamma}$ , and  $q = z/x$  as well as the labor resource constraints  $\ell = \ell_z + \ell_x$  to Column 1, we obtain nine equations determining the efficient allocation consisting of the nine unknowns  $\{\ell, \ell_z, \ell_x, z, x, q, (\lambda_z/\lambda_\ell), (\lambda_x/\lambda_\ell), (\lambda_q/\lambda_\ell)\}$ . Similarly, adding the technologies as well as the consumer's budget constraint  $p_x x = p_\ell \ell$  to Column 2, gives a system of eight equations in the eight laissez-faire variables  $\{\ell, \ell_z, \ell_x, z, x, q, (p_z/p_\ell), (p_x/p_\ell)\}$ . We ignore the labor market clearing condition under laissez-faire due to the Walras law.

## 7.2. Calibration of parameters

We start by calibrating the laissez-faire solution in Column 2 of Table 3 to UK data from 2015. The data used and generated by the calibration are summarized in Table 3.

**Table 3.** Empirical calibration of the laissez-faire allocation

	Value	Units
<b>Calibration input</b>		
$z$	12.20	gram
$x$	330.72	gram
$q$	0.03688921	—
$p_\ell$	13.50	£ per hour
$p_z$	0.00013228	£ per gram
$p_x$	0.00158654	£ per gram
$\beta$	0.50	—
$c_h$	0.00171861	hours per gram <sup>2</sup>
<b>Calibration output</b>		
$\ell$	0.03886664	hours
$\ell_z$	0.00011954	hours
$\ell_x$	0.03874710	hours
$c_z$	0.00000980	hours per gram
$\delta$	8385.67	(gram per hour) <sup>γ</sup>
$\gamma$	0.996924	—
$\alpha$	-0.306838	—

In our benchmark simulation, we pursue a conservative strategy and choose all variables and parameters such that our main insight from the calibration is the least likely given the range of data available. In the sensitivity analysis, we show that our conclusion is strengthened if we choose a less conservative strategy.

From Bandy et al. (2020, table 3), in 2015, sugar intake from SSB consumption per capita and day was  $z = 12.20$  gram, where we have excluded the sugar intake from exempt drinks such as fruit juices or milk drinks that are not subject to the UK's soft drink levy. Moreover, Bandy et al. (2020, figure 1) found an SSB consumption per capita and day of 0.318 liter, again corrected for exempt soft drinks. Taking cola as a reference point, 1 liter SSB equals 1,040 gram SSB.<sup>10</sup> Hence, as SSB consumption we obtain  $x = 330.72$  gram per capita and day. From  $q = z/x$ , it then follows that  $q = 0.03688921$ .

Next, we estimate the market prices in our model. In contrast to the theoretical analysis, for the calibration it is not suitable to normalize the price of labor to one. Instead, we use the data from National Statistics (2015). They found that in 2015 the per-capita weekly earning in the UK was £528 and the average weekly working hour amounted to 39.1 hours, implying a wage rate

<sup>10</sup>See, for example, <https://studenten365.com/library/lecture/read/102350-wie-schwer-ist-ein-liter-cola#0>.

of  $p_\ell = £13.50$  per hour. On the webpage [macrotrends.net](https://www.macrotrends.net), we found a range for the sugar price of \$0.10–0.15 per £ in 2015,<sup>11</sup> from which we choose the lower bound. Taking into account that £1 equals 453.6 gram, and that the exchange rate in 2015 was around £0.6 per \$, we obtain  $p_z = £0.00013228$  per gram. Scarborough et al. (2020, table 1) show that, on average, an SSB treated by the UK's soft drink levy costs £1.73 per liter in February 2019 prices. They use an inflation rate of 1.7 percent, yielding an SSB price of £1.65 per liter in end of 2015 prices. Again, taking into account that 1 liter SSB equals 1,040 gram SSB, we obtain an SSB price of  $p_x = £0.00158654$  per gram.

It remains to specify  $\beta$  and  $c_h$ . Based on the estimates of Allcott et al. (2019b), Kalamov and Runkel (2022) show that the self-control parameter  $\beta$  lies between 50 and 70 percent. We choose the lower bound  $\beta = 0.50$  and show in the sensitivity analysis that higher values strengthen our results. For specifying  $c_h$ , we use the marginal internality  $m$ , which reflects the part of the marginal health costs  $c_h(xq)^2/2$  that consumers do not take into account when choosing SSB consumption  $x$ . Formally, the marginal internality is

$$m = (1 - \beta)c_h x q^2. \quad (26)$$

Allcott et al. (2019b) estimate the marginal internality to be equal to 0.93 cents per ounce of the SSB, with a range of 0.91–2.14 cents per ounce. We choose the lower bound of 0.91 cents per ounce, and show in our sensitivity analysis that higher values strengthen our main conclusion. Taking into account the exchange rate of £0.6 per \$, the relation 28.35 gram per ounce and the SSB sugar content  $q = 0.03688921$  gram sugar per gram SSB, we obtain a marginal internality of £0.00522084 per gram. As utility is measured in terms of the numéraire, we divide this measure of the marginal internality by the wage rate  $p_\ell = £13.5$  per hour and obtain  $m = 0.00038673$  hours per gram. Inserting the values for  $m$  and  $\beta$  together with the values for  $x$  and  $q$  in equation (26) implies  $c_h = 0.00171861$  hours per gram<sup>2</sup>.

We insert the calibration input from Table 3 into the laissez-faire conditions in Column 2 of Table 2 and the technologies  $z = \ell_z/c_z$ ,  $x = \delta \ell_x^\gamma z^{1-\gamma}$  as well as the budget constraint  $p_x x = p_\ell \ell$ . Solving this set of equations gives the calibration output in Table 3.

### 7.3. Baseline simulation

With the calibrated model parameters, we simulate the efficient allocation determined by the conditions in Column 1 of Table 2. The results are given in the first panel of Table 4.

<sup>11</sup> See, for example, <https://www.macrotrends.net/2537/sugar-prices-historical-chart-data>.

