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Welfare Consequences of Government Budget Closure Assumptions Under New Environmental Policies*

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Abstract

Recent subsidy-based environmental policies directly affect the government's budget. Computable general equilibrium (CGE) models used to assess the costs and benefits of environmental policies typically assume a fiscal closure rule that holds government consumption fixed meaning budget shortfalls or surpluses induced by a policy are reconciled through transfers or the tax system. Revised guidance for regulatory analysis in the United States suggests that this closure rule potentially be considered in sensitivity in economy-wide analysis of environmental policies. In this paper, we shed light on instances when the closure rule may or may not be an important dimension of a policy analysis by modeling the overall welfare, emissions, and distributional consequences of different closure assumptions across a range of CGE models with different dynamics and policy types. We find that the closure rule does not create significant deviations in overall welfare unless a policy induces direct budgetary imbalances (e.g., tax or subsidy). Further, the choice of the balancing instrument can lead to very different distributional impacts and for lump sum transfers, distributionally neutral closure rules come at virtually no cost. Finally, Ricardian Equivalence, or the inconsequentiality of when the budget imbalance occurs, holds for debt-financed imbalances for lump sum transfers only (e.g., not for changes to tax rates).

JEL Codes: D58; Q43; Q52; Q54; H60

Keywords: computable general equilibrium; emissions cap; clean energy subsidies; clean energy standard; government budget closure

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1 Introduction

Energy and environmental policies can affect the public budget constraint in non-trivial ways. For instance, the United States passed the Inflation Reduction Act in 2022 that is expected to produce fiscal costs, or reductions in tax revenues or increased federal payments, from its subsidy-based climate related provisions of roughly $1 trillion between 2022-2031 (Bistline et al., 2023). In the European Union, the Emission Trading System accounted for nearly $40 billion in auctioned permit revenues in 2022, with expected increases into the future.[1] Changes in the fiscal budget are not social costs (or the sum of all opportunity costs to society) but rather part of a transfer payment which do not reflect the use of real economic resources (SAB, 2017; EPA, 2010). However, accounting for changes in government expenditures or revenues in the assessment of the costs and benefits of a policy can be important, especially if the transfer mechanism interacts with pre-existing distortions in the economy or if it induces changes in incidence across households.

For energy and environmental policies that are expected to have significant general equilibrium implications, analysts have turned to computable general equilibrium (CGE) models to assess economy-wide impacts (e.g., Brown et al. (2023); EPA (2024)). In many CGE models, the optimization problem behind government spending is not well represented because the value of public expenditures is largely exogenous. A common assumption is to assume that the utility function is additively separable in public and private consumption, hold government consumption fixed, and allow the model to calculate welfare impacts inclusive of economy-wide changes to the tax base through a government budget closure rule (e.g., Marten et al. (2024); Yuan et al. (2019); Rutherford and Schreiber (2019); Goulder et al. (2016)).[2] Government budget closures are typically implemented by allocating government budget surpluses or deficits induced by a policy back to households through a lump sum transfer or the tax system.

The specific mechanism used to close the government budget can affect the estimated welfare costs (or benefits) and incidence of a policy. Recognizing this potential model-based uncertainty, OMB (2023), the revised Circular A-4 which is guidance from the Office of Management and Budget to

[1] See: https://www.eea.europa.eu/en/analysis/indicators/use-of-auctioning-revenues-generated?activeAccordion=ecdb3bcf-bbe9-4978-b5cf-0b136399d9f8.

[2] Generally, model closure rules are exogenous assumptions for aspects of the economy that are not captured in the model.

executive branch agencies in the United States, suggests that while government budget closures are a means to account for government budget implications of a policy in general equilibrium models, such closures may be "hypothetical [if] they assume policy changes that are not part of the regulation" and recommends that the closure assumption potentially be treated in sensitivity. Analysis of environmental policy in a CGE framework has always been subject to potential uncertainties from government closure assumptions. However, the potentially significant amount of resource shifts stemming from new subsidy-based policies or interactions with such policies have resurfaced questions about the welfare consequences of these closure rules.[3] Fiscal closures and revenue neutrality assumptions have been extensively studied under price-based climate policy (e.g., Goulder (2013)), but these sets of assumptions have not been systematically evaluated under a wider scope of environmental policies (e.g., subsidies, performance standards). Therefore, this paper fills this gap in the literature by examining the implications of government budget closure assumptions in CGE models across a broad range of environmental policy types and model-based assumptions. Importantly, while the policy scope considered in this paper is geared toward environment and energy, the modeled impacts could extend to other policy settings that may impact the federal budget constraint in similar ways.

We evaluate these questions using WiNDC-based (Wisconsin National Data Consortium, see Rutherford and Schreiber (2019)) CGE models of the United States economy to simulate the effect of alternative closure assumptions for environmental policies on the electricity sector. Environmental policies can have both a direct effect on the government's budget which is dependent on the chosen policy mechanism and an indirect effect through changes in tax revenues from equilibrium changes to output, trade, factor supply, etc. We examine policies that that have a directly positive (taxes or auctioned permits from cap and trade markets), directly negative (clean technology subsidies), or only an indirect (performance standards) impact on the government's budget. In the context of these policies, we consider three basic types of budget closures in which budget imbalances can be reconciled: (1) using a lump sum transfer between the government and households, (2) by modifying existing tax rates, or (3) by deferring payment to a later date by adding or subtracting to the existing deficit (with an option to pay off by the end of the model horizon). Our set of policy counterfactuals are modeled under different temporal assumptions using internally consistent model templates

[3] For an example of policy analysis that accounts for interactions with the subsidy-based provisions of the Inflation Reduction Act, see EPA (2024).

which allows us to capture the role of temporal and anticipatory effects in the welfare implications of our considered scenarios: (1) a static model that does not explicitly represent time, (2) a myopic agent dynamic framework (recursive dynamic model), and (3) a perfectly foresighted agent dynamic framework (intertemporal model).

Across model variants and policy types, we find that emissions responses are not very sensitive to the closure choice, so any closure should suffice if emissions responses are the primary model output of concern. Also, the closure rule associated with the indirect effect on the government's budget does not have large effects on estimates of welfare changes in most cases but can have non-trivial distributional consequences under some assumptions. This is an important result for environmental regulatory analysis where most regulations take the form of standards with only an indirect effect on the government budget. We also find that lump sum instruments can be calibrated to generate distributionally equivalent policies across our cap and trade and clean technology subsidy cases at a small welfare difference relative to lump sum transfer allocations that exogenously define an allocation to or from households based on income or population. Alternatively, distortionary capital and labor income taxes can lead to significant welfare differences, in relative terms. This is especially true in intertemporal models and models with elastic capital supply when increased capital taxes are used to pay for clean subsidies. Finally, model variants that indefinitely defer repayment of policy-induced government budget imbalances effectively remove the closure assumption from the welfare effect of the given policy, which is misleading because the full cost of the policy is not appropriately captured.

In our dynamic model templates, we also consider model budget closures where the imbalances from clean technology subsidy policies are debt-financed and paid off in later time periods. In most cases, especially lump sum, our debt closure results suggest the long-run welfare consequences of modeling the complicated budget balance can be well approximated using conventional techniques within the period that costs occur (i.e., imbalances reconciled contemporaneously in the model). While this is implicitly true in some cases in the Ramsey-based model (i.e., Ricardian Equivalence), we also find a similar result with recursive dynamic models. However, in both forward-looking and recursive models, careful consideration is needed around the domestic versus foreign source of debt principal which is an important determinant of the time path of welfare. This assumption can also lead to significant long-run total welfare differences in intertemporal models. Additionally, of the combinations of closures modeled, the capital tax closure in the Ramsey model template is most sensitive to assumptions on debt. Capital taxes are known to be distortionary (Ballard et al., 1985; Fullerton and Henderson, 1989). When combined with debt in the clean subsidy policy case, the capital tax leads to larger welfare costs than a contemporaneous capital tax and is accompanied by a small increase in regressivity. Debt repayment has exogenous interest and principal components. While the principal portion is the same total value, the interest portion grows with maturity length which must be covered by increased taxes. Because capital taxes are distortionary, any benefit to delay is outweighed by the ultimate tax increase required to cover the interest.[4]

This paper is organized as follows. Section 2 discusses the relevant literature on the importance of closure rules in environmental policy analysis using CGE models. We then walk through the modeling methodology in Section 3. Results from our modeling scenarios are discussed in Section 4 followed by a concluding discussion in Section 5.

2 Background

This paper draws on several aspects of the economics literature. Generally, the economics literature comments on the issue of government budget closure rules in general equilibrium modeling, but not in a systematic way. There is existing work looking at the implications of revenue recycling in carbon pricing policies (carbon taxes and cap and trade) which is typically operationalized by assuming a government budget closure (balancing both the direct and indirect effects on the government's budget). This work looks at both the overall welfare implications (efficiency) of different policies as well as incidence (equity). We also connect to literature comparing modeling results from models with different expectations, including early work that illustrates the implications of debt-financed budget imbalances in simple Ramsey-based models.

Goulder (2013) summarizes the literature on the interactions between the tax system and carbon taxes or cap and trade policies. The authors focus on impact pathways like the tax interaction effect or the revenue recycling effect to assess whether a double dividend is achievable, how fiscal interactions can amplify importance of policy design, and how alternative policies might interact with the fiscal

[4] We only model a hypothetical debt security associated with the clean subsidy, not the optimal use of debt from a broader portfolio tax-smoothing perspective.

system. This body of work generally establishes income tax recycling as more cost effective compared to lump-sum rebates, with capital income tax recycling preferred to labor income tax recycling.[5] For instance, Bovenberg and Goulder (1996) find that the use of revenue does not much affect the percentage reduction in emissions, but it does affect welfare. Bovenberg and Goulder (1997) focuses on the tax shifting effect and potential for a double dividend. Their analytical model shows that the prospect for a double dividend depends on the extent to which reforms shift the tax burden from the overtaxed (more elastic) to undertaxed (less elastic) factor. This is a main reason why the revenue recycling effect is larger for capital income taxes than labor income taxes in static models with highly elastic capital supply or models with intertemporal consumption-savings decisions.

The economy-wide effects of a federal clean energy standard (CES) in the United States is summarized in Goulder et al. (2016). The authors compare a CES policy to variants of a cap and trade policy with different revenue recycling assumptions and find that the cost disadvantage of a CES compared to an emissions cap can be small if the subsidy induces a price reduction that mutes the tax interaction effect. While Goulder et al. (2016) explores a CES (i.e., clean subsidy paired with a tax on a dirty alternative), it highlights a need for extensions of existing literature to fiscal interactions and clean-subsidy policies. Brown et al. (2023) explore welfare and distributional consequences of the clean electricity tax credits in the U.S. Inflation Reduction Act using a linked model of the U.S. electricity system and a recursive dynamic CGE model of the U.S. economy – also based on the same WiNDC benchmark dataset. They model the tax credits as subsidies to clean electricity production and investment covered with an increase in capital income taxes. The modeling effort finds this policy-closure combination to be progressive and calls for future research surrounding the effects of fiscal closure.

The distributional effects of alternative closures have also been considered under carbon pricing and "polluter-pays" regulatory instruments. Under carbon pricing, Williams et al. (2015) and Rausch and Reilly (2015) generally find that there are inherent efficiency-equity trade-offs between conventional revenue recycling assumptions. For instance, both studies find that while carbon tax revenue is most efficiently recycled through the capital tax, labor income tax, and lump sum, in that order,

[5] Existing literature for relative cost effectiveness of income tax recycling versus lump-sum rebates in the U.S. economy includes: Bovenberg and de Mooij (1994); Bovenberg and Goulder (1996, 1997); Goulder et al. (1997, 1999); Fullerton and Metcalf (2001); Pizer et al. (2006); Rausch (2013); Parry (1995); Caron et al. (2018); Williams et al. (2015); McKibbin et al. (2015).

the equity implications are opposite. Lump sum transfers tend to be most progressive while capital tax revenue recycling is most regressive. Rausch et al. (2010) compare an alternative budget closure assumption around household transfer payments — that transfer payments to households are indexed to inflation and constant in real terms — and find that the direct effect of a carbon price can be progressive. García-Muros et al. (2022) highlight hybrid revenue recycling schemes that help to improve cost-effectiveness and distributional effects noting that distributional goals can be achieved at a small cost. For polluter-pays regulatory instruments, Rausch and Mowers (2014) finds that CES and RPS (Renewable Portfolio Standards) are regressive across the income spectrum and that they entail substantial efficiency costs compared to carbon pricing using a linked model with a recursive dynamic CGE model. Goulder et al. (2016) find the CES to be less cost-effective than carbon pricing for stringent policies but less so than in Rausch and Mowers (2014) because of more substantial tax interaction effects in their intertemporal model.[6]

It is worth noting that much of the discussed literature, and our own modeling results, pertain to findings for the United States economy. Some researchers have advised caution in assuming external validity for model results in other areas of the world. For instance, Babiker et al. (2003) caution against applying single-region results more broadly based on their findings that the benchmark tax system in other parts of the world can undermine the potential for a weak double dividend found in the US fiscal interactions literature. We note that documented results in the literature like the relative cost effectiveness across alternative expectations do not necessarily hold in our own results. For instance, Babiker et al. (2009) compare detailed forward-looking and recursive dynamic models for assessing global climate policy and find that forward-looking and recursive models produce similar physical energy sector behavior but the forward-looking model results in a lower cost than the recursive model. Our modeling results for the US suggest that the relative cost-effectiveness across alternative expectations may be dependent on the budget closure.[7]

Finally, Carbone et al. (2013) and Rausch (2013), motivated by a desire to consider intergenerational equity, explore carbon taxes as an option for fiscal reform and debt reduction using overlapping generations (OLG) models. The authors note that the OLG modeling framework is suited for that

[6] Other studies have also found regressive effects of CES and RPS policies (Deryugina et al., 2019; Davis and Knittel, 2019; Landis et al., 2019).

[7] Also, our modeled scenarios initiate the policy shock in the base year without any lead-time for pre-policy intertemporal responses, which could alleviate costs in an intertemporal model.

context because a characteristic of infinitely lived agent models with perfect foresight is Ricardian Equivalence. In instances when consumers have full information over the model horizon, Ricardian Equivalence states that consumers can fully internalize the government's budget constraint and will optimally reallocate consumption and savings such that the timing of the budget imbalance is immaterial to welfare impacts in the model.[8] Importantly, stylized models suggest that the assumption may break down when debt repayment is covered with distortionary labor or capital income taxes and that the timing of repayment matters when taxes are distortionary (Barro, 1974, 1979). We test these conjectures in a more complicated and comprehensive model of the U.S. economy.[9]

3 Methodology

We explore the effect of budget closure assumptions through a set of scenarios consisting of three main dimensions: i) model template, ii) policy instrument class, and iii) closure rule. For each model template, we simulate different closure rules for each policy instrument class. This section describes these three dimensions.

