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Economic Implications of the Climate Provisions of the Inflation Reduction Act

ABSTRACT The Inflation Reduction Act (IRA) represents the largest US federal response to climate change to date. We highlight the key climate provisions and assess the act's potential economic impacts. Substantially higher investments in clean energy and electric vehicles imply that fiscal costs may be larger than projected. However, even at the high end, IRA provisions remain cost-effective. The IRA has large impacts on power sector investments and electricity prices, lowering retail electricity rates and resulting in negative prices in some wholesale markets. We find small quantitative macroeconomic effects, including a small decline in headline inflation, but macroeconomic conditions—particularly higher interest rates and materials costs—may have substantial negative effects on clean energy investment. We show that the subsidy approach in the IRA has expansionary supply-side effects relative to a carbon tax but, in a representative-agent dynamic model, is preferable to a carbon tax only in the presence of a strong learning-by-doing externality. We also discuss the economics of the industrial policy aspects of the act as well as the distributional impacts and the possible incidence of the different tax credits in the IRA.

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Introduction

President Biden described the climate provisions of the Inflation Reduction Act (IRA) as "the most aggressive action ever, ever, ever to confront the climate crisis" (White House 2022). Other observers similarly describe it as "the most ambitious funding ever for tackling climate change" and "the largest climate legislation in U.S. history."[1] Consistent with preliminary analysis, modeling suggests that the IRA puts the United States on track to reduce greenhouse gas (GHG) emissions 33 percent to 40 percent below 2005 levels in 2030 (Bistline, Blanford, and others 2023), which is 8 to 17 percentage points lower than without the IRA, closing the gap toward its nationally determined contribution under the Paris Agreement to halve economy-wide GHG emissions by 2030. The problem the IRA confronts is massive—reorienting the way the United States and global economies produce and consume energy. The IRA's incentives span the entire energy sector, from producers of raw materials to end-use consumers, and will set considerable new forces in motion.

The IRA is vast, and the economics profession will likely devote considerable attention over the next decade to analyzing the impacts of many of the individual programs embodied in this important piece of legislation. We offer a broad-stroke analysis of the law, summarizing the major climate-related provisions and noting some of the possible economic impacts. We focus on several major themes.

First, we discuss the possible fiscal implications of the act and note a wide range of uncertainty in the extent to which firms and households will take up the different tax credits. The Congressional Budget Office (CBO), using inputs from the Joint Committee on Taxation (JCT), estimates that over two-thirds of the fiscal costs of the climate-related provisions of the IRA ($271 billion) will be tax credits that target clean electricity production and investment, new and used electric vehicle purchases, and investments in clean energy and energy efficiency by individuals (table 1 in section I). The remaining fiscal costs ($121 billion of the $392 billion total), per CBO/JCT, will be direct expenditures on

1. The Nature Conservancy, "A 'New Day for Climate Action in the United States' as U.S. Congress Passes Historic Clean Energy and Climate Investments," https://www.nature.org/en-us/newsroom/us-house-passes-landmark-climate-bill/; and U.S. Green Building Council, "Largest Climate Bill in History Holds Good News for Green Building," https://www.usgbc.org/articles/largest-climate-bill-history-holds-good-news-green-building.

forestry and agriculture, energy loans and other financial investments, and other items. Most of the tax credits are uncapped and are a function of individual firm investment decisions and individual household consumption decisions.

We summarize evidence from the Electric Power Research Institute's US Regional Economy, Greenhouse Gas, and Energy (EPRI's US-REGEN) model in section II suggesting that initial estimates of the fiscal costs may be understated in several areas due to greater deployment of IRA-supported technologies such as clean electricity and electric vehicles. Central and higher-end estimates of tax credit expenditures range from $781 to $1,070 billion over the ten-year budget window; these are 2.9–4.0 times higher than the CBO/JCT score for comparable credits. When these tax credits are combined with direct expenditures, total budgetary effects of the IRA's climate provisions are approximately $900 to $1,200 billion cumulatively through 2031 (table 2 in section II). Even after accounting for these higher fiscal costs, IRA tax credits reduce carbon dioxide (CO_2) emissions at an average abatement cost of $36–87 per metric ton for the power sector—considerably less than recent estimates of the social cost of CO_2, with mean values between $120/t$CO_2$ and $400/t$CO_2$ in 2030 (Rennert and others 2022), depending on the near-term discount rate, even before accounting for avoided air pollution damages and other co-benefits. On the other hand, the IRA's fiscal costs may be considerably lower. We document that the costs for clean electricity generating plants, for which the IRA includes large subsidies, are more sensitive to interest rates than conventional fossil fuel generators. In addition, continued supply constraints, delays from permitting, and other factors may increase costs and reduce the pace of clean energy deployment, depressing take-up for IRA incentives. Our lower-end estimates of tax credit expenditures are about $240 billion in a scenario with higher interest rates and technology costs; total fiscal costs are slightly lower than with CBO/JCT estimates but with more limited economy-wide CO_2 reductions.