**Table 4.** Simulation of the efficient allocation and the optimal tax rates

	Value	Units
<b>Efficient allocation</b>		
$\ell$	0.11942886	hours
$\ell_z$	0.00000486	hours
$\ell_x$	0.11942400	hours
$z$	0.50	gram
$x$	1005.85	gram
$q$	0.00049302	–
$\lambda_z/\lambda_\ell$	0.00000980	hours per gram
$\lambda_x/\lambda_\ell$	0.00011874	hours per gram
$\lambda_q/\lambda_\ell$	–0.73744500	hours
<b>Optimal tax rates</b>		
$\tau_{xq}/p_\ell$	0.00073316	hours per gram
$\tau_x^d/p_\ell$	–0.00000036	hours per gram

The efficient sugar consumption  $z$  is half a gram per capita and day, whereas efficient SSB consumption  $x$  is almost 1 liter per capita and day, implying a low efficient sugar content  $q$  that lies substantially below 1 percent. Notice that the sugar and SSB shadow prices  $\lambda_z/\lambda_\ell$  and  $\lambda_x/\lambda_\ell$  are positive, whereas the sugar content shadow price  $\lambda_q/\lambda_\ell$  is negative, as presupposed in our theoretical model.

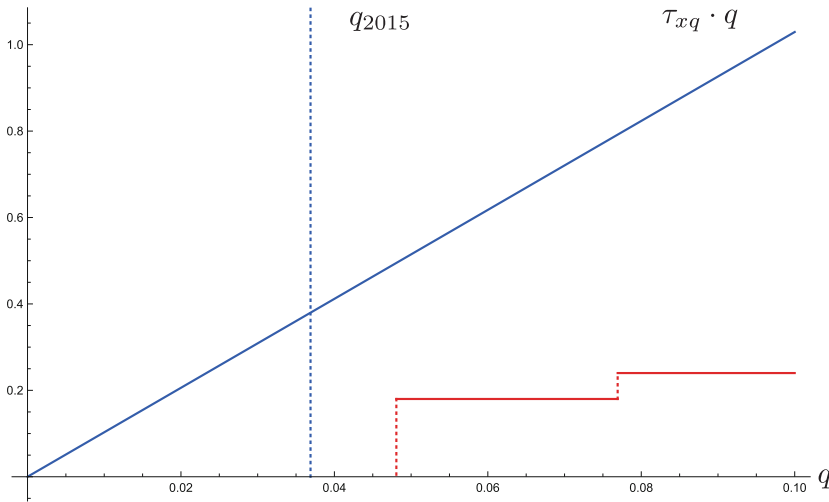
In the final step, we use the efficient allocation in order to calculate the optimal tax rates from equations (24). The results are given in the second panel of Table 4. Remember that in the empirical analysis the wage rate is not normalized to one, so all tax rates in equations (24) have to be divided by  $p_\ell$  and are expressed in units of the numéraire good, labor per gram of the SSB. To make them comparable to the tax rates implemented in the UK, which are expressed in £ per liter of the SSB, we multiply the tax rates from Table 4 by the wage rate  $p_\ell = £13.5$  per hour and the factor 1,040 gram SSB per liter SSB. We then obtain

$$\tau_{xq} = 10.29360 \text{ £ per liter}, \quad \tau_x^d = -0.00508 \text{ £ per liter}. \quad (27)$$

While the UK's soft drink levy has a stepwise tax schedule, we suppose a linear tax schedule. Both tax schedules are displayed in Figure 1.

The solid line is the optimal linear tax schedule  $\tau_{xq} \cdot q$  calculated with the optimal tax rate from equation (27), while the stepped line represents the UK's stepwise tax schedule. The optimal tax rates are considerably larger than the tax rates implemented in the UK. To be more specific, the optimal tax at the average sugar content in 2015,  $q_{2015} = 0.03688921$  represented by the dotted line, is

$$\tau_{xq} \cdot q_{2015} = 0.37972 \text{ £ per liter}, \quad (28)$$

**Figure 1.** Optimal versus UK tax schedule

which is more than twice as large as the UK's tax rate of £0.18 per liter for low-sugar drinks and more than one and a half times as large as the UK tax rate of £0.24 per liter for high-sugar drinks. This relation remains largely unchanged if we subtract the optimal subsidy rate  $\tau_x^d$  from equation (27), as this subsidy amounts only to roughly half a pence per liter SSB.

Next, we compute the welfare gain associated with the optimal tax–subsidy policy, as measured by the equivalent variation (EV). Because the policy corrects only the missing market for sugar content and not the present bias  $\beta < 1$ , we cannot use the calibrated laissez-faire equilibrium contained in Table 3, but instead have to recalculate this equilibrium from the conditions in Column 2 of Table 2 with  $\beta = 1$ . Using the calibrated parameters from Table 3 and denoting the laissez-faire by a tilde, it follows that  $\tilde{\ell} = 0.02985800$  hours,  $\tilde{\ell}_z = 0.00009183$  hours,  $\tilde{\ell}_x = 0.02976620$  hours,  $\tilde{z} = 9.37$  gram,  $\tilde{x} = 254.07$  gram,  $\tilde{q} = 0.0368892$ ,  $\tilde{p}_\ell = £13.50$  per hour,  $\tilde{p}_x = £0.00158654$  per gram, and  $\tilde{p}_z = £0.00013228$  per gram. Let a star indicate the efficient allocation given in Table 4. The EV is the amount of money that the consumer has to be given in the laissez-faire economy such that she is just indifferent to the efficient allocation. Using the consumer's budget constraint in order to replace labor supply, the EV is implicitly determined by

$$U \left[ \tilde{x}, \tilde{q}, \frac{\tilde{p}_x}{\tilde{p}_\ell} \tilde{x} - \frac{\text{EV}}{\tilde{p}_\ell}, H(\tilde{x}\tilde{q}) \right] = U [x^*, q^*, \ell^*, H(x^*q^*)]. \quad (29)$$

Because, in the empirical analysis, the utility function is quasi-linear in labor, equation (29) can be solved for the closed-form solution<sup>12</sup>

$$\frac{EV}{\tilde{p}_\ell} = U[x^*, q^*, \ell^*, H(x^* q^*)] - U\left[\tilde{x}, \tilde{q}, \frac{\tilde{p}_x}{\tilde{p}_\ell} \tilde{x}, H(\tilde{x} \tilde{q})\right]. \quad (30)$$

Inserting the efficient allocation from Table 4 and the above-mentioned laissez-faire allocation into equation (30), we obtain  $EV/\tilde{p}_\ell = 0.18440$  hours. Hence, on average, each UK inhabitant would accept around 11 additional minutes per day in order to be indifferent between laissez-faire and the efficient allocation implemented by the optimal tax–subsidy policy.