3.1 CGE Model Template

The CGE model template uses the 2017 WiNDC blueNOTE energy-environment benchmark dataset. The WiNDC benchmark is aggregated to a single U.S. region, 5 household income quintiles, 11 industrial sectors, and calibrated to a steady-state investment growth path.[10] We construct three models based on our CGE model template that differ by temporal treatment: a static model, recursive dynamic model, and Ramsey-based perfectly foresighted model. For comparability across model variants, where possible, we ensure a consistent set of model assumptions and employ the same benchmark economic dataset.[11] Energy commodities associated with CO_2 emissions are coal, natural gas, crude oil, and refined oil. The electricity sector is disaggregated into non-renewable (henceforth, called

[8] Ricardian Equivalence was first discussed in Ricardo (1821) and formalized in Barro (1974) and Buchanan (1976).

[9] Notably, we do not consider the optimal use of public debt, but rather focus on exogenous repayment schedules and mechanisms. However, one could think about modeling the optimal use of public debt as a way to smooth tax distortions generated from environmental policy (Barro, 1980, 1995).

[10] The steady-state growth path is defined by a depreciation rate of 5%, interest rate of 4%, and growth rate of 2%. The underlying social accounting matrix is re-calibrated to align capital demands and investment according to our steady-state assumptions.

[11] Notably, the Ramsey model deviates from the benchmark steady-state due to the disaggregation of fixed resources from capital.

dirty) and renewable (henceforth, called clean) production using electricity generation data from the State Energy Data System (SEDS).[12] Primary fuel and clean electricity production sectors employ a fixed-resource factor calibrated to empirical supply elasticities to ensure upward-sloping supply (Marten et al., 2024; Johnson, 2014). The benchmark dataset also accounts for existing taxes and subsidies on capital income, labor income, production, consumption, and imports.

For the sake of simplicity, the United States is modeled as a small open economy with international trade characterized by an Armington composite of foreign and domestic varieties. Household consumption and sectoral production decisions are modeled using nested constant elasticity of substitution functions. Each production sector employs a combination of intermediate goods, capital, labor, and in some cases, a fixed resource to produce output.[13] Capital markets are perfectly mobile across sectors within the US, but immobile internationally. Labor is restricted to the same mobility assumptions as capital, however, it is supplied through a time endowment that can be used for either labor or leisure (Ballard et al., 1985; Bovenberg and de Mooij, 1994). Each household consumes a bundle of commodities and leisure. The full consumption composite consisting of goods and leisure is used to measure welfare and distributional effects (see Figure 12 for the associated tree diagram). Household income endowments consist of their time (labor and leisure), capital, resources, and government transfer payments. Two types of government transfer payments exist, those that exist in the benchmark economy (which are representative of a sum total of payments from government transfer programs) and those that arise in a counterfactual that are associated with a government budget closure rule. In each model, the U.S. government is generally responsible for collecting tax revenues and dispersing transfers, subsidies, and public expenditures.

These model templates differ in their treatment of capital investment. All else equal, the static and recursive models assume a constant marginal propensity to save function (Ballard et al., 1985). The static model is a base-year solve of the recursive model, where the latter has an evolving capital stock between solve years via an accumulation function. In the Ramsey-based model, households optimize

[12] The existing electricity sector is disaggregated based on the renewable energy generation share of total generation. We characterize renewable generation as a composite of wind, solar, geothermal, and hydro technologies. Non-renewable generation are defined as fossil-fuel based generation and nuclear generation. The disaggregation is implemented by assuming all fossil fuel inputs are attributed to dirty generation and that clean technologies are more capital intensive to maintain zero profit accounting identities in the reference dataset.

[13] See Figure 13 for a tree diagram describing the nesting structure for non-electricity production. For electricity production disaggregated to account for both renewable and non-renewable technologies, see Figure 14. Variable names and indices are described in Tables 5-11.

the present value of final consumption with investment and capital stock accumulation embedded into the intertemporal problem. For a complete inventory of model equations, see Appendix B.[14]

3.2 Policy Instrument Class

We consider three policy instrument classes that differ in their impact on the government's budget. All policies considered in this paper are illustrative. We use carbon pricing to proxy for policies that have a direct positive effect on the government's budget (CAP), a clean energy subsidy that has a direct negative effect on the government's budget (CLSUB), and a clean energy standard (CES) that is representative of policies that only impact the government's budget through indirect means (e.g., changes in tax revenues through shrinking or expanding industries).[15] Table 1 describes the three classes of policy instruments and the illustrative policies we have selected. Notably, we treat the CES policy as a proxy for many of the environmental regulatory standards imposed in the United States that typically take the form of technology or emissions standards and do not directly impact the federal budget constraint. In all of the illustrative electricity sector policies, the stringency is calibrated to a "raw dollar policy target" such that the direct policy instrument generates USD 50 billion in the initial 2017 policy base year (and grows each year at the annual steady-state growth rate in the Ramsey and Recursive models). In the case of the carbon pricing or subsidy instruments, the tax or subsidy is endogenously determined to meet the raw dollar policy target for each year in carbon tax revenues or subsidy expenditures. Likewise, the CES policy endogenizes the tax instrument on dirty electricity generation to generate the raw dollar policy target for each year in *net* dirty tax revenue which is offset with the *net* subsidy to clean electricity. The decision to hold direct policy implications consistent (rather than model emissions equivalency) allows us to better assess a given policy's welfare cost across closure assumptions.[16] For equations that implement our illustrative policies, see Appendix B.7.

[14]We solve the model templates as mixed complementarity problems using the GAMS/MPSGE programming language (Rutherford, 1995, 1999).

[15]All policy types are associated with indirect impacts on the government's budget.

[16]The benefits of pollution reductions are not incorporated into the welfare effect calculated by the model. Therefore, welfare, in our case, can be interpreted as a social cost (SAB, 2017).

3.3 Budget Closure Rules

In each of our policy cases, government expenditures are held fixed through a government budget neutrality constraint. In complementarity problems, the constraint is associated with an endogenous instrument which governs our budget closure assumption and ensures that the constraint holds. Table 2 summarizes the closure rules considered in this paper.[17] Closure options assumed in this study can generally be categorized as a variant of a lump sum transfer, changes to a pre-existing market-distorting tax rate, or changes to the deficit. While the model will calculate a total budget imbalance in a counterfactual, we are left to decide how that deficit or surplus is allocated back to households. For lump sum transfers, we consider instances where the allocation is assumed to follow income shares (LSITAX) or is equivalent per-capita (LSPTAX). When redistributed through the existing tax system, we consider instances where the redistribution occurs through the labor income tax rate (LTAX) or the capital income tax rate (KTAX).[18] Finally, we allow for the budget imbalance to be added to the existing government deficit which effectively removes most of the policy cost or benefit from the welfare effect (UDS).[19] We assume that the same closure mechanism is used for policies that have both a direct and indirect effect on the government budget (CAP and CLSUB). While it is possible to model different combinations (e.g., García-Muros et al. (2022)), we choose to combine them to reduce the number of scenarios.

Most CGE models assume that budget imbalances are reconciled in the model time step that they occur (e.g., contemporaneously) (Marten et al., 2024; Goulder et al., 2016). Another dimension of the problem that we consider in this paper is the timing of when the budget imbalance is resolved. We compare the contemporaneous case with scenarios that explicitly model budget imbalances that are financed through debt which is paid off in later time periods. We only model the debt closure for the clean subsidy policy case which produces a direct fiscal cost. The direct balancing is covered by the debt closure while any indirect balancing is covered contemporaneously under the same type of

[17] In the Ramsey model, because the BaU policy case deviates from the steady-state growth path, we ensure revenue neutrality via a proportional adjustment to benchmark transfer payments which is loaded in as a baseline parameter in counterfactual policy scenarios.

[18] The capital and labor tax rates are adjusted by the same percentage point amount across all dimensions (i.e., $(1 + \tau_K + KTAX)$ or $(1 - \tau_{L,h} - LTAX)$). For details, see appendix B equations B.2.1 and B.2.5 for KTAX and LTAX respectively.

[19] Because we value the government deficit using the price of foreign exchange in the model, the only pathway through which this closure rule can affect model welfare is through changes in the foreign exchange price.

instrument. The debt closure requires assumptions about the timing of repayment, interest, source of debt principal (domestic vs. foreign), and source of funds to repay the debt (i.e., LSITAX, LSPTAX, LTAX, or KTAX). In our central case, we assume that debt is amortized over a 10-year lifetime with equal parts principal and interest paid annually at 4% interest (consistent with our steady-state), under the LSITAX closure.[20] For equations that characterize our alternative government budget closures, see Appendix B.6.

4 Results

To ease exposition, we segment the scenarios and results into two categories based on contemporaneous (non-debt) closures and those related to debt. For the contemporaneous closure results, we assume each policy is implemented in the first model year (2017) and continues into perpetuity. For the debt-financed closures, we consider both policies that exist into perpetuity as well as those that end in 2030. The contemporaneous closure results are discussed in Section 4.1 and the debt closure results are discussed in Section 4.2. Summaries of the contemporaneous and debt scenarios are shown in Tables 3 and 4, respectively. These tables take an inventory of the scenarios and side-cases that are run for these sections. Notably, for debt closure results in Section 4.2, we provide a comparison with contemporaneous results.

4.1 Contemporaneous Closure Results

In this section, we focus on changes to overall welfare or social costs (present value, or PV, of equivalent variation), emissions, and equity outcomes (as measured by both a change in the Gini coefficient[21] and household-specific equivalent variation) associated with alternative contemporaneous model closure

[20]We assume that the interested rate on debt related to the policy mechanism is fixed. For debt financed through foreign investors, we implicitly assume that the policy shock does not displace investments already being made from abroad. For domestically financed debt, we assume that less income is available for consumption and savings. We also consider alternatives to our central assumptions by modeling a 30 year maturity, 0% interest, and other closure rules. In reality, US debt is not amortized but repaid at maturity and yields periodic coupons for interest. Alternative structures could be modeled, but it is ultimately a question of timing which we can test with sensitivities around maturity length. As we will show, this matters more for models with limited foresight than those with perfect foresight and when distortionary taxes are used to repay debt in perfect foresight models.

[21]The Gini coefficient is an indicator of income equality that increases when equity decreases (more regressive) and decreases when equity increases (more progressive). It is computed using a Lorenz curve which relates all households to their income position relative to others. We slightly modify the Lorenz curve by substituting household income with household full consumption (which includes leisure time), the same metric underlying our equivalent variation calculation.

assumptions across the dimensions of our scenario matrix.[22] Figure 1 reports counterfactual impacts as changes relative to a business-as-usual (BaU) baseline for each model template (x-axis), policy instrument (columns), and closure assumption (rows). Equivalent variation is reported as a percentage of baseline full consumption.

Several things are worth noting in Figure 1. First, by targeting an equivalent policy value (in absolute value), each policy type yields differing total emissions impacts. For instance, the emissions impact of raising USD 50 billion a year from an emissions tax (CAP, adjusted for growth in the dynamic models) is substantially higher than emissions reductions from spending the same value on clean energy subsidies. However, the contemporaneous closure assumption yields virtually no difference in emissions impacts within a policy type and model template (with potential exception to capital income tax recycling in the Ramsey model).

Because each policy has differing emissions implications, the relevant comparisons for welfare changes are within the policy type and model template. For the CAP scenario, the closure can significantly affect the welfare outcomes of the policy. When carbon tax revenues are not recycled or put to any productive use by the government (UDS), the welfare costs are nearly doubled. Furthermore, in the foresighted Ramsey model, the KTAX closure is the most cost-effective while the lump sum transfer closures (LSITAX, LSPTAX) are relatively costlier which is a similar finding to existing literature. For the CES policy which only produces an indirect effect on the government's budget, the closure rule has minimal impacts on overall welfare costs. This is particularly true for lump sum transfers. Finally, for CLSUB, the closure can also significantly affect overall welfare implications. When the cost to the fiscal budget is not accounted for, welfare changes are positive because households experience subsidized prices for electricity without being responsible for funding the subsidy. Conversely, when fiscal costs are accounted for, the welfare impacts are negative. Opposite of the carbon tax case in the Ramsey model, the largest welfare impact occurs in the KTAX case because capital taxes are relatively more distortionary and the capital income tax would need to increase to pay for the subsidy.[23]

[22] Note, the various modeling heterogeneities that we consider may elicit alternative disaggregate model outcomes (e.g., sectoral output). However, to limit the scope of the analysis, we consider aggregate metrics that are often focal points of a benefit-cost analysis.

[23] The KTAX closure is not as sensitive in the static model or recursive dynamic models because capital is relatively inelastic. We report the time path of welfare changes in the dynamic model templates in Figure 2. In the recursive dynamic case, labor is the relatively more elastic factor of production (labor-leisure choice). For the CAP scenario, recycling carbon tax revenues through the labor income tax rate produces a relatively more cost-effective welfare outcome. Conversely, the Ramsey model endogenizes savings and capital formation differently through the ability to smooth consumption over

While this study is focused on government budget closures, we find interactions with capital market assumptions to generally be an important aspect of the analysis, especially when capital income taxes are central to the policy design and modeled using a Ramsey framework. For example, in the case of the Ramsey model with clean subsidy and capital income tax recycling (CLSUB + KTAX), emissions deviate slightly from the other assumptions. Welfare is also more sensitive in the (CAP + KTAX) and (CLSUB + KTAX) cases. The Ramsey model outcomes suggest that a shift in the capital income tax rate can yield heterogeneous sectoral outcomes affecting emissions and can induce larger changes to welfare due to increases or decreases in aggregate investment and consumption through the reallocation of savings.

Figure 1 also reports aggregate changes in equity as measured by changes to the Gini coefficient. The closure rule can effect the distributional outcomes of a policy scenario in relatively stable ways across model types. For instance, in the CAP scenario, lump sum transfers recycled on the basis of income versus per capita can flip the sign on the change to the Gini coefficient (where a reduction generally indicates progressivity). This is also true in the CES scenario where the per-capita lump sum allocation is less regressive. Conversely, for CLSUB, a per-capita lump sum allocation is most regressive because lower income households fund a larger proportion of the subsidy than they would have if based on income. Notably, the clean subsidies still appear regressive under the UDS closure, which is not necessarily expected. While the subsidies lower the cost of electricity to consumers, they also cause a large positive shock to the economy and induce a shift towards capital-intensive technologies. This positive shock causes non-energy commodity prices to rise which negatively affect household budgets. The combined effect of income shifting more towards capital returns and rising non-energy prices induces a regressive effect. Under the CLSUB, KTAX is the most progressive closure. It is progressive for the static and recursive templates and slightly regressive under the Ramsey template.[24]

We also report distributional impacts as changes in household specific equivalent variation in Figure

time by having perfect foresight of future changes in the economy. Using carbon tax revenues to reduce the capital income tax increases near-term investment and reduces near-term consumption producing negative welfare in earlier years but positive welfare effects in later model years. The opposite effects are observed in the clean energy subsidy case, where raising the capital income tax to fund the subsidies reduces aggregate near-term investment and increases consumption. In the static and recursive models, one could force similar cost-effectiveness outcomes by making the capital supply perfectly elastic.

[24] Relative to Brown et al. (2023), our study greatly simplifies the electricity sector, yet we capture essential behavior and find ordinally similar cost-effectiveness and distributional rankings for the same Recursive-CLSUB-KTAX combination that they used.

3. The lowest income and highest income groups are generally subject to larger relative swings in welfare impacts. Lower income groups tend to experience this partly because a dollar of extra income has a larger percentage impact and their income endowments are less diversified with most income from labor and government transfer programs. Higher income groups have a more diversified portfolio mainly through the addition of capital income. Most policy, model template, and closure rule combinations yield regressive outcomes for our scenarios. However, we also note that lump sum transfers can be allocated in an infinite number of ways in the model. We assess the potential welfare consequences of endogenizing the lump sum allocation to produce distributionally neutral welfare outcomes across households. The endogenous constraint is defined by forcing the Gini coefficient to the benchmark level, resulting in the percent change in equivalent variation to be the same across households.[25] Figure 4 reports equivalent variation changes by household (and in aggregate) for both the static and recursive dynamic model (see LSGINI for the neutral closure).[26] We find that a distributionally neutral lump sum government budget closure is feasible for the range of policies considered in this paper and comes at virtually no cost (and potentially some cost savings).

4.2 Debt-financed Closure Results

We move to instances where the policy cost is paid off over time for the clean energy subsidies which produces a direct policy cost on the fiscal budget. In a contemporaneous closure for the policy discussed in the previous section, the implicit assumption is that the policy is funded immediately by households by ultimately reducing investment and consumption that would have happened absent the policy through different channels dependent on the assumed closure rule. The different model templates handled this household decision in sensitivity (e.g., constant marginal propensity to save, endogenous savings). In this section, we consider an extension to the contemporaneous closure where we incorporate an exogenous schedule of debt purchases and repayments to finance the clean energy subsidies. We assume that the government funds the subsidies by selling debt sufficient for covering the fiscal burden of the policy. The government then returns the principal to the debtor (plus

[25]For another example of this type of lump sum closure, see Grainger et al. (2019). Our method could target any Gini coefficient.

[26]Note that this problem is more complicated in an intertemporal framework. We restrict ourselves to the static and recursive dynamic models for simplicity because the distributional outcomes for the LSITAX and LSPTAX cases across model templates are virtually identical.

interest) over the length of the loan by raising additional revenues from domestic households under a contemporaneous closure rule. Because debt can be purchased from abroad, we explore instances when the government borrows the direct policy cost from either foreign or domestic investors. These set of simulations are simplified by assuming that the purchase of policy induced government debt does not affect economy-wide interest rates for other endogenous investments in the model. First, we discuss debt cases assuming a LSITAX closure, 10 year loan maturity, and 0-8% debt interest rates. We then explore sensitivities to loan maturity (30 years) and budget closure variable (LSPTAX, LTAX, KTAX).

Figure 5 shows a decomposition of the debt accounting for two separately modeled situations: (i) where the policy terminates in 2030 but the time horizon continues through 2100 (left), or (ii) where the policy is active through the full 2100 time horizon and carries a balance into the terminal period which is never repaid (right).[27] The top row of Figure 5 shows the frozen household savings not available for use elsewhere in the economy, corresponding to the policy's fiscal cost path (starting at USD 50 billion in 2017 and growing at the baseline growth rate of 2%).[28] This fiscal policy cost coincides with the amount of debt principal that needs to be raised by the government to disburse the subsidy, which must come from either domestic or foreign income. The middle row of Figure 5 contains the amortization repayment schedule associated with the policy's fiscal cost in the top row. This shows the timing and amount that the government must repay to the debtor which includes both principal and interest. The amortization repayment is covered by raising revenue via the balancing closure variable. The net effect on foreign or domestic income is reported on the bottom row (the sum of the first and second rows).

Figures 6 and 7 report the time path of the percent change in welfare from the BaU by the assumed interest rate (attached to exogenous debt) across model template (rows) and closure assumption (columns). The figures compare instances when debt associated with policy costs are purchased from foreign ("Debt - Foreign") or domestic ("Debt-Domestic") relative to the no debt contemporaneous closures from the previous section (here, LSITAX). When debt is purchased by domestic households, we assume that a portion of household incomes are frozen (e.g., cannot be used to invest or consume elsewhere until repaid) in proportion to capital income endowments. Foreign purchases of debt are

[27]To clarify, figure 5 does not show outputs from the model, but exogenous inputs to the model describing the closure.
[28]Note the scales for both the horizontal and vertical axes are free in Figure 5.

tied to the price of foreign exchange (PFX) and it's associated market clearance condition.

In comparing the first and second columns in figures 6 and 7, the source of funding for the policy cost can significantly influence the time path of welfare impacts estimated by the model, especially in a Ramsey framework. Assuming that the loan principal is funded entirely from foreign investors in our framework is akin to procuring investment from global markets that does not displace or otherwise impact domestic capital markets. This represents a bounding case where changes to the current account are exogenous in the model with minimal adverse effects on domestic household budgets. Here, domestic households initially benefit in the first model time step due to subsidized electricity prices and changes in the returns to factors, and in subsequent periods, must fund the repayments leading to negative welfare consequences. When the policy terminates in 2030, amortized repayments increase until 2035 and decrease to zero by 2040. In the recursive model, myopic agents do not respond to future changes causing welfare changes to similarly revert toward zero in 2040 and in subsequent model time steps. Because agents cannot consumption smooth in this framework, the assumed interest rate acts as a scalar on welfare. In the Ramsey model, the ability to reallocate consumption and investment over time leads to welfare gains when borrowing is costless (i.e., 0% debt interest rate). Higher interest rates put downward pressure on overall welfare. When the policy terminates in 2100, the time path of welfare is smoother, but generally follows similar trends. Notably, in Ramsey model with 0% interest, the welfare path never falls below zero due to the debt balance that is left unpaid by the end of the model horizon (similar to the UDS closure).[29]

This contrasts to the "Debt-Domestic" case which has little deviation from the "No-Debt" case (which is identical to the CLSUB+LSITAX results in Figure 2). In the recursive model, there is a small smoothing effect that occurs due to the different repayment streams. However, in the Ramsey model, there is virtually no difference between the debt financed and contemporaneous closures for lump sum transfers. This is due to Ricardian Equivalence; since forward-looking consumers fully internalize the government's budget constraint the method of financing such government spending does not affect household consumption decisions (Barro, 1974). We can observe this mathematically in Appendix B.6

[29] Here, we assume a small open economy with exogenous international investment flows. The differences in results for the foreign investor versus domestic investor debt-financed simulations suggest that another important inter-related closure assumption in CGE models is related to foreign and domestic capital markets. Some existing work has tried to capture global capital scarcity at the nexus of foreign exchange, capital markets, and government budget closures in global multi-regional models, for instance, in Goulder et al. (1983); Goulder and Eichengreen (1988); Bovenberg and Goulder (1991); Goulder and Eichengreen (1992); Bovenberg and Goulder (1993); Islam (1999); Lemelin et al. (2013).

for Ricardian Equivalence. The assumed interest rate on government debt only affects welfare when purchased by foreign investors. When domestic households fund the clean energy subsidy, the interest rate produces minimal changes in welfare outcomes (note that 4% is the benchmark economy-wide interest rate in the model templates). Essentially, because the repayment of the loan is funded by domestic households, the repayment received for the investment largely cancels out with the funding of that payment.

Figure 8 shows the percentage change in the present value of welfare and the change in the Gini coefficient across policy termination cases (2030 and 2100), model template, and closure assumption at a 4% debt interest rate. PV welfare and Gini coefficient differences are relatively stable across the "Debt-Domestic" and "No Debt" cases across model templates. This is also true for the foreign debt case in the recursive template when the assumed debt interest rate is equivalent to the reference economy-wide interest rate. However, the Ramsey model produces large differences between the "Debt-Foreign" case and domestic cases which indicates that the intertemporal model is reallocating consumption and investment decisions to mitigate policy costs. When debt is financed domestically, households are forced to purchase debt limiting their ability to consumption smooth because they have access to relatively less income. The change in the Gini coefficient is also smaller indicating that the foreign closure is slightly less regressive than the domestic cases. In the latter, investment is relatively more scarce leading to higher rates of return for capital owners. Finally, the total PV welfare change is smaller in the Ramsey model for the 2100 policy termination relative to the recursive framework because the forward-looking agent can smooth consumption knowing the government will not have to pay its remaining balance in 2100.

Simple modeling applications have noted that Ricardian Equivalence may not hold when closing the public budget constraint through distortionary taxes (Barro, 1974). We've shown that Ricardian Equivalence holds under the LSITAX closure in a large scale Ramsey-based CGE model of the United States. We next test whether this is true for other lump sum transfers (via LSPTAX) and then explore closing the public budget constraint through distortionary capital or labor income taxes (KTAX and LTAX) focusing on the policy case ending in 2030. We also consider different loan maturities to test how alternate closures respond to the timing of repayment. Figures 9 and 10 report the welfare paths by debt assumption, closure rule, and debt maturity length for the Ramsey and recursive model templates, respectively. While the Ramsey model is the focus here, we note that the Recursive model results in Figure 10 are very similar across all cases (with only small differences).

The reported path of welfare effects from the Ramsey model in Figure 9 show that welfare differences for the LSPTAX and LSITAX closures are very similar across all debt assumptions and maturity lengths which suggests that Ricardian Equivalence should hold under alternative lump-sum distributional assumption. For closures that propagate through the tax system, we find a divergence between the contemporaneous cases and the debt-finance cases that can be seen by examining alternative loan maturities. For the LTAX case, by comparing the 10 and 30 year maturities, a longer loan maturity flattens out the welfare response since smaller incremental loan repayments in a given model time period reduce the tax interaction effects from labor supply shifts. Conversely, we find that extending the maturity of the loan from 10 to 30 years is more costly in the KTAX case early on. The initial acceleration of capital tax rate increases becomes slower with increased maturity length and the cumulative tax increase grows with maturity length due to additional interest. Regardless of maturity, the increased capital tax encourages earlier consumption and reduced investment in exchange for reduced future consumption. The slower tax rate ramp-up leaves more lead time for the consumption smoothing to take place, muting the welfare response in the first period by spreading it over multiple years. Furthermore, while the principal portion of the loan is the same total value, the total interest portion grows with maturity length which must be covered by increased taxes meaning there is a larger cumulative distortion associated with greater loan maturity. In the foreign debt cases, increased maturity length leads to greater benefits earlier followed by greater costs in later time periods when households are expected to pay for loan repayments.

The present value of welfare and changes to the Gini coefficient are reported in Figure 11. For lump sum transfer cases, there is no difference in welfare across maturities in the "Debt-Domestic" case. However, the "Debt-Foreign" case results indicate a significant relative welfare improvement for the LSITAX and LSPTAX closures which is compounded by increased maturity length. The welfare effect is even slightly positive in the "Debt-Foreign" + LSITAX case for the 30-year maturity length. The use of debt and increased maturity length under 4% interest improves welfare in the LTAX closure but worsens welfare in the KTAX closure. As discussed previously, the benefit that can be derived from increased early-horizon repayment flexibility and the extent to which consumption shifting arises from the tax distortion compete with the distortionary cost of the larger cumulative tax burden that accrues later on. This is a net positive under LTAX and net negative under KTAX. Furthermore, increased maturity length leads to improvements in the Gini coefficient in all but the KTAX closure. While KTAX is still the most progressive scenario, the use of debt increases regressivity under KTAX in the Ramsey model (evidenced by the Gini coefficient). Finally, the assumption on the source of the debt principal matters less on a relative basis when closing the public budget through the tax system where tax interaction effects begin to dominate the overall welfare estimate.

5 Discussion

In this paper, we test the importance of government budget closures in CGE models across a range of environmental policies. We use several internally consistent CGE modeling templates that differ by both the representation of time and expectations and test the importance of these assumptions in combination with alternative closure rules that propagate through lump-sum transfers, the tax system, or government debt. We also test the importance of contemporaneous closures where the model reconciles budget surpluses or deficits in the period that they occur or debt-financed closures that allows the model to pay off imbalances over time. This work is intended to be informative to policy-makers and analysts by providing perspective on how closure assumptions affect changes in overall welfare, environmental endpoints, and distributional outcomes in CGE models.

Several findings arise from our core scenarios. First, changes in emissions are not sensitive to the closure choice across our model templates but are sensitive to the policy instrument class as found in previous work. Second, we find that public budget closures matter most to changes in welfare when a policy has a direct impact on the public budget constraint (e.g., tax or subsidy). In instances where a policy only induces indirect changes through changes in economic activity (e.g., the majority of environmental regulations in the United States), the closure assumption does not produce significant differences in overall welfare, even when recycled through the tax system. However, some potential caveats apply. This result holds for the policy sizes considered in this paper (e.g., $50 billion a year). The result does not hold when budget imbalances are added to debt indefinitely. Allowing the model to add to the deficit indefinitely without expectation to pay back the policy cost can produce misleading results. Third, we also find that the closure rule can be an important determinant for distributional analysis, especially for policies that have a direct impact on the public budget constraint. In some instances, the closure assumption can directly effect the progressivity or regressivity of a policy. For instance, the lump sum per capita closure is the most regressive for subsidy policies (poorer households pay for a larger share of the policy relative to reference income) whereas it is most progressive for carbon tax scenarios (poorer households receive largest benefit relative to reference income). We also find that lump-sum instruments can be used to create distributionally equivalent policies across cap and clean subsidy cases at a small relative welfare differences.

Our debt closure results suggest that in most instances, the long-run welfare consequences of modeling the complicated budget balance can be well-approximated using conventional techniques within the period that costs occur, especially when using lump-sum transfers (Ricardian Equivalence). The efficacy of the contemporaneous closure assumption can break down in Ramsey frameworks when recycling budget imbalances through the tax system and can over (labor income tax) or under (capital income tax) approximate overall welfare impacts relative to a debt-financed closure. Further, careful consideration is also needed around the domestic versus foreign source of debt principal which can lead to significant long-run welfare differences in intertemporal models. We have generally found that it is important to consider how the debt is being procured and how the financial system can spread the savings impact across agents (e.g., domestic vs. foreign savings impacts) not only for the total present value of welfare but also for the distribution of welfare changes across time.