One interpretation of this result is that the average consumer would be indifferent between laissez-faire and efficiency, if in the former she obtains an additional 1.25 hours per week in order to compensate the negative health effects of her SSB consumption, for example, by engaging more in physical exercise. Another interpretation is obtained if we express the EV in monetary terms. Multiplying  $EV/\tilde{p}_\ell$  by the wage rate  $\tilde{p}_\ell = £13.50$  per hour gives  $EV = £2.48933$  per capita and day. Scaling this to a yearly and nationwide level with around 68 million UK inhabitants in 2023,<sup>13</sup> the welfare increase caused by the optimal tax–subsidy policy amounts to around £62 billion in total. At first glance, this number seems high and may perhaps overestimate the true welfare increase. However, from Bradshaw and Dace (2023), total welfare costs per year caused by obesity and overweight in the UK equal £98 billion in 2023, from which £63 billion are individual costs reflecting, to the largest part, the value of lost quality-adjusted life years. Also, a substantial part of the gap to the total costs of £98 billion may be associated with individual costs. For instance, the loss in worker productivity, estimated as £15 billion, may imply a lower wage income of obese or overweight people. Moreover, the estimated costs of £19 billion for the National Health Service is financed by governmental revenues that partially also come from obese and overweight contributors. These data show that our estimated welfare increase of £62 billion is not that unrealistic.

#### 7.4. Sensitivity analysis

In this subsection, we vary some key model parameters and investigate how the optimal tax rates in equations (27) and (28) change. The results are summarized in Table 5, together with the optimal tax rates from the benchmark

<sup>12</sup> Alternatively, we can calculate the EV with the help of the consumer's expenditure function. Due to quasi-linearity, however, using the utility function yields exactly the same result and is much easier.

<sup>13</sup> See, for example, [https://en.wikipedia.org/wiki/United\\_Kingdom](https://en.wikipedia.org/wiki/United_Kingdom).



**Table 5.** Sensitivity analysis (units as before)

	Parameter varied		Optimal tax rates	
	Parameter	Value	$\tau_{xq} \cdot q_{2015}$	$\tau_x^d$
1	Benchmark simulation		0.37972	-0.00508
2	$p_z$	0.00016534	0.42765	-0.00635
3		0.00019841	0.47098	-0.00764
4	$c_h$	0.00175638	0.38739	-0.00508
5		0.00343722	0.73753	-0.00512
6	$\beta$	0.6	0.50471	-0.00510
7		0.7	0.72358	-0.00512
8	$p_x$	0.00081731	0.48397	-0.00516
9		0.00235577	0.32551	-0.00504

simulation (Row 1). Consistently with the available range of \$0.10–0.15 per pound, we increase the sugar price from \$0.10 per pound to \$0.125 and \$0.15 per pound, leading to the values of  $p_z$  in Rows 2 and 3 of Table 5. From the range of marginal internality estimates 0.91–2.14 cents per ounce identified by Allcott et al. (2019a), we take the most likely value of 0.93 cents per ounce and the doubled value of 1.82 cents per ounce, instead of 0.91 cents per ounce used in our benchmark simulation. This leads to the values of  $c_h$  given in Rows 4 and 5 of Table 5. From Kalamov and Runkel (2022), we use the middle and upper bounds of the self-control parameter  $\beta$  (i.e.,  $\beta = 0.6$  and  $\beta = 0.7$ ) instead of  $\beta = 0.5$ , as shown in Rows 6 and 7 of Table 5. For the SSB price, we only have the point estimate £1.65 per liter derived by Scarborough et al. (2020). In order to investigate the impact of the SSB price, we therefore considerably reduce and increase this price by almost 50 percent to £0.85 and £2.45 per liter, implying the values of  $p_x$  in Rows 8 and 9 of Table 5, respectively.

Compared with the results of our benchmark simulation, the sensitivity analysis in Table 5 shows that variations in the model parameters leave the optimal subsidy rate  $\tau_x^d$  almost unchanged and increase the optimal tax rate  $\tau_{xq} \cdot q_{2015}$  on sugar content.<sup>14</sup> This insight strengthens the conclusion from the benchmark simulation that the UK's soft drink levy is too low compared

<sup>14</sup>Regarding the variation in  $\beta$ , it is clear from our calibration of the health cost parameter  $c_h$  with the help of equation (26) that an increase in  $\beta$  goes along with an increase in  $c_h$ , as we keep constant the marginal internality  $m$ . This is the reason why an increase in  $\beta$  raises the optimal sugar content tax  $\tau_{xq}$ , even though the present bias is mitigated. Remember that  $\beta < 1$  is only used for calibrating the model and that the estimated tax rates correct only for the missing market of sugar content, but not for the internality caused by  $\beta < 1$ . Internality-correcting taxes are considered in the extension in Section 8.

with its socially optimal level. The only exception is an increase in the SSB price, as shown in the last row of Table 5. But even if we considerably increase the SSB price (by almost 50 percent), the optimal subsidy rate is largely unchanged and the optimal tax on sugar content falls only slightly to  $\tau_{xq} \cdot q_{2015} = \text{£}0.32551$  per liter and, thus, still substantially exceeds the UK tax rates of  $\text{£}0.18$  and  $\text{£}0.24$  per liter.

## 8. Extensions

### 8.1. Second-best sugar content taxation

The SSB subsidy  $\tau_x^d$  included in our favorite policy may hardly be implementable in practical policy. In this subsection, we thus assume that the social planner can only levy the sugar content tax per unit of the SSB and characterize the second-best tax rate  $\tau_{xq}$ . Conceptually, we have to set all tax rates except for  $\tau_{xq}$  in the conditions in Column 3 of Table 1 equal to zero, run a comparative static analysis of these conditions in order to determine the effects of  $\tau_{xq}$  on the market outcome, and finally maximize utility (4) with respect to  $\tau_{xq}$ , taking into account the impact of  $\tau_{xq}$  on the market solution. The result of this procedure is a first-order condition that can be solved with respect to the second-best sugar content tax rate  $\tau_{xq}$ .