Of the combinations of closures modeled, the capital tax closure in the Ramsey model requires the most care. First, the capital tax is the most distortionary in our model and can lead to significant welfare discrepancies relative to other closures. Second, the use of debt exacerbates the distortion in the 4% interest rate case. Third, lengthening the loan maturity to 30 years further exacerbates the relative welfare effect to roughly double the contemporaneous (No Debt) case. Finally, this worsened welfare effect is accompanied by a small increase in regressivity. Debt repayment has an interest and principal component. While the principal component is the same total value, the interest portion grows with maturity length which must be covered by increased taxes. Because capital taxes are distortionary, any benefit to delay is outweighed by the ultimate tax increase required to cover the interest.[30]

Some additional caveats are worth mentioning. We model policies that begin in the reference year of the model. Allowing for policy lead time may have important interactions with the closure rule in intertemporal frameworks not captured here. We also assume the same closure assumption for both direct (in cases of taxes or subsidies) and indirect effects on the public budget constraint. Future research might consider additional combinations of closure assumptions where a separate closure is assumed for the direct effect of a policy relative to changes in economy-wide economic activity. Our clean technology also does not benefit from endogenous technology improvement through R&D investment, spillovers, or learning-by-doing. Finally, our debt-financed closure results consider instances where the principal is funded by either foreign or domestic sources of investment. In the former, we assume that the policy shock does not displace investments already being made from abroad. Reflecting the scarcity of foreign investment could lead to important interactions with the government budget closure rule that we are not able to capture. Future work could consider use of a global CGE model that captures global investments explicitly. A benefit of this global closure is that it can capture the scarcity effects in capital markets depending on what the rest of the world is doing; capital could be more or less available to those transitioning to clean energy with subsidies and debt.

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[30] To confirm that interest is driving this behavior, we modeled a case with a 0% interest rate, where we see the opposite directional welfare effect for a capital tax increase across the 10 to 30-year maturity dimension. See Figures 15 and 16 in Appendix C.

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Tables

Policy Instrument	Sector Coverage	Description
CAP	Electricity	Emissions cap set to produce a pre-specified revenue target. The revenue from the CAP creates a budget surplus balanced with a closure rule.
CES	Electricity	Clean energy standard set to produce a pre-specified revenue target. The CES implicitly balances direct revenues/costs via a net-subsidy to clean and net-tax on dirty but produces an indirect effect on the budget which is balanced with a closure rule.
CLSUB	Electricity	Ad-valorem subsidy to clean electricity producers set to produce a pre-specified government budgetary shortfall value that is balanced by a closure rule.

Table 1: Policy Instrument Class Descriptions

Closure Rule	Balancing Variable	Description of closure assumption
BAU	Not Applicable	Business as usual - closure isn't relevant due to benchmark calibration
UDS	Uncovered deficit/surplus	Deficit/surplus balances the budget with no intention to repay or distribute to households
KTAX	Capital income tax rate	Increase/decrease in capital income tax rate to balance budget
LTAX	Labor income tax rate	Increase/decrease in labor income tax rate to balance budget
LSITAX	Lump-sum tax/transfer	Lump-sum tax/transfer to households proportional to household income share of total income balances budget
LSPTAX	Lump-sum tax/transfer	Lump-sum tax/transfer in equal payments to each household - population-based - to balance budget
LSGINI	Lump-sum tax/transfer	Lump-sum tax/transfer that targets the BAU Gini coefficient. Only run for static model.

Table 2: Closure Descriptions

	UDS	KTAX	LTAX	LSITAX	LSPTAX	LSGINI*
CAP	X	X	X	X	X	X*
CES	X	X	X	X	X	
CLSUB	X	X	X	X	X	X*

Template: Static, Recursive, Ramsey
* Static and Recursive models only

Table 3: Contemporaneous Scenarios Summary

	UDS	KTAX	LTAX	LSITAX	LSPTAX	LSGINI
Debt-Foreign		X	X	X	X	
Debt-Domestic		X	X	X	X	
No Debt*		X	X	X	X	

Policy: CLSUB
Template: Recursive, Ramsey
Policy Termination: 2030, 2100
Interest Rate (%): 0%, 4%, 8%
Loan Maturity Length (yrs): 10, 30
* Corresponds to contemporaneous result