Unfortunately, the complexity of our general equilibrium model prevents us from deriving clear-cut analytical results. However, in an Online Appendix we compute the second-best tax rate  $\tau_{xq}$  with the help of the empirical calibration from the previous section. The result is  $\tau_{xq}/p_\ell = 0.00073320$  hours per gram or  $\tau_{xq} \cdot q_{2015} = \text{£}0.37973$  per liter. Compared to the first-best sugar content tax rate  $\tau_{xq}/p_\ell = 0.00073316$  hours per gram or  $\tau_{xq} \cdot q_{2015} = \text{£}0.37972$  per liter from Table 4 and equation (28), the second-best tax rate on sugar content per unit of the SSB is slightly higher, indeed, but for practical purposes the difference is negligible. This is consistent with the result from the baseline calibration that the first-best subsidy  $\tau_x^d$  is also negligible, so correcting market failure solely with the sugar content tax per unit of the SSB will not change this tax much.

The intuition as to why the second-best  $\tau_{xq}$  exceeds the first-best level becomes obvious if we take a look at the SSB quantity. Recall from Tables 3 and 4 that the first-best policy increases the SSB quantity from  $x = 330.72$  gram to  $x = 1005.85$  gram.<sup>15</sup> If we were to use only the first-best sugar content tax  $\tau_{xq}/p_\ell = 0.00073316$  hours per gram and ignore the first-best SSB subsidy  $\tau_x^d$  from Table 4, then the corresponding SSB quantity can be computed as

<sup>15</sup>In terms of Proposition 3, we thus have an example where the laissez-faire SSB quantity  $x$  is inefficiently low and the first-best policy increases the SSB quantity  $x$ .

$x = 1003.5227$  gram, which is lower than the first-best level  $x = 1005.85$  gram. Hence, the first-best sugar content tax increases the SSB quantity, but not the whole way up to the first-best level. This is why we need the SSB subsidy in the first-best. But when the SSB subsidy is not available, the second-best sugar content tax rate is larger than the first-best level in order to bring the SSB quantity closer to the first-best quantity, even though the increase to  $x = 1003.5229$  gram is tiny.

## 8.2. Correcting sugar consumption internalities

So far, our analysis has focused on policies correcting the missing market for sugar content. As mentioned in Section 1, sugar taxation is often justified by internalities caused, for example, by a present bias. In this subsection, we introduce such an externality into our framework and investigate the corresponding policy implications, with and without markets for sugar content. The present bias of the consumer is modeled as follows. The consumer's true utility is specified as  $u = V(x^d, q^d, \ell^s) + W[H(x^d q^d)]$  with  $V_x, V_q > 0$ ,  $V_\ell < 0$ , and  $W_h > 0$ , whereas in making a decision, the consumer uses the perceived utility  $u = V(x^d, q^d, \ell^s) + \beta W[H(x^d q^d)]$  with  $\beta \in [0, 1[$ . As the social planner takes into account the true utility, the efficient allocation remains unchanged and is still determined by the conditions in Column 1 of Table 1. But the conditions for the market solutions in Columns 2 and 3 of Table 1 as well as the correcting policies may change, because the consumer uses the perceived utility and her decision is distorted by the present bias.

Consider first the case with an indirect market for sugar content. In the Online Appendix, we show that efficiency can then be restored either by the tax combination

$$\tau_q = (1 - \beta)x \frac{W_h H_z}{V_\ell} > 0, \quad \tau_x^s + \tau_x^d = (1 - \beta)q \frac{W_h H_z}{V_\ell} > 0, \quad (31)$$

or by a single tax on sugar content per unit of the SSB

$$\tau_{xq} = (1 - \beta) \frac{W_h H_z}{V_\ell} > 0. \quad (32)$$

Because the externality stems from total sugar intake  $z = xq$ , the social planner may tax either the SSB quantity  $x$  and sugar content  $q$  separately, as shown in equations (31), or the total sugar intake  $z$  by imposing a tax on the sugar content per unit of the SSB, as shown in equation (32). Estimating equation (32) gives  $\tau_{xq} = \text{£}5.98283$  per liter, which implies  $\tau_{xq} \cdot q_{2015} = \text{£}0.220702$  per liter. These estimates are roughly half as large as equations (27) and (28) from the baseline simulation and well in line with the UK tax rates. Put differently, externality arguments may justify the current implementation of the sugar content tax implemented in the UK.

At first glance, when market failure occurs due to both internalities and a missing market for sugar content, one might expect that the tax rates from the two sources of market failure add up. But in the Online Appendix, we derive the optimal policy

$$\begin{aligned}\tau_{xq} &= \frac{1}{x} \frac{V_q + xW_h H_z}{V_\ell} > 0, \\ \tau_x^s + \tau_x^d &= -\frac{q}{x} \frac{V_q + xW_h H_z}{V_\ell} + (1 - \beta)q \frac{W_h H_z}{V_\ell} \leq 0.\end{aligned}\tag{33}$$

Comparing equations (33) with equations (24), (31), and (32), it becomes clear that only the tax rates on the SSB quantity add up when both sources of market failure are present. The tax rate on sugar content still reflects the missing market, but not the externality. This is because without a market for sugar content, the consumer does not receive price signals for  $q$  and, while still choosing  $x$ , takes  $q$  as given. Hence, the consumer's externality with respect to sugar content vanishes. Estimating equations (33), we find  $\tau_{xq} \cdot q_{2015} = \text{£}0.37972$  per liter and  $\tau_x = \text{£} -0.00213$  per liter. Adding externalities to the missing market thus leaves unchanged the tax rate on sugar content, whereas the subsidy on the SSB quantity is further marginalized to less than quarter of a pence, compared with equations (27) and (28). In this sense, the missing market justification of sugar content taxation dominates the externality justification.

### 8.3. Heterogeneous SSBs

So far, we have focused on a single or average SSB, whereas in practice a variety of SSBs are observed. In this subsection, we show that our main results remain qualitatively unchanged in an economy with heterogeneous SSBs. There is still one representative sugar firm with the production technology (1). On the consumption side, we assume  $n > 1$  consumer types, where  $i, j = 1, \dots, n$  are type indices. Without loss of generality, the number of type  $i$  consumers is normalized to one. Consumer type  $i$  has utility  $u_i = U^i(x_i^d, q_i^d, \ell_i^s, h_i)$  and health  $h_i = H^i(z_i)$ . All variables and functions are the same as in case of a single SSB, except that they are now indexed by  $i$ .<sup>16</sup> Following Rosen (1974), in the long-run equilibrium, each consumer type is served by exactly one type of SSB producer. The SSB firm of type  $i$  faces the technology  $x_i^s \leq X^i(\ell_{xi}^d, z_i^d)$  and the supplied sugar content

<sup>16</sup>It is assumed that each consumer type demands only one variant of the SSB, but the basic mechanism identified by our analysis also applies to the case where a consumer type demands several SSB variants.

$q_i^s := z_i^d / x_i^s$ . Finally, the resource constraints (5)–(8) are replaced by  $\sum_{j=1}^n \ell_j^s \geq \ell_z^d + \sum_{j=1}^n \ell_{xj}^d$ ,  $z^s \geq \sum_{j=1}^n z_j^d$ ,  $x_i^s \geq x_i^d$ , and  $q_i^s = q_i^d$  for all  $i$ .

In the Online Appendix, we derive the efficient allocation determined by the social planner who maximizes Utilitarian welfare  $\sum_{j=1}^n U^j(\cdot)$  subject to all technologies and resource constraints. This allocation is then compared to the allocation in a market economy with missing markets for sugar content and policy instruments  $\tau_{xqi}$ ,  $\tau_{xi}^s$  and  $\tau_{xi}^d$  for all  $i$ , which turned out to be most promising in the single SSB model.<sup>17</sup> The policy instruments may be SSB-specific. The result of the comparison yields the optimal policy

$$\tau_{xqi} = \frac{1}{x_i} \frac{U_q^i + x_i U_h^i H_z^i}{U_\ell^i} > 0, \quad \tau_{xi}^s + \tau_{xi}^d = -\frac{q_i}{x_i} \frac{U_q^i + x_i U_h^i H_z^i}{U_\ell^i} < 0, \quad (34)$$

for all  $i$ . Thus, (34) extends the optimal tax–subsidy scheme (24) to the case of heterogeneous SSBs, except that the optimal tax and subsidy rates are now SSB-specific. The intuition of the optimal scheme is the same as in the economy with a single SSB. We leave the calibration of (34) for further research, as highly disaggregated data for the different SSBs and, thus, a much more comprehensive empirical analysis are needed.

## 9. Conclusion

This paper provides a novel foundation of SSB taxation. Within a general equilibrium model encompassing production of a sugar input, SSB production, and consumption as well as the health costs of sugar consumption, we endogenize the sugar content of SSBs. For a full set of markets with an indirect market for sugar content, the competitive equilibrium is efficient. In contrast, if the market for sugar content is missing and the price for sugar content becomes zero, a negative sugar content externality arises and the laissez-faire economy results in an inefficiently high sugar content and an inefficiently low SSB price. This market failure can be corrected by a sugar content tax per SSB unit combined with a subsidy on the SSB quantity, a tax–subsidy combination that can be incorporated in deposit–refund systems for beverage containers. In a calibration of our theoretical model to the UK, we show that the UK’s soft drink levy falls short of its optimal level.

Of course, there are many possible extensions of our analysis. Perhaps most important, our general equilibrium model focuses on perfectly competitive markets, ignoring that SSB producers often act under conditions of imperfect

<sup>17</sup>It can be shown that our results with respect to the taxes on the sugar content,  $\tau_q$ , and on the sugar supply and demand,  $\tau_z^s$  and  $\tau_z^d$ , extend to the case with several SSBs as well.

competition and possess a considerable degree of market power. Competition between producers regarding the sugar content of their SSBs is also an important aspect of real-world markets that is not captured by our general equilibrium model. Such competition issues create additionally distortions of the price, quantity, and sugar content of SSBs that have to be taken into account by the optimal corrective policy. Finally, optimal taxation analyses such as those investigated by Allcott et al. (2019b) may also benefit from taking into account the phenomenon of missing markets for sugar content. All these extensions are promising, but they are beyond the scope of the present paper and therefore left for future research.

## Appendix

### A.1. First-order conditions for the Pareto efficient allocation

The Lagrangian of the social planner's maximization problem in Section 3 is given by

$$\begin{aligned}\mathcal{L} = & U[x^d, q^d, \ell^s, H(x^d q^d)] + \phi_z [Z(\ell_z^d) - z^s] \\ & + \phi_x [X(\ell_x^d, z^d) - x^s] + \lambda_q^s \left( \frac{z^d}{x^s} - q^s \right) + \lambda_\ell (\ell^s - \ell_z^d - \ell_x^d) \\ & + \lambda_z (z^s - z^d) + \lambda_x (x^s - x^d) + \lambda_q^d (q^s - q^d),\end{aligned}$$

where  $\phi_z$ ,  $\phi_x$ , and  $\lambda_q^s$  represent Lagrange multipliers associated with the technologies (1)–(3) and  $\lambda_\ell$ ,  $\lambda_z$ ,  $\lambda_x$ , and  $\lambda_q^d$  are the Lagrange multipliers for the constraints (5)–(8).

Differentiating the Lagrangian yields the first-order conditions

$$\mathcal{L}_{\ell_z^d} = \phi_z Z_\ell - \lambda_\ell = 0, \quad (\text{A1})$$

$$\mathcal{L}_{z^s} = -\phi_z + \lambda_z = 0, \quad (\text{A2})$$

$$\mathcal{L}_{\ell_x^d} = \phi_x X_\ell - \lambda_\ell = 0, \quad (\text{A3})$$

$$\mathcal{L}_{z^d} = \phi_x X_z + \lambda_q^s \frac{1}{x^s} - \lambda_z = 0, \quad (\text{A4})$$

$$\mathcal{L}_{x^s} = -\phi_x - \lambda_q^s \frac{z^d}{(x^s)^2} + \lambda_x = 0, \quad (\text{A5})$$