Table 4: Debt Scenarios Summary

6 Figures

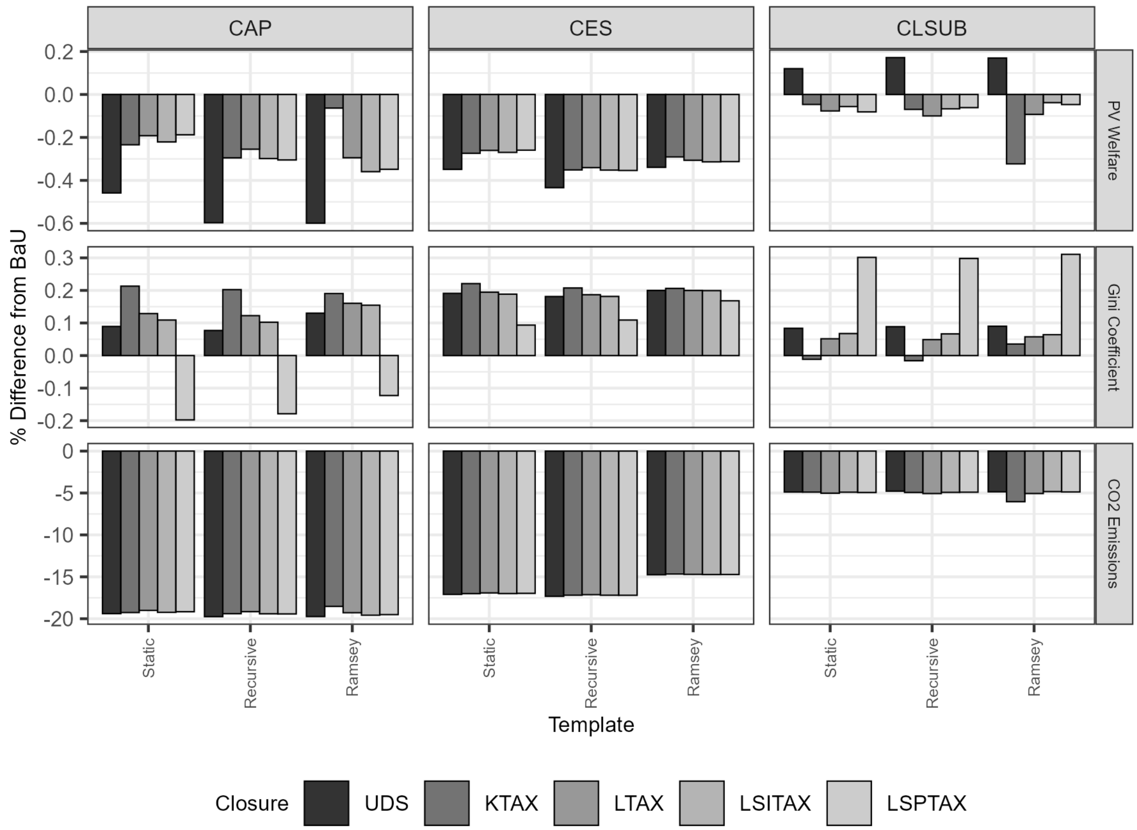

Figure 1: Welfare - Core closure scenario comparison

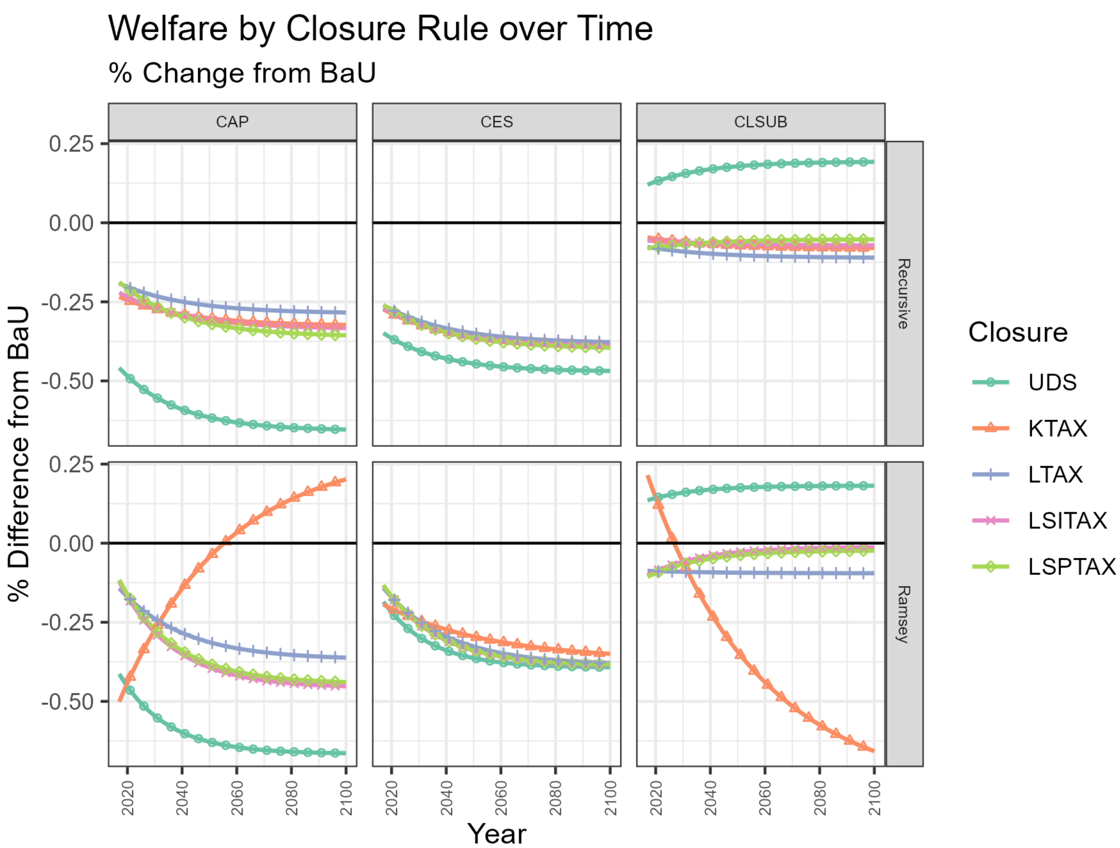

Figure 2: Welfare Path - Core closure scenario comparison

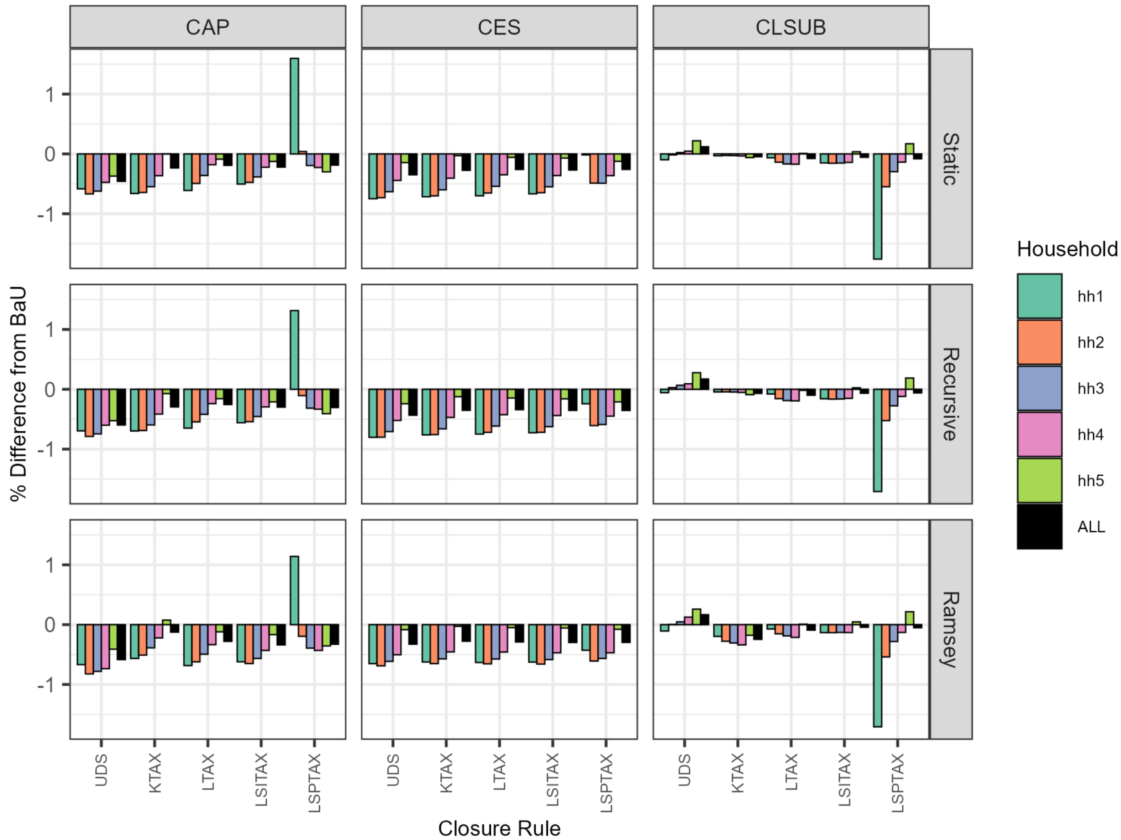

Figure 3: Household welfare by model template

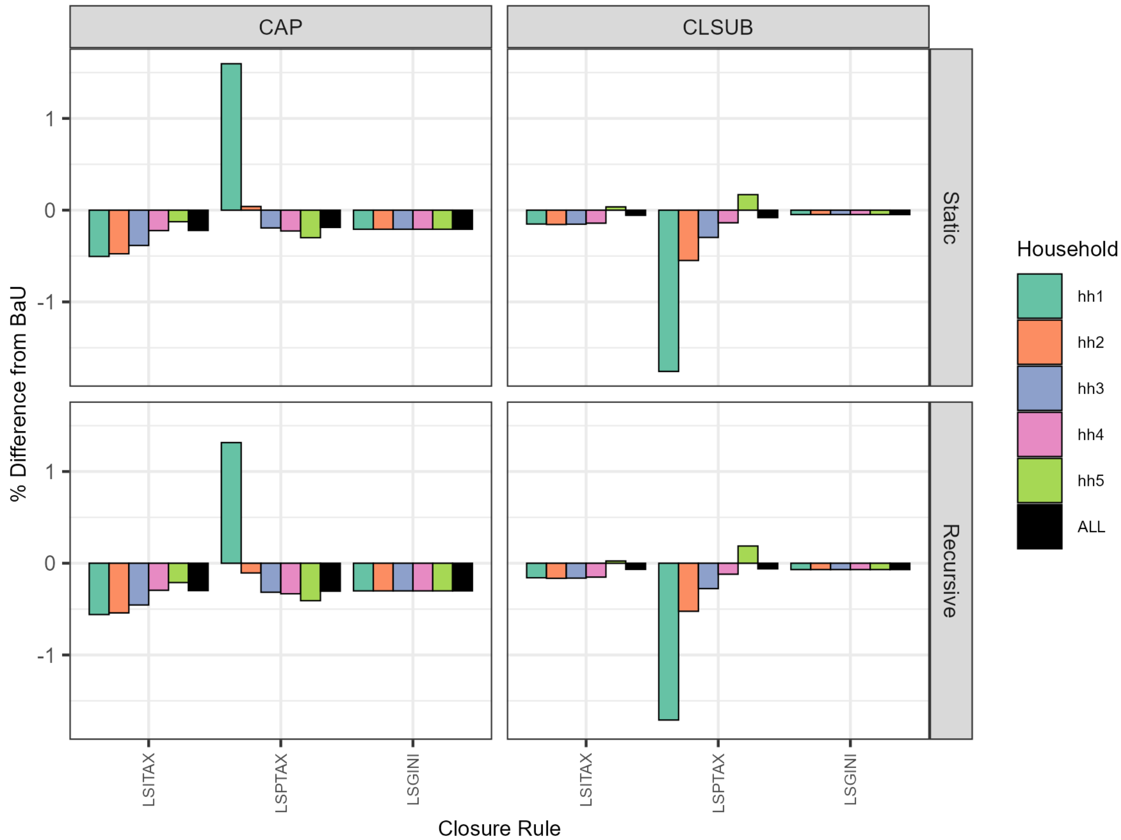

Figure 4: Comparison to distributionally neutral lump sum transfer mechanism

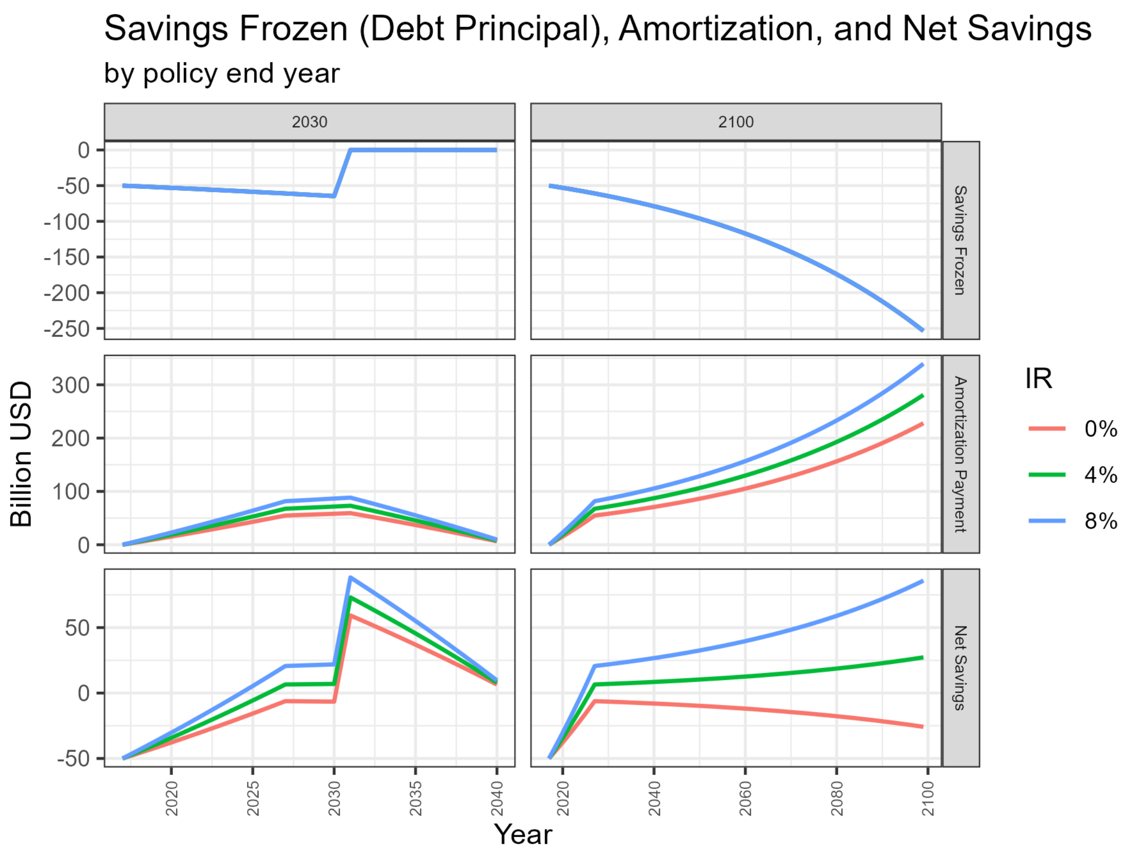

Figure 5: Net savings accounting

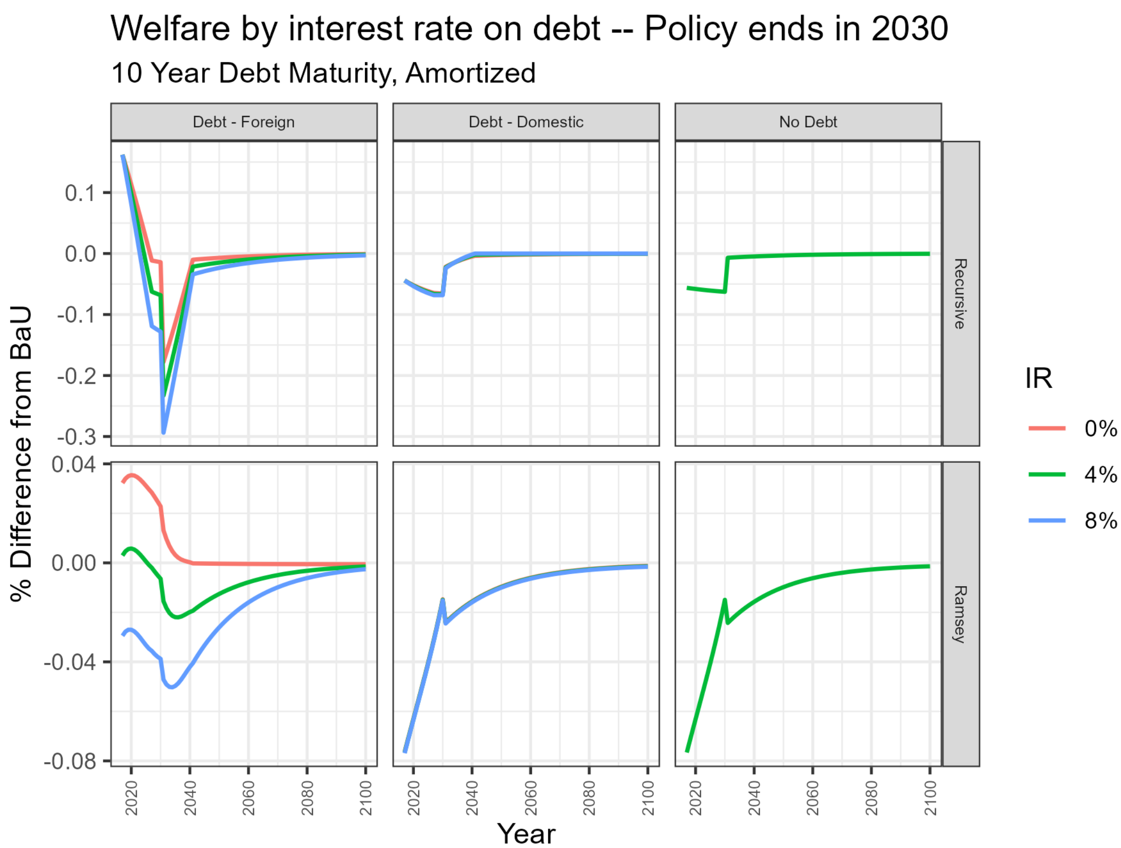

Figure 6: Debt closure - Policy ends by 2030

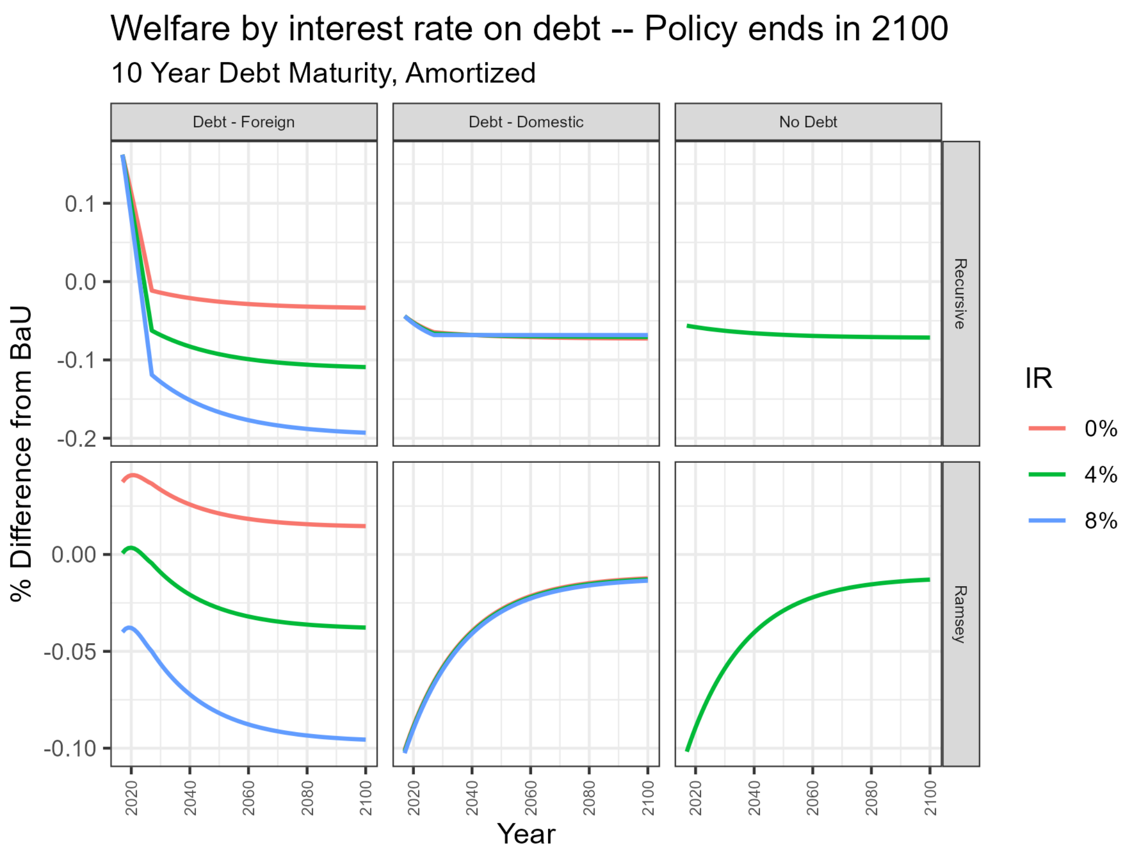

Figure 7: Debt closure - Policy ends by 2100

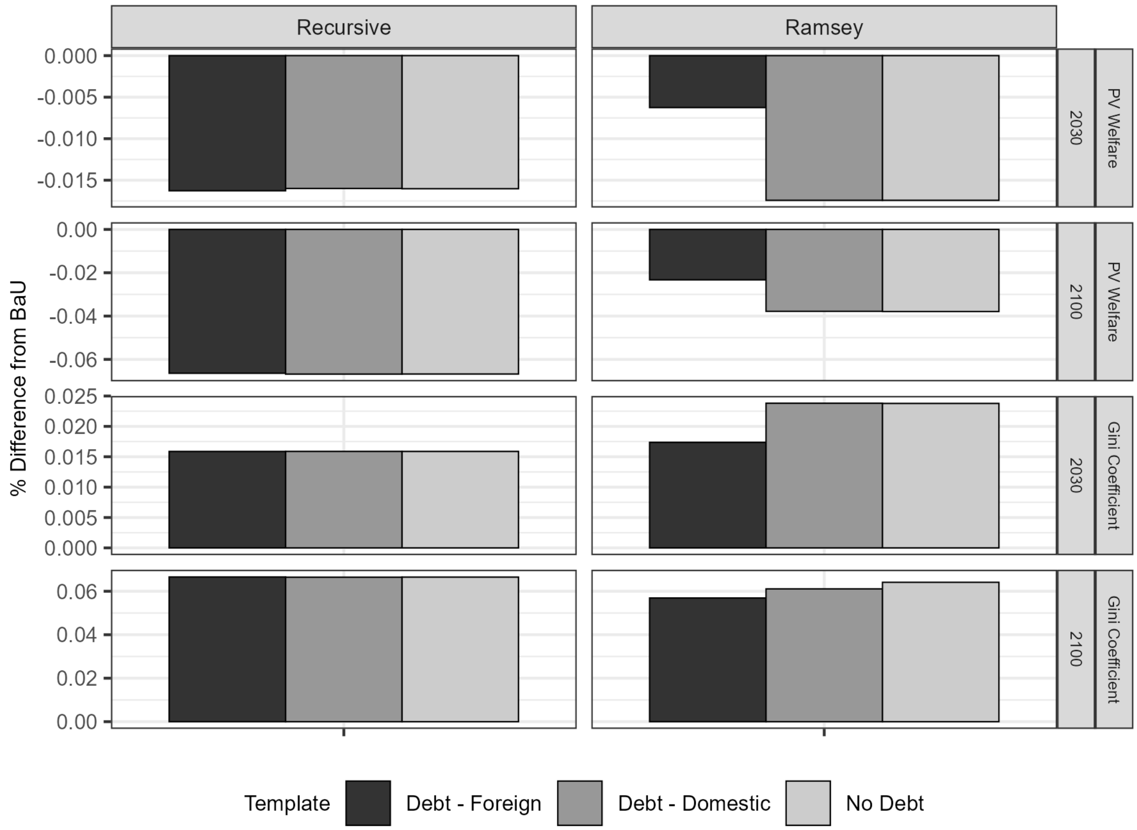

Figure 8: Debt closure total welfare effects (4% debt interest rate)