$$\mathcal{L}_{q^s} = -\lambda_q^s + \lambda_q^d = 0, \quad (\text{A6})$$

$$\mathcal{L}_{x^d} = U_x + q^d U_h H_z - \lambda_x = 0, \quad (\text{A7})$$

$$\mathcal{L}_{q^d} = U_q + x^d U_h H_z - \lambda_q^d = 0, \quad (\text{A8})$$

$$\mathcal{L}_{\ell^s} = U_\ell + \lambda_\ell = 0. \quad (\text{A9})$$

Eliminating  $\phi_z$  from equations (A1) and (A2) gives the condition in Column 1, Row 1 of Table 1. From equation (A6), it follows that  $\lambda_q^s = \lambda_q^d =: \lambda_q$ . With this property, solve equation (A3) for  $\phi_x$ , insert into equation (A5) and take into account  $z^d/(x^s)^2 = q/x$  in order to obtain the condition in Column 1, Row 2 of Table 1. The condition in Column 1, Row 3 of Table 1 is obtained by inserting  $\phi_x$  from equation (A3) into (A4) and using  $x^s = x$  as well as  $\lambda_q^s = \lambda_q$ . Finally, the conditions in Column 1, Rows 4 and 5 are obtained by taking into account  $q^d = q$ ,  $x^d = x$  as well as  $\lambda_q^d = \lambda_q$ , and dividing equations (A7) and (A8), respectively, by equation (A9).

## A.2. Market equilibrium conditions with indirect market for sugar content

The Lagrangians to the maximization problems in equations (11), (12), and (13) are, respectively,

$$\mathcal{L}^z = p_z z^s - p_\ell \ell_z^d + \mu_z [Z(\ell_z^d) - z^s],$$

$$\mathcal{L}^x = P(q^s)x^s - p_\ell \ell_x^d - p_z z^d + \mu_x [X(\ell_x^d, z^d) - x^s] + \mu_q \left( \frac{z^d}{x^s} - q^s \right),$$

$$\mathcal{L}^c = U[x^d, q^d, \ell^s, H(x^d q^d)] + \mu_c [p_\ell \ell^s + \pi - P(q^d)x^d],$$

where  $\mu_z$ ,  $\mu_x$ ,  $\mu_q$ , and  $\mu_c$  are multipliers associated with the technologies for sugar and the SSB, the definition of the supplied sugar content, and the budget constraint, respectively.

Differentiating the Lagrangians gives the first-order conditions

$$\mathcal{L}_{\ell_z^d}^z = \mu_z Z_\ell - p_\ell = 0, \quad (\text{A10})$$

$$\mathcal{L}_{z^s}^z = -\mu_z + p_z = 0, \quad (\text{A11})$$

$$\mathcal{L}_{\ell_x^d}^x = \mu_x X_\ell - p_\ell = 0, \quad (\text{A12})$$

$$\mathcal{L}_{z^d}^x = \mu_x X_z + \mu_q \frac{1}{x^s} - p_z = 0, \quad (\text{A13})$$

$$\mathcal{L}_{x^s}^x = -\mu_x - \mu_q \frac{z^d}{(x^s)^2} + P(q^s) = 0, \quad (\text{A14})$$

$$\mathcal{L}_{q^s}^x = P_q(q^s)x^s - \mu_q = 0, \quad (\text{A15})$$

$$\mathcal{L}_{x^d}^c = U_x + q^d U_h H_z - \mu_c P(q^d) = 0, \quad (\text{A16})$$

$$\mathcal{L}_{qd}^c = U_q + x^d U_h H_z - \mu_c P_q(q^d) x^d = 0, \quad (\text{A17})$$

$$\mathcal{L}_{\ell s}^c = U_\ell + \mu_c p_\ell = 0. \quad (\text{A18})$$

Eliminating  $\mu_z$  from equations (A10) and (A11) yields the condition in Column 2, Row 1 of Table 1. Determining  $\mu_x$  from equation (A12) and  $\mu_q$  from equation (A15), inserting into equation (A14) and taking into account  $x^s = x$ ,  $z^d/(x^s)^2 = q/x$ ,  $P(q^s) = P(q)$ , and  $P_q(q^s) = P_q(q)$  yields the condition in Column 2, Row 2 of Table 1. The condition in Column 2, Row 3 of Table 1 is obtained by inserting  $\mu_x$  from equation (A12) and  $\mu_q$  from equation (A15) into (A13) and using  $x^s = x$  and  $P_q(q^s) = P_q(q)$ . The conditions in Column 2, Rows 4 and 5 follow from dividing equation (A16) by (A18) and equation (A17) by (A18), respectively, and using  $q^d = q$ ,  $x^d = x$ ,  $P(q^d) = P(q)$  and  $P_q(q^d) = P_q(q)$ .

*Proof of Proposition 3:* For the proof of Proposition 3, we make use of the equilibrium conditions for the regulated market, which we derive in Section 6 and which are listed in Column 3 of Table 1. If we set all tax rates equal to zero (i.e.,  $\tau_z^s = \tau_z^d = \tau_x^s = \tau_x^d = \tau_q = \tau_{xq} = 0$ ), then these conditions are equivalent to the conditions in the competitive economy without a market for sugar content (which can equivalently be obtained by setting  $P_q(q) \equiv 0$  and  $P(q) = p_x$  in Column 2 of Table 1 and ignoring the condition in Row 5). Moreover, in Section 6 we show that  $\tau_z^s = \tau_x^d = \tau_q = \tau_{xq} = 0$  and  $\tau_z^d = -\tau_x^s/q = \tau_z^* := (1/x)(U_q + xU_h H_z)/U_\ell > 0$  implements the efficient allocation if markets for sugar content are missing. Hence, in order to characterize the inefficiency in case of missing markets for sugar content, we assume  $\tau_z^s = \tau_x^d = \tau_q = \tau_{xq} = 0$  in Column 3 of Table 1, and conduct a comparative static analysis of marginal changes in  $\tau_x^s$  and  $\tau_z^d$ , taking advantage of the equality  $\tau_x^s = -q\tau_z^d$  and restricting our attention to changes of  $\tau_z^d$  in the interval  $[0, \tau_z^*]$ .