Figure 9: Welfare effects over time by debt closure - Ramsey

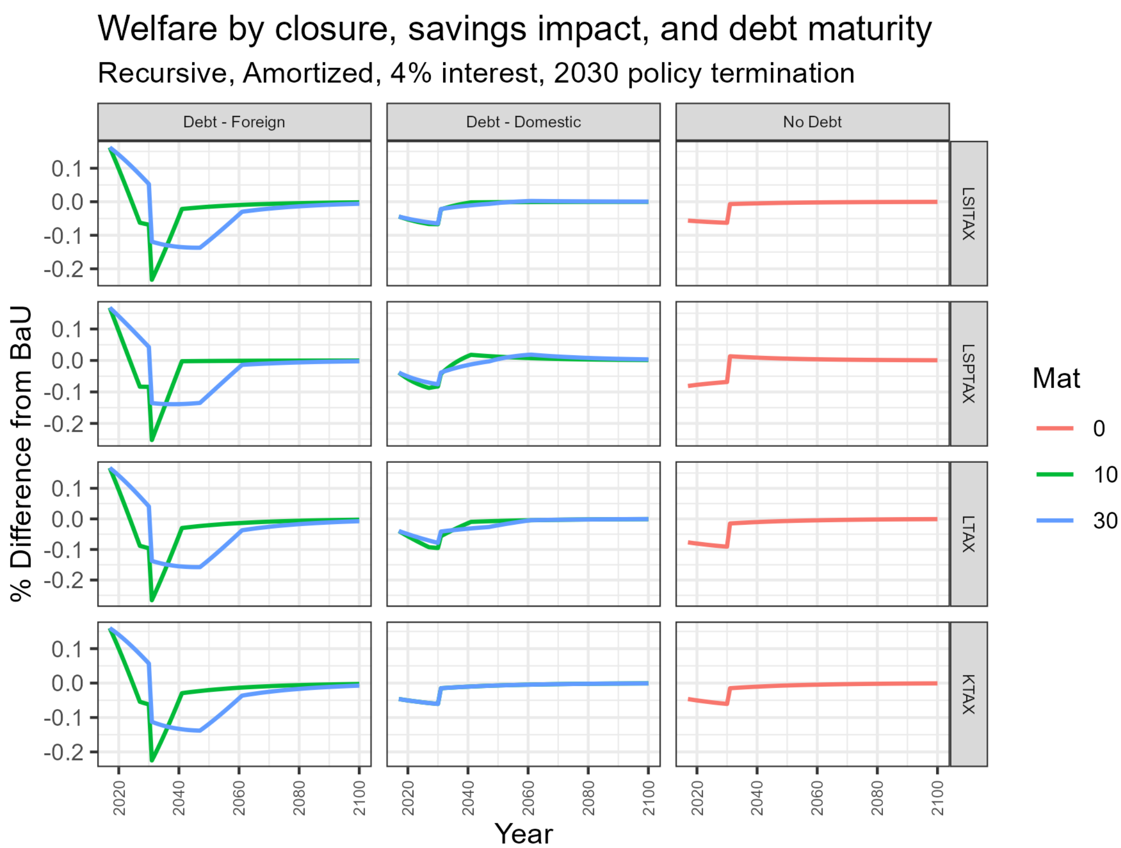

Figure 10: Welfare effects over time by debt closure - Recursive

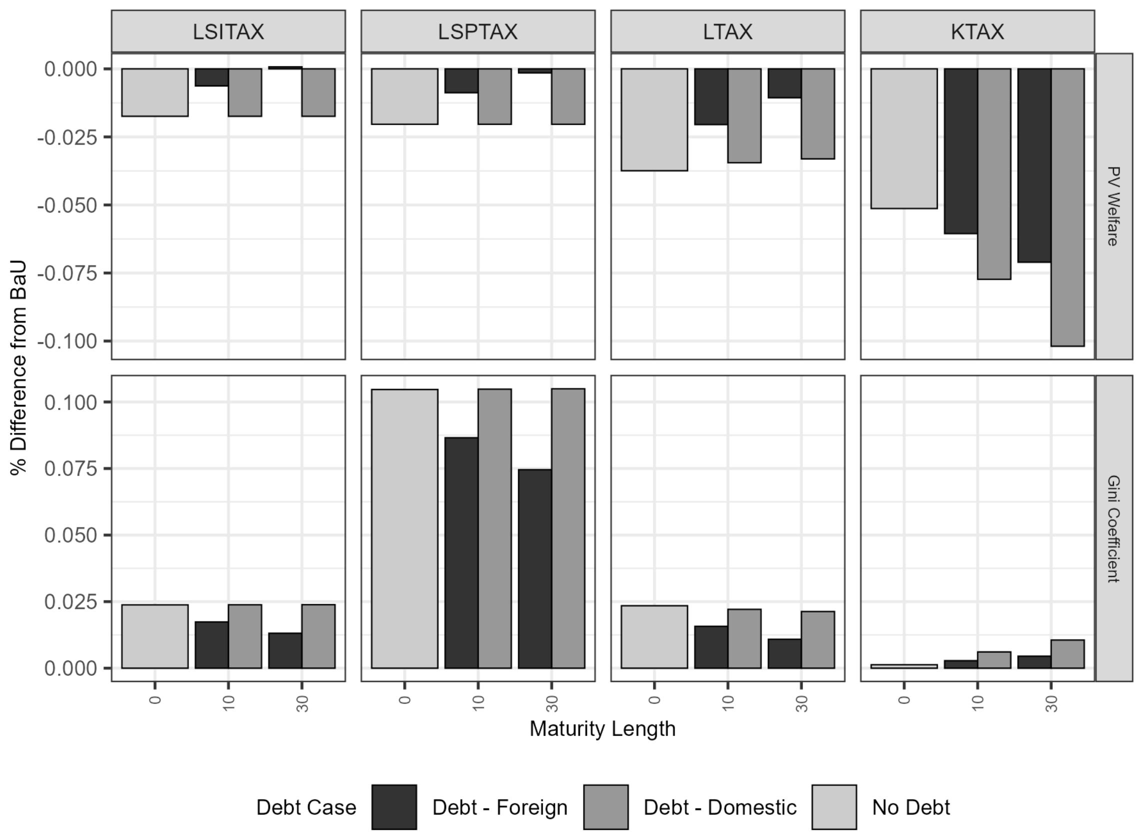

Figure 11: Debt closure total welfare effects by maturity length - 2030 termination - Ramsey (4% debt interest rate)

A Select Nesting Diagrams

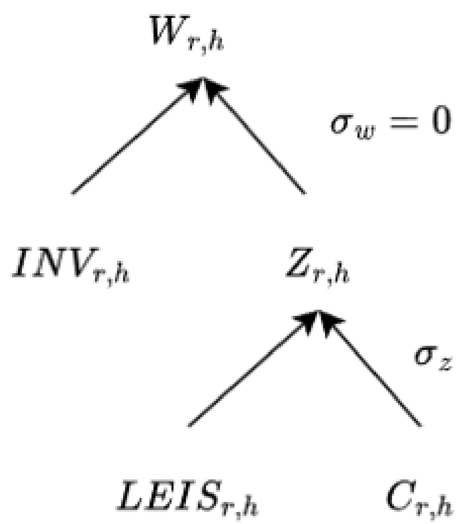

Figure 12: Household Consumption and Savings Nesting

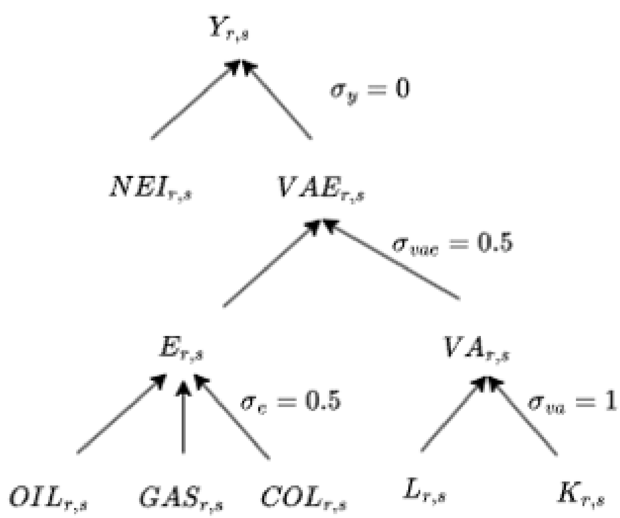

Figure 13: Non-electricity Production Nesting

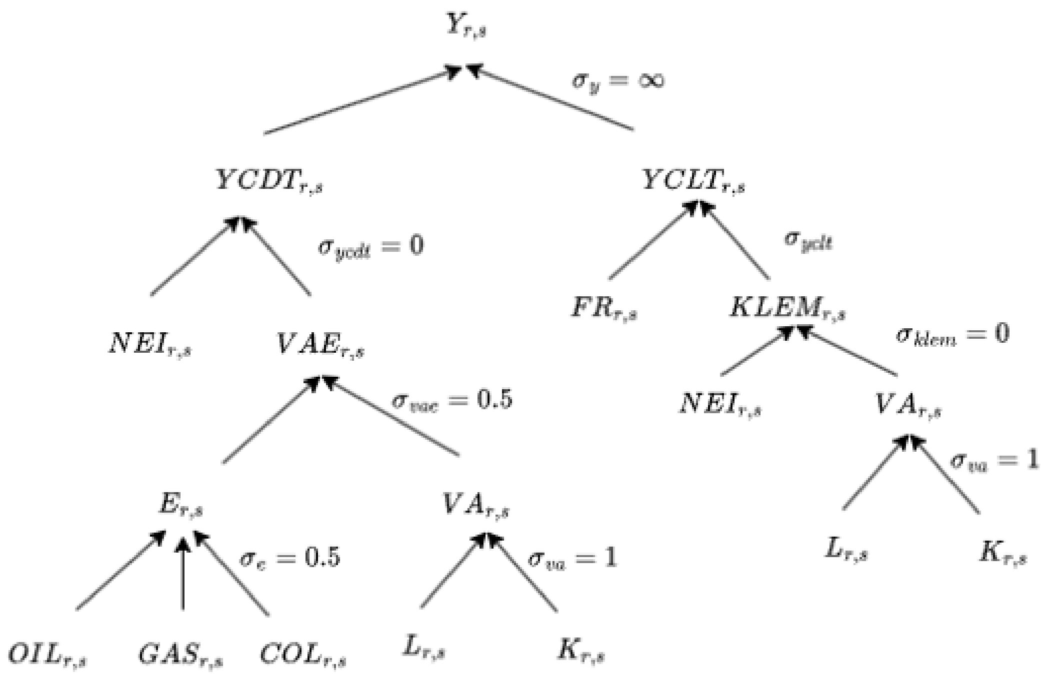

Figure 14: Electricity Production Nesting

B Algebraic model formulation

In what follows, we abstract from the precise model definition in the modeling code by not including reference tax rates to ease exposition. Variables associated with alternative government budget closures are in bold (defined in Tables 1 and 2).

B.1 Definitions

Sets and indices are listed in Table 5. Activity levels are listed in Table 6. Prices are listed in Table 7. Income is listed in Table 8. Cost shares and elasticities are listed in Table 9 and Table 10, respectively. Endowments and other parameters are listed in Table 11.

Table 5: Indices and sets

g	Index for sectors and goods. For sectors this includes an aggregate accounting index for private consumption good (C), govt (G), and investment (I)
i ($alias$ j)	Subset of g representing goods not including C, G, I.
f	Index for factors. Capital and Labor.
NE	Set of non-energy goods. Can also be used to represent aggregate index of these goods
FE	Set of final-energy goods, fuels with co2 emissions. Can also be used to represent aggregate index of these goods
XE	Set of primary fossil-fuel goods. Can also be used to represent aggregate index of these goods

Table 6: Variables - Activity Levels

Y_g	Output/production in sector g
A_i	Armington absorption composite in sector i
M_i	Import composite in sector i
X_i	Disposition of i
VA_i	Value added composite
FE_g	FE inputs composite
E_g	Energy inputs composite
VAE_g	Value-added-energy composite
$KLEM_g$	KLEM cost composite
C_h	Household consumption
Z_h	Household full consumption
INV	Investment
LS_h	Labor supply

Table 7: Variables - Price Levels

p_f^F	Price of factor f
p_i^{FE}	Price index of FE used to produce i
p_i^E	Price index of E used to produce i
p_i^{VA}	Price index of VA used to produce i
p^{co2}	Price of raw co2 emissions
p_i^A	Price index of Armington good i
p_g^{KLEM}	Price index of KLEM index.
p_i^M	Price index on imported goods
p_g^Y	Price of output
p_i^{RS}	Price of fixed natural resource factor for $i \in XE$
p^{KE}	Price of household capital endowment
p^{TAX}	Government tax revenue endowment scaling
p_h^{LS}	Price of leisure
p^{FX}	World foreign exchange price
p_i^D	Price of good i produced for domestic market

Table 8: Variables - Income Levels

RA_h^{bal}	Household income for representative household h
$GOVT^{bal}$	Government income balance
$NYSE^{bal}$	Capital market
IRS^{bal}	Tax revenue agent

Table 9: Cost shares

	General Model
$\theta^{VA}_{f,g}$	Share of value-added attributable to factor f
$\theta^{FE}_{i,g}$	Share fossil energy attributable to input $i \in FE$
$\theta^{ELE}_{i,g}$	Share of electricity attributable to input $i \in E$
$\theta^{ELE}_{i,g}$	Share of electricity attributable to input $i \in E$
$\theta^{VAE}_{VA,g}$	Share of value added in value-added-energy composite
$\theta^{KLEM}_{*,g}$	Share of non-R&D and non-resource factor output attributable to VA, E, and $i \in NE$
$\theta^{RS}_{*,g}$	Share of output in g attributable to RS
θ^{A}_{i}	Share of domestic variety input i in total imports + domestic
θ^{MD}_{m}	Margins as a share of total absorption
θ^{X}_{xs}	Share of domestic production attributable to export or for domestic
$\theta^{C}_{i,h}$	Share of good consumption in household h attributable to good i
$\theta^{Z}_{C,h}$	Share of goods consumption in full consumption for household h
θ^{INV}_{i}	Share of investment demand attributable to good i

Table 10: Elasticities

σ^{VA}	Substitution between factor inputs capital and labor in the VA composite
σ^{FE}	Substitution between final energy inputs in the FE composite
σ^{ELE}	Substitution between FE composite and electricity in E composite
σ^{VAE}	Substitution between E composite and value added VA composite
σ^{KLEM}	Substitution between the VA index, and all other inputs in the KLEM composite
σ^{RS}	Substitution between RS, and KLEM in the output block for primary-fossil resources
σ^{M}	Substitution between imports from different regions
σ^{A}	Substitution between the import aggregate (M) and the domestic input (Y)
σ^{X}	Substitution between exports for different regions (XS) in the South-North Export Composite (X)
σ^{C}	Substitution between final consumption inputs
σ^{Z}	Substitution between full consumption inputs consumption and leisure
σ^{INV}	Substitution between goods in investment

Table 11: Endowments and other parameters

$\overline{RS}_g$	Fixed natural resource factor endowment
$\overline{G}$	Benchmark public good demand
$\overline{I}$	Benchmark investment demand
$\overline{CO2}$	CO_2 emissions cap
$a_{i,g}$	CO_2 emissions coefficient for fuel i in sector g and region r
$\overline{TIME}$	Time endowment
$\overline{KE}_h$	Household capital endowment
$\overline{gdef}$	Government fixed benchmark deficit
$\overline{taxrev}$	Benchmark tax revenue
$\overline{rawtar}$	Raw policy target value
$\overline{tp}_h$	Benchmark transfer payments
$\overline{govt}_g$	Benchmark government spending
$\overline{inc\_shr}_h$	Household income share of total
$\overline{pop\_shr}_h$	Household population share of total
$\overline{yh}_h$	Fixed household production

B.2 Zero Profit Conditions

B.2.1 Production of goods

Unit profit function for the value-added index:

$$\Pi_i^{VA} = p_i^{VA} - \left[\theta_{K,i}^{VA} p_K^F (1 + \tau_K + \mathbf{KTAX})^{1-\sigma^{VA}} + (1 - \theta_{K,i}^{VA}) p_L^{F\,1-\sigma^{VA}}\right]^{\frac{1}{1-\sigma^{VA}}} \leq 0 \tag{1}$$