We start by determining the set of equations that have to be differentiated. Remember that  $p_\ell = 1$  as well as  $x^s = x^d =: x$ ,  $q^s = q^d =: q$ ,  $z^s = z^d =: z$  and  $\ell = \ell_z + \ell_x$  with  $\ell := \ell^s$ ,  $\ell_z := \ell_z^d$  and  $\ell_x := \ell_x^d$ . The term  $q^s = z^d/x^s$  can then be rewritten as

$$z = xq. \quad (\text{A19})$$

If the sugar technology is linear homogeneous, we can write (1) as

$$z = Z(\ell_z) = \ell_z/c_z, \quad (\text{A20})$$

with  $c_z > 0$ . The SSB production technology (2) is given by

$$x = X(\ell_x, z), \quad (\text{A21})$$

and, due to linear homogeneity, satisfies the conditions  $x = \ell_x X_\ell + z X_z$ ,  $\ell_x X_{\ell\ell} + z X_{\ell z} = 0$ , and  $X_{zz} = \ell_x^2 X_{\ell\ell}/z^2$ . Using  $p_\ell = 1$ ,  $Z_\ell = 1/c_z$ ,  $\tau_x^s = -q\tau_z^d$



and setting all other tax rates equal to zero, the conditions in Column 3, Rows 1–3 of Table 1 can be rewritten as

$$p_z = c_z, \quad (\text{A22})$$

$$\frac{1}{X_\ell} = p_x + q\tau_z^d, \quad (\text{A23})$$

$$\frac{X_z}{X_\ell} = c_z + \tau_z^d. \quad (\text{A24})$$

Repeating the consumer's first-order condition in Column 3, Row 4 in Table 1 gives

$$-\frac{U_x + qU_h H_z}{U_\ell} = p_x. \quad (\text{A25})$$

As profit income of the consumer, we obtain  $\pi = \pi_z + \pi_x = 0$ , because  $\pi_z = \pi_x = 0$  due to the zero profit conditions under linear homogeneous production functions  $Z$  and  $X$ . The same is true for the consumer's lump-sum transfer, because

$$\psi = \tau_z^s z^s + \tau_z^d z^d + \tau_x^s x^s + \tau_x^d x^d + \tau_q q^s + \tau_{xq} x^s q^s = 0$$

due to  $\tau_z^s = \tau_x^d = \tau_q = \tau_{xq} = 0$  and  $\tau_x^s = -q\tau_z^d$ . The consumer's budget constraint specified in the maximization problem (18) thus simplifies to

$$\ell = p_x x. \quad (\text{A26})$$

Equations (A19)–(A26) represent a system of eight equations that determine the eight unknowns  $\ell_z$ ,  $z$ ,  $p_z$ ,  $\ell_x$ ,  $x$ ,  $q$ ,  $p_x$ , and  $\ell$  as functions of  $\tau_z^d$ .<sup>18</sup> In the following, we run a comparative static analysis along the lines suggested by Jones (1965) using the so-called hat calculus, where  $\hat{y} := dy/y$  denotes the relative change in  $y \in \{\ell_z, z, p_z, \ell_x, x, q, p_x, \ell\}$ . In deviation from this convention, let  $\hat{\tau}_z^d := d\tau_z^d/(c_z + \tau_z^d)$  to avoid the fact that  $\hat{\tau}_z^d$  is not defined if  $\tau_z^d = 0$ .

In order to prove part (i) of Proposition 3, we need to differentiate only equations (A19)–(A24), without referring to equation (A25), which is the only equation that depends on the consumer's preferences. From totally differentiating equations (A19)–(A22), we immediately obtain

$$\hat{z} = \hat{x} + \hat{q}, \quad (\text{A27})$$

$$\hat{z} = \hat{\ell}_z, \quad (\text{A28})$$

<sup>18</sup>Actually, we also have the labor market clearing condition given by  $\ell = \ell_z + \ell_x$  in the competitive market equilibrium. Due to the Walras law, however, this condition can be ignored.

$$\hat{x} = \frac{\ell_x X_\ell}{x} \hat{\ell}_x + \frac{z X_z}{x} \hat{z}, \quad (\text{A29})$$

$$\hat{p}_z = 0. \quad (\text{A30})$$

Differentiating equation (A23) implies

$$-\frac{1}{X_\ell^2} (\ell_x X_{\ell\ell} \hat{\ell}_x + z X_{\ell z} \hat{z}) = p_x \hat{p}_x + q \tau_z^d \hat{q} + q(c_z + \tau_z^d) \hat{\tau}_z^d. \quad (\text{A31})$$

If we differentiate equation (A24), then, after some tedious rearrangements, we obtain

$$\frac{1}{\theta} \frac{X_z}{X_\ell} (\hat{\ell}_x - \hat{z}) = (c_z + \tau_z^d) \hat{\tau}_z^d, \quad (\text{A32})$$

where  $\theta := -z X_\ell X_z / (x \ell_x X_{\ell\ell}) > 0$  follows from  $x = \ell_x X_\ell + z X_z$ ,  $\ell_x X_{\ell\ell} + z X_{\ell z} = 0$  and  $X_{zz} = \ell_x^2 X_{\ell\ell} / z^2$  due to the linear homogeneity of  $X$ .

Solving equation (A29) for  $\hat{\ell}_x$ , inserting into equation (A31) as well as (A32) and using again  $x = \ell_x X_\ell + z X_z$  and  $\ell_x X_{\ell\ell} + z X_{\ell z} = 0$  as well as  $\hat{x} - \hat{z} = -\hat{q}$  from equation (A27) yields

$$\left( \frac{x X_{\ell\ell}}{X_\ell^3} - q \tau_z^d \right) \hat{q} = p_x \hat{p}_x + q(c_z + \tau_z^d) \hat{\tau}_z^d, \quad (\text{A33})$$

$$-\frac{1}{\theta} \frac{x X_z}{\ell_x X_\ell^2} \hat{q} = (c_z + \tau_z^d) \hat{\tau}_z^d. \quad (\text{A34})$$

If we eliminate  $(c_z + \tau_z^d) \hat{\tau}_z^d$  in equation (A33) with the help of equation (A34) and use the definition  $\theta := -z X_\ell X_z / (x \ell_x X_{\ell\ell})$  as well as  $z = xq$  from equation (A19), we finally obtain

$$\hat{p}_x = -\frac{q \tau_z^d}{p_x} \hat{q}. \quad (\text{A35})$$

Part (i) of Proposition 3 can now be proven as follows. If  $\hat{\tau}_z^d > 0$ , then  $\hat{q} < 0$  due to equation (A34) and  $\hat{p}_x > 0$  due to equation (A35). Hence, if we move from the competitive equilibrium without markets for sugar content to the efficient solution (increase in  $\tau_z^d$ ),  $q$  decreases while  $p_x$  increases. Put differently, in the competitive equilibrium,  $q$  is inefficiently high, while  $p_x$  is inefficiently low. The efficiency of  $p_z$  follows immediately from equation (A30).