Unit profit function for the final energy index:

$$\Pi_g^{FE} = p_g^{FE} - \left[\sum_{i \in fe} \theta_{i,g}^{FE} \; (p_i^A + p^{co2} a_{i,g}^{co2})^{1-\sigma^{FE}}\right]^{\frac{1}{1-\sigma^{FE}}} \leq 0 \tag{2}$$

Unit profit function for the energy composite index:

$$\Pi_g^E = p_g^E - \left[(1 - \theta_g^{ELE}) p_g^{FE^{1-\sigma^{ELE}}} + \theta_g^{ELE} p_{ele}^{A^{1-\sigma^{ELE}}}\right]^{\frac{1}{1-\sigma^{ELE}}} \leq 0 \tag{3}$$

Unit profit function for the VA-energy composite index:

$$\begin{aligned} &\Pi_i^{VAE} = p_i^{VAE} - \\ &\left[\theta_{VA,i}^{VAE} p_i^{VA^{1-\sigma^{VAE}}} + (1 - \theta_{VA,i}^{VAE}) p_i^{E^{1-\sigma^{VAE}}}\right]^{\frac{1}{1-\sigma^{VAE}}} \\ &\leq 0 \end{aligned} \tag{4}$$

Unit profit function for all goods shows substitution between VA, FE, and all other goods:

$$\begin{aligned} &\Pi_i^{KLEM} = p_i^{KLEM} - \\ &\left[\theta_{VAE,i}^{KLEM} p_i^{VAE} + \sum_{i \in NE} \theta_{i,i}^{KLEM} p_i^A\right] \\ &\leq 0 \end{aligned} \tag{5}$$

Unit profit function for non-primary-fuel or non-clean electricity (dirty): $i \notin xe|ele$

$$\Pi_i^Y = p_i^Y (1 - \tau_i) - p_i^{KLEM} \leq 0 \tag{6}$$

Unit profit function for primary-fuels: $g \in xe$

$$\begin{aligned} &\Pi_g^Y = p_g^Y (1 - \tau_g) - \\ &\left[\theta_{RS,g}^{RS} p_g^{RS^{1-\sigma^{RS}}} + (1 - \theta_{RS,g}^{RS}) p_g^{KLEM^{1-\sigma^{RS}}}\right]^{\frac{1}{1-\sigma^{RS}}} \\ &\leq 0 \end{aligned} \tag{7}$$

Unit profit function for clean electricity (clt): $g \in ele$

$$\Pi_g^Y = p_g^Y(1 - \tau_g^Y + \textbf{CLSUB}) - \\ \left[\theta_{RS,g}^{RS} {p_g^{RS}}^{1-\sigma^{RS}} + (1 - \theta_{RS,g}^{RS}) {p_g^{KLEM}}^{1-\sigma^{RS}}\right]^{\frac{1}{1-\sigma^{RS}}} \\ \leq 0 \tag{8}$$

B.2.2 Disposition

Unit profit for Disposition for $xs \in [FX, D]$

$$\Pi_i^X = \left[\sum_{xs} \theta_{xs,i}^X {p_i^{xs}}^{1+\sigma^X}\right]^{\frac{1}{1+\sigma^X}} \\ + p_i^Y \\ \leq 0 \tag{9}$$

B.2.3 Absorption

Unit profit function for Armington index:

$$\Pi_i^A = p_i^A - \\ \sum_m \theta_m^{MD} p_m^{MD} + \\ (1 - \sum_m \theta_m^{MD})\left[(1 - \theta_i^A) {p^{FX}}^{1-\sigma^A} + \theta_i^A {p_i^Y}^{1-\sigma^A}\right]^{\frac{1}{1-\sigma^A}} \\ \leq 0 \tag{10}$$

B.2.4 Consumption, Full Consumption, Investment

Unit profit for household goods consumption:

$$\Pi_h^C = p_h^C - \\ \left[\sum_{i \in NE} \theta_{i,h}^C {p_i^A}^{1-\sigma^C} + \theta_{E,h}^C {p_C^E}^{1-\sigma^C}\right]^{\frac{1}{1-\sigma^C}} \\ \leq 0 \tag{11}$$

Unit profit for household full consumption:

$$\Pi_h^Z = p_h^Z - \\ \left[\theta_{C,h}^Z {p_h^C}^{1-\sigma^Z} + (1 - \theta_{C,h}^Z) {p_h^{LS}}^{1-\sigma^Z}\right]^{\frac{1}{1-\sigma^Z}} \\ \leq 0 \tag{12}$$

Unit profit for investment:

$$\Pi^{INV} = p^{INV} - \left[\sum_i \theta_i^{INV} p_i^{A^{1-\sigma^{INV}}}\right]^{\frac{1}{1-\sigma^{INV}}} \leq 0 \tag{13}$$

Unit profit for government:

$$\Pi^{GOVT} = p^{GOVT} - \left[\sum_i \theta_i^{GOVT} p_i^{A}\right] \leq 0 \tag{14}$$

B.2.5 Labor supply

Unit profit for labor supply:

$$\Pi_h^{LS} = p_h^L(1 - \tau_{L,h} - \mathbf{LTAX}) - p_h^{LS} \leq 0 \tag{15}$$

B.3 Income Balance Conditions

Income balance for the households:

$$RA_h^{bal} = p^{FX} * \overline{tp}_h + p_h^{LS} * \overline{TIME}_h + p^{KE} * \overline{KE}_h \tag{16}$$

Income balance for the capital market (NYSE):

$$NYSE^{bal} = \sum_i p_i^Y * \overline{yh}_i + p_K^{VA} * \overline{F}_K + \sum_g p_g^{RS} * \overline{RS}_g \tag{17}$$

Income balance for the Govt and IRS (GOVT and IRS):

$$
\begin{aligned}
IRS^{bal} = & \\
(capital\ taxes) \quad & \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial p_{K,i}^{VA}} p_{K,i}^{VA} \tau_i^K \\
(labor\ taxes) \quad & + \sum_h LS_h p_{L,h}^{VA} \tau_{L,h} \\
(Commodity\ taxes) \quad & + \sum_i A_i p_i^A \tau_i^A \\
(Import\ taxes) \quad & + \sum_i A_i \frac{\partial \Pi_i^A}{\partial p^{FX}} p^{FX} \tau_i^M \\
(Output\ taxes) \quad & + \sum_i Y_i p_i^Y \tau_i^Y
\end{aligned}
\tag{18}
$$

$$
\begin{aligned}
GOVT^{bal} = & \\
& \sum_h p^{FX} * \overline{gdef} \\
& - \sum_h p^{FX} * \overline{tp}_h \\
& + p^{TAX} * \overline{taxrev}
\end{aligned}
\tag{19}
$$

B.4 Market Clearance Conditions

B.4.1 Factor market clearance

Market clearance for p^{KE}:

$$\sum_h p^{KE} * \overline{KE}_h \geq NYSE^{bal} \quad \perp p^{KE} \tag{20}$$

Market clearance for p^{TAX}:

$$p^{TAX} * \overline{taxrev} \geq IRS^{bal} \quad \perp p^{TAX} \tag{21}$$

Market clearance for factors of production labor associated with the opportunity cost of working:

$$\overline{F}_{TIME,h} \geq Z_h \frac{\partial \Pi_h^Z}{\partial p_h^{LS}} + LS_h \frac{\partial \Pi_h^{LS}}{\partial p_h^{LS}} \quad \perp p_h^{LS} \tag{22}$$

Market clearance condition for labor associated with wage:

$$\sum_h LS_h \geq \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial p_{L,i}^F} \quad \perp p_{L,i}^F \tag{23}$$

Market clearance for capital:

$$\overline{F}_K \geq \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial p_{K,i}^F} \quad \perp p_{K,i}^F \tag{24}$$

Market clearance for the fixed natural resource factors ($g \in [xe, ele]$):

$$\overline{RS}_g \geq Y_g \frac{\partial \Pi^Y_g}{\partial p^{RS}_g} \quad \perp p^{RS}_g \tag{25}$$

B.4.2 Goods market clearance

p^A_j Armington goods market clearance:

$$A_j \geq \sum_i Y_i \frac{\partial \Pi^Y_i}{\partial p^A_i} + \sum_{i,h} C_h \frac{\partial \Pi^C_h}{\partial p^A_i} + \sum_i INV \frac{\partial \Pi^{INV}}{\partial p^A_i} + \sum_i GOVT \frac{\partial \Pi^{GOVT}}{\partial p^A_i} \quad \perp p^A_j \tag{26}$$

p^Y market clearance:

$$Y_i \geq X_i \frac{\partial \Pi^X_i}{\partial p^Y_i} \quad \perp p^Y_i \tag{27}$$

p^D market clearance:

$$X_i \frac{\partial \Pi^X_i}{\partial p^D_i} \geq A_i \frac{\partial \Pi^A_i}{\partial p^D_i} \quad \perp p^D_i \tag{28}$$

p^{FX} market clearance:

$$\sum_i X_i \frac{\partial \Pi^X_i}{\partial p^{FX}} \geq \sum_i A_i \frac{\partial \Pi^A_i}{\partial p^{FX}} \quad \perp p^{FX} \tag{29}$$

B.5 Ramsey Dynamic Extensions

B.5.1 Ramsey capital and investment

Unit profit for capital motion:

$$\Pi^K_t = (p^K_{t+1}(1-\delta) + p^{VA}_{K,t}) - p^K_t \leq 0 \tag{30}$$

Unit profit for investment motion:

$$\Pi^I_t = p^K_{t+1} - p^{INV}_t \leq 0 \tag{31}$$

Unit profit for investment:

$$\Pi^{INV}_t = p^{INV}_t - \left[\sum_i \theta^{INV}_{i,t} p^{A^{1-\sigma^{INV}}}_{i,t}\right]^{\frac{1}{1-\sigma^{INV}}} \leq 0 \tag{32}$$

B.6 Closures

B.6.1 TRANS - Proportional adjustment to benchmark transfer payments

Revenue neutrality constraint:

$$GOVT^{bal} = \sum_i p^A_i \overline{govt}_i \quad \perp TRANS \tag{33}$$

Income balance for the household:

$$
\begin{aligned}
RA_h^{bal} = \\
& p^{FX} * \overline{tp}_h * \mathbf{TRANS} \\
& + p_h^{LS} * \overline{TIME}_h \\
& + p^{KE} * \overline{KE}_h
\end{aligned}
\tag{34}
$$

Income balance for the government:

$$
\begin{aligned}
GOVT^{bal} = \\
& \sum_h p^{FX} * \overline{gdef} \\
& - \sum_h p^{FX} * \overline{tp}_h * \mathbf{TRANS} \\
& + p^{TAX} * \overline{taxrev}
\end{aligned}
\tag{35}
$$

B.6.2 UDS - Free deficit closure

Revenue neutrality constraint:

$$GOVT^{bal} = \sum_i p_i^A \overline{govt}_i \quad \perp UDS \tag{36}$$

Income balance for the government:

$$
\begin{aligned}
GOVT^{bal} = \\
& \sum_h p^{FX} * \overline{gdef} \\
& - \sum_h p^{FX} * \overline{tp}_h \\
& + p^{TAX} * \overline{taxrev} \\
& - p^{FX} * \mathbf{UDS}
\end{aligned}
\tag{37}
$$

B.6.3 LSTAX - Lump-sum tax instrument adjustment (LSITAX, LSPTAX)

Revenue neutrality constraint:

$$GOVT^{bal} = \sum_i p_i^A \overline{govt}_i \quad \perp LSTAX \tag{38}$$

Distribute lump sum payment either via LSITAX or LSPTAX:

$$LSITAX_h = LSTAX * \overline{inc_s hr}_h \quad \perp LSITAX_h \tag{39}$$

$$LSPTAX_h = LSTAX * \overline{pop_s hr}_h \quad \perp LSITAX_h \tag{40}$$

Income balance for government:

$$\begin{aligned} GOVT^{bal} = & \\ & \sum_h p^{FX} * \overline{gdef} \\ & - \sum_h p^{FX} * \overline{tp}_h \\ & + p^{TAX} * \overline{taxrev} \\ & + p^{FX} * \mathbf{LSTAX} \end{aligned} \tag{41}$$

Income balance for household:

$$\begin{aligned} RA_h^{bal} = & \\ & p^{FX} * \overline{tp}_h \\ & + p_h^{LS} * \overline{TIME}_h \\ & + p^{KE} * \overline{KE}_h \\ & - p^{FX} * \mathbf{LSITAX}_h \\ & OR: \\ & - p^{FX} * \mathbf{LSPTAX}_h \end{aligned} \tag{42}$$

B.6.4 LTAX - Labor income tax adjustment

Revenue neutrality constraint:

$$GOVT^{bal} = \sum_i p_i^A \overline{govt}_i \quad \perp LTAX \tag{43}$$

Income balance for the IRS:

$$\begin{aligned} IRS^{bal} = & \\ (capital\ taxes) \quad & \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial p_{K,i}^{VA}} p_{K,i}^{VA} \tau_K \\ (labor\ taxes) \quad & + \sum_h LS_h p_{L,h}^{VA} (\tau_{L,h} + \mathbf{LTAX}) \\ (Commodity\ taxes) \quad & + \sum_i A_i p_i^A \tau_A \\ (Import\ taxes) \quad & + \sum_i A_i \frac{\partial \Pi_i^A}{\partial p^{FX}} p^{FX} \tau_M \\ (Output\ taxes) \quad & + \sum_i Y_i p_i^Y \tau_Y \end{aligned} \tag{44}$$

B.6.5 KTAX - Capital income tax adjustment

Revenue neutrality constraint:

$$GOVT^{bal} = \sum_i p_i^A \overline{govt}_i \quad \perp KTAX \tag{45}$$

Income balance for the IRS:

$$\begin{aligned}
& IRS^{bal} = \\
(capital\ taxes) \quad & \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial p_{K,i}^{VA}} p_{K,i}^{VA} (\tau_K + \mathbf{KTAX}) \\
(labor\ taxes) \quad & + \sum_h LS_h p_{L,h}^{VA} \tau_{L,h} \\
(Commodity\ taxes) \quad & + \sum_i A_i p_i^A \tau_A \\
(Import\ taxes) \quad & + \sum_i A_i \frac{\partial \Pi_i^A}{\partial p^{FX}} p^{FX} \tau_M \\
(Output\ taxes) \quad & + \sum_i Y_i p_i^Y \tau_Y
\end{aligned} \tag{46}$$

B.6.6 DEBT - Debt closure and Ricardian Equivalence

The debt closure for the clean subsidy policy is combined with a contemporaneous closure. The contemporaneous closure will cover any indirect budget balancing and the cumulative amortization payment; we use an exemplary case of a lump-sum tax for this.