In an analogous way, we could determine  $\hat{x}$ ,  $\hat{\ell}$ , and  $\hat{z}$  from differentiating equations (A25) and (A26) and taking into account equation (A27),  $\hat{p}_x > 0$ , and  $\hat{q} < 0$ . It is straightforward to show that the resulting expressions are indeterminate in sign, which means that in the competitive equilibrium the SSB quantity  $x$  and the sugar quantity  $z$  may be inefficiently low or high. In order to illustrate, we solve equations (A19)–(A26) numerically with

$\tau_z^d = 0$  and compare the resulting competitive equilibrium with the efficient allocation  $(\ell_z, z, \lambda_z, \ell_x, x, q, \lambda_x, \lambda_q, \ell)$  obtained from equations (A19)–(A21), the five equations in Column 1 of Table 1 and the labor resource constraint  $\ell = \ell_z + \ell_x$ . We assume CES production

$$X(\ell_x, z) = [\gamma \ell_x^{-\mu} + \delta z^{-\mu}]^{-1/\mu},$$

with  $\gamma, \delta > 0$ ,  $\gamma + \delta = 1$  and  $\mu \geq -1$ , CES utility

$$U(x, q, \ell, h) = [\alpha x^{-\rho} + \nu q^{-\rho} + \kappa(1 - \ell)^{-\rho} + \varepsilon h^{-\rho}]^{-\sigma/\rho}$$

with  $\alpha, \nu, \kappa, \varepsilon > 0$ ,  $\alpha + \nu + \kappa + \varepsilon \leq 1$ ,  $\sigma \leq 1$ , and  $\rho \geq -1$ , and a linear health function  $H(z) = \bar{h} - c_h z$  with  $\bar{h}, c_h > 0$ . For the parameter constellation  $(c_z, \gamma, \delta, \mu, \alpha, \nu, \kappa, \varepsilon, \rho, \sigma, \bar{h}, c_h) = (2, 0.5, 0.5, -0.001, 0.2, 0.01, 0.01, 0.78, 1, 1, 1, 1)$ , we obtain  $x = 0.2942$  and  $z = 0.1540$  in the efficient allocation, but higher values  $x = 0.3016$  and  $z = 0.2132$  in the competitive equilibrium. Taking the same parameter constellation but reducing the substitution parameter in the utility function to  $\rho = -0.001$ , the efficient allocation becomes  $x = 0.2626$  and  $z = 0.0936$ , whereas in the competitive equilibrium we have  $x = 0.2570$  and  $z = 0.1817$ , so  $z$  is still inefficiently high whereas  $x$  becomes inefficiently low. If we decrease the substitution parameter further to  $\rho = -0.7$ , then  $z$  also becomes inefficiently low, as  $x = 0.1853$  and  $z = 0.0379$  in the efficient allocation and  $x = 0.0282$  and  $z = 0.0199$  in the market equilibrium. These numerical examples prove part (ii) of Proposition 3.<sup>19</sup> □

### A.3. Equilibrium conditions for regulated markets

The Lagrangians to the maximization problems (16), (17), and (18) are, respectively,

$$\begin{aligned}\mathcal{L}^z &= (p_z - \tau_z^s)z^s - p_\ell \ell_z^d + \omega_z [Z(\ell_z^d) - z^s], \\ \mathcal{L}^x &= (p_x - \tau_x^s)x^s - \tau_q q^s - p_\ell \ell_x^d - (p_z + \tau_z^d)z^d - \tau_{xq} x^s q^s \\ &\quad + \omega_x [X(\ell_x^d, z^d) - x^s] + \omega_q \left( \frac{z^d}{x^s} - q^s \right), \\ \mathcal{L}^c &= U[x^d, q^d, \ell^s, H(x^d q^d)] + \omega_c [p_\ell \ell^s + \pi + \psi - (p_x + \tau_x^d)x^d],\end{aligned}$$

where  $\omega_z$ ,  $\omega_x$ ,  $\omega_q$ , and  $\omega_c$  are Lagrange multipliers.

<sup>19</sup>We run the numerical examples with the help of the algebra software Mathematica. Note that, in all examples, the shadow prices are  $\lambda_x > 0$  and  $\lambda_q < 0$ , consistent with our assumptions. The examples also confirm the inefficiency properties of  $q$  and  $p_x$  in part (i) of Proposition 3. Details on the numerical computations can be obtained from the authors upon request.

Differentiating the Lagrangians gives the first-order conditions

$$\mathcal{L}_{\ell_z^d}^z = \omega_z Z_\ell - p_\ell = 0. \quad (\text{A36})$$

$$\mathcal{L}_{z^s}^z = -\omega_z + p_z - \tau_z^s = 0, \quad (\text{A37})$$

$$\mathcal{L}_{\ell_x^d}^x = \omega_x X_\ell - p_\ell = 0, \quad (\text{A38})$$

$$\mathcal{L}_{z^d}^x = \omega_x X_z + \omega_q \frac{1}{x^s} - p_z - \tau_z^d = 0, \quad (\text{A39})$$

$$\mathcal{L}_{x^s}^x = -\omega_x - \omega_q \frac{z^d}{(x^s)^2} + p_x - \tau_x^s - \tau_{xq} q^s = 0, \quad (\text{A40})$$

$$\mathcal{L}_{q^s}^x = -\tau_q - \tau_{xq} x^s - \omega_q = 0, \quad (\text{A41})$$

$$\mathcal{L}_{x^c}^c = U_x + q^d U_h H_z - \omega_c (p_x + \tau_x^d) = 0, \quad (\text{A42})$$

$$\mathcal{L}_{\ell^s}^c = U_\ell + \omega_c p_\ell = 0. \quad (\text{A43})$$

Combining equations (A36) and (A37) gives the condition in Column 3, Row 1 of Table 1. Inserting equations (A38) and (A41) into equations (A40) and (A39) implies the conditions in Column 3, Rows 2 and 3, respectively. Finally, dividing equation (A42) by (A43) yields the condition in Column 3, Row 4.

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## Supporting information

Additional supporting information can be found online in the supporting information section at the end of the article.

### Online appendix Replication file

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