Income balance for the government:.

$$\begin{aligned}
& GOVT_t^{bal} = \\
& \sum_h p_t^{FX} * \overline{gdef}_t \\
& - \sum_h p_t^{FX} * \overline{tp}_{h,t} \\
& + p_t^{TAX} * \overline{taxrev} \\
(direct\ subsidy\ cost) \quad & - p_{ele,t}^Y Y_{ele,t} \mathbf{CLSUB}_t \\
(remove\ direct\ subsidy\ cost) \quad & + p_{ele,t}^Y Y_{ele,t} \mathbf{CLSUB}_t \\
(cumulative\ loan\ payment) \quad & - AMORT_t * p_t^{FX} \\
(taxincrease) \quad & + p_t^{FX} * LSTAX
\end{aligned} \tag{47}$$

Income balance for the capital market (NYSE) is adjusted so that household income is adjusted proportional to capital share of total income:

$$
\begin{aligned}
& NYSE^{bal} = \\
& \qquad \sum_{i,t} p^{Y}_{i,t} * \overline{yh}_{i,t} \\
& \qquad + \sum_{t} p^{VA}_{K,t} * \overline{F}_{K,t} \\
& \qquad + \sum_{i,t} p^{RS}_{i,t} * \overline{RS}_{i,t} \\
(direct\ subsidy\ cost) \quad & \qquad - \sum_{ele,t} p^{Y}_{ele,t} Y_{ele,t} \mathbf{CLSUB}_{t} \\
(cumulative\ loan\ payment) \quad & \qquad + \sum_{t} AMORT_{t} * p^{FX}_{t}
\end{aligned} \tag{48}
$$

Income balance for household:

$$
\begin{aligned}
& RA^{bal}_{h} = \\
& \qquad p^{FX} * \overline{tp}_{h} \\
& \qquad + p^{LS}_{h} * \overline{TIME}_{h} \\
& \qquad + p^{KE} * \overline{KE}_{h} \\
& \qquad - p^{FX} * \mathbf{LSITAX}_{h} \\
& \qquad OR: \\
& \qquad - p^{FX} * \mathbf{LSPTAX}_{h}
\end{aligned} \tag{49}
$$

Expanded and merged income balance for the household:

$$
\begin{aligned}
\sum_{h} RA_h^{bal} = & \\
\textbf{... RA ...} & \\
& \sum_{h} p^{FX} * \overline{tp}_h \\
& + \sum_{h} p_h^{LS} * \overline{TIME}_h \\
& - \sum_{h,t} p_t^{FX} * \mathbf{LSITAX}_{h,t} \\
& OR: \\
& - \sum_{h,t} p_t^{FX} * \mathbf{LSPTAX}_{h,t} \\
\textbf{... NYSE ...} & \\
& \sum_{i,t} p_{i,t}^{Y} * \overline{yh}_{i,t} \\
& + \sum_{t} p_{K,t}^{VA} * \overline{F}_{K,t} \\
& + \sum_{i,t} p_{i,t}^{RS} * \overline{RS}_{i,t} \qquad (50) \\
(direct\ subsidy\ cost) \quad & - \sum_{ele,t} p_{ele,t}^{Y} Y_{ele,t} \mathbf{CLSUB}_t \\
(cumulative\ loan\ payment) \quad & + \sum_{t} AMORT_t * p_t^{FX} \\
\textbf{... GOVT ...} & \\
& \sum_{h,t} p_t^{FX} * \overline{gdef}_t \\
& - \sum_{h,t} p_t^{FX} * \overline{tp}_{h,t} \\
& + p_t^{TAX} * \overline{taxrev} \\
(direct\ subsidy\ cost) \quad & - \sum ele, tp_{ele,t}^{Y} Y_{ele,t} \mathbf{CLSUB}_t \\
(remove\ direct\ subsidy\ cost) \quad & + \sum ele, tp_{ele,t}^{Y} Y_{ele,t} \mathbf{CLSUB}_t \\
(cumulative\ loan\ payment) \quad & - \sum_{t} AMORT_t * p_t^{FX} \\
(tax\ increase) \quad & + \sum_{t} p_t^{FX} * LSTAX_t
\end{aligned}
$$

Isolating debt specific accounting:

$$
\begin{aligned}
\sum_h RA_h^{bal} = & \\
& \dots \\
\textbf{... RA ...} & \\
(tax\ increase) \quad & -\sum_t p_t^{FX} * LSTAX_t \\
& \dots \\
\textbf{... NYSE ...} & \\
(direct\ subsidy\ cost) \quad & -\sum_{ele,t} p_{ele,t}^{Y} Y_{ele,t} \mathbf{CLSUB}_t \\
(cumulative\ loan\ payment) \quad & +\sum_t AMORT_t * p_t^{FX} \\
& \dots \\
\textbf{... GOVT ...} & \\
(cumulative\ loan\ payment) \quad & -\sum_t AMORT_t * p_t^{FX} \\
(tax\ increase) \quad & +\sum_t p_t^{FX} * LSTAX_t
\end{aligned}
\tag{51}
$$

Reducing we are left with the subsidy cost:

$$
\begin{aligned}
\sum_h RA_h^{bal} = & \\
\textbf{... RA ...} & \\
& \dots \\
\textbf{... NYSE ...} & \\
(direct\ subsidy\ cost) \quad & -\sum_{ele,t} p_{ele,t}^{Y} Y_{ele,t} \mathbf{CLSUB}_t \\
\textbf{... GOVT ...} & \\
& \dots
\end{aligned}
\tag{52}
$$

This is Ricardian Equivalence, the government's budget is internalized within the household's intertemporal budget constraint, so timing does not matter when using lump sum transfers. Interest cancels in this case, so interest rate and maturity don't matter either, and the amortization payment could be anything.

B.7 Policies

B.7.1 CAP

Carbon emissions market clearance:

$$\overline{CO2} * \mathbf{ELIM} = \sum_i \sum_g E_g \frac{\partial \Pi_g^E}{\partial (p_i^A + a_{i,g}^{co2} p^{co2})} a_{i,g}^{co2} \quad \perp p^{co2} \tag{53}$$

Where ELIM is chosen such that:

$$\overline{rawtar} = p^{co2} \sum_i \sum_g E_g \frac{\partial \Pi_g^E}{\partial (p_i^A + a_{i,g}^{co2} p^{co2})} a_{i,g}^{co2} \quad \perp \mathbf{ELIM} \tag{54}$$

and revenues are added to the government or IRS income balance condition:

$$\begin{aligned} GOVT_t^{bal} = & \\ & \sum_h p_t^{FX} * \overline{gdef}_t \\ & - \sum_h p_t^{FX} * \overline{tp}_{h,t} \\ & + p_t^{TAX} * \overline{taxrev} \\ & + p^{co2} * \overline{CO2} * \mathbf{ELIM} \end{aligned} \tag{55}$$

B.7.2 CES

Rewriting the zero profit conditions for electricity production updated with CES. The unit profit function for electricity of type clean (clt): $i \in ele$

$$\begin{aligned} \Pi_i^Y = & \left[p_i^Y (1 - \tau_i^Y + \mathbf{CLSUB}) + p^{CES}\right] \\ & - \left[\theta_{RS,i}^{RS} p_i^{RS^{1-\sigma^{RS}}} + (1 - \theta_{RS,i}^{RS}) p_i^{KLEM^{1-\sigma^{RS}}}\right]^{\frac{1}{1-\sigma^{RS}}} \\ & - p^{CES} * \mathbf{CES} \\ & \leq 0 \quad \perp Y_{i,clt} \end{aligned} \tag{56}$$

The unit profit function for dirty electricity (drt):

$$\Pi_i^Y = p_i^Y (1 - \tau_i) - (p_i^{KLEM} + p^{CES} * \mathbf{CES}) \leq 0 \quad \perp Y_{i,drt} \tag{57}$$

CES market clearance condition:

$$Y_{i,clt} \geq \left[Y_{i,clt} \frac{\partial \Pi_{i,clt}^Y}{\partial p^{CES}} + Y_{i,drt} \frac{\partial \Pi_{i,drt}^Y}{\partial p^{CES}}\right] \quad \perp p^{CES} \tag{58}$$

Constraint to force the net subsidy to the raw target:

$$\overline{rawtar} = p^{CES} Y_{ele,clt} - p^{CES} Y_{ele,clt} \frac{\partial \Pi_{ele,clt}^Y}{\partial p^{CES}} \quad \perp \mathbf{CES} \tag{59}$$

B.7.3 CLSUB

The subsidy rate is set such that the raw target value is met:

$$\overline{rawtar} = p^{Y}_{ele} Y_{ele,clt} * \textbf{CLSUB} \quad \perp \textbf{CLSUB} \tag{60}$$

C Additional Figures

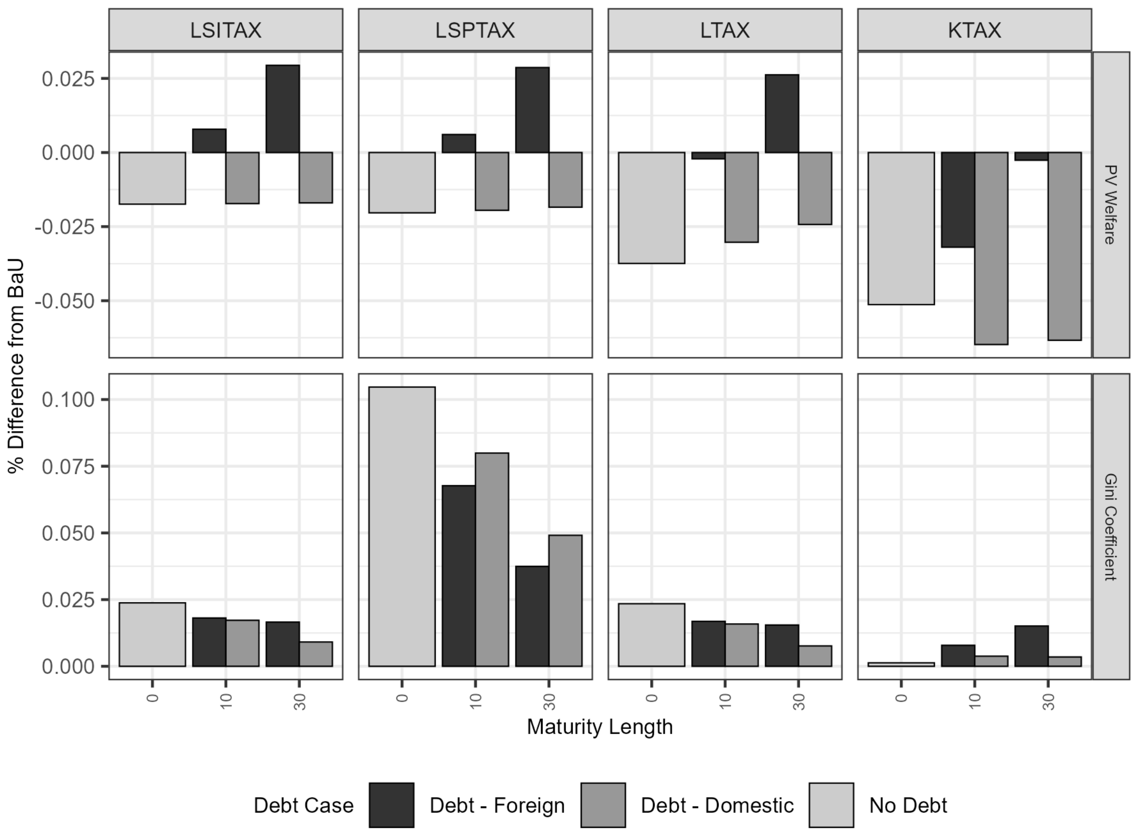

Figure 15: Debt closure total welfare effects by maturity length - 2030 termination - 0% interest rate - Ramsey

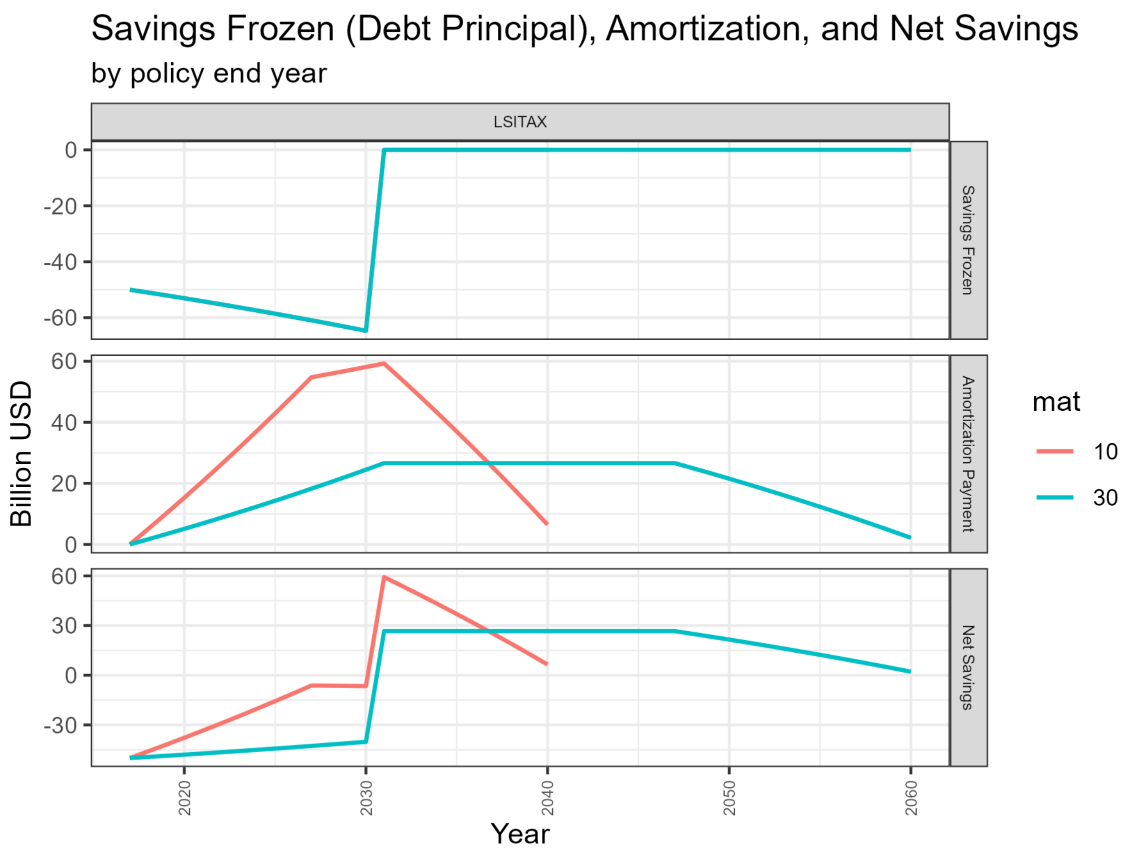

Figure 16: Amortization path by maturity - 2030 termination - 0% interest rate