Second, we highlight potential market impacts of IRA incentives, including negative prices in wholesale electricity markets (section III). Electricity generation technologies that collect production-based tax credits will have strong incentives to operate even when wholesale prices are low and even negative (which are more common during hours when output from these resources is highest) to receive these credits. For example, a wind project may be willing to pay –$33 per megawatt-hour (MWh) (suppliers make payments when prices are negative), because it could receive as much as \$33 per MWh in tax credits. Some areas of the country are already seeing negative prices, but their prevalence will likely increase with the IRA, which can alter economic signals for market entry and exit of generators, shift incentives for locational decisions and balancing resources (e.g., energy storage, transmission), and change the economics of end-use electrification and new loads (e.g., hydrogen production, cryptocurrency mining).

Third, we discuss distributional impacts and the possible incidence of the different subsidies in the IRA. We note the extent to which the IRA may drive down retail prices for energy due to subsidies for electricity generation and investment, reflecting transfers from the federal government to consumers and clean electricity providers. In addition to potentially decreasing retail electricity prices, the IRA could lower expenditures on fossil fuels due to its incentives for end-use electrification, especially petroleum for transportation. We describe patterns in energy expenditures by income. We also present results from US-REGEN under a counterfactual scenario without IRA subsidies to inform the extent of inframarginal transfers to firms and households that would have adopted these technologies anyway.

Fourth, we consider the relationship between the IRA and the macroeconomy. To elucidate the potential macroeconomic impacts of the IRA, we develop a representative agent model of the economy, which features subsidized clean energy as an input in section IV. We show how clean energy subsidies function as a supply-side policy that boosts output, investment, wages, and labor productivity while reducing the price of electricity. These dynamic effects work to partially offset the static fiscal cost of the policy. Along the transition path, increased investment demand raises interest rates and lowers private consumption. Bottlenecks lower real clean energy investment but may raise investment expenditures and the fiscal cost of the investment tax credit as the relative price of investment in clean energy capital rises. However, the slower pace of investment under bottlenecks mitigates the rise in the real interest rate. We show how elastic labor supply and learning-by-doing externalities increase the clean energy capital stock in steady state under a subsidy policy. Even labor and domestic sourcing requirements as structured in the IRA would increase the steady-state clean energy capital stock. We also show that clean energy investment may crowd out non-energy investment in the short run but increases non-energy capital in the long run.

Fifth, we turn to a normative analysis in section V and compare the subsidies approach in the IRA to carbon pricing. Our comparison is both conceptual and quantitative, as we derive a carbon price that would yield comparable emissions reductions over a similar time frame. Conceptually, while both policies lower the relative price of clean to fossil fuel power generation, a carbon tax raises energy prices, encouraging energy conservation but carrying negative supply-side implications for output, investment, and wages. The conservation margin means that a carbon tax results in a larger decline in emissions. In the context of our model, we define optimal policy and show that, despite its positive supply-side effects, optimal climate policy generically involves a positive carbon tax and a zero clean energy subsidy. The case for an approach centered on clean energy subsidies relies heavily on strong learning-by-doing externalities.

We describe further dimensions along which carbon taxes and subsidies differ that are not captured in our model, including fuel switching, differential carbon intensity, and impacts from usage along the intensive margin. We also compare subsidies and carbon pricing in terms of the incentives created for innovation. In this section, we also discuss the economics of some of the industrial policy aspects of the IRA, which offers higher tax credits for firms that adopt certain labor practices and buy inputs manufactured in the United States. In addition, some of the electric vehicle tax credits are only available if the vehicle meets battery sourcing requirements and North American assembly. We explain how these provisions may be addressing market failures, but if not, they may raise costs.

Last, we use outputs from the US-REGEN model in section VI as inputs into the Federal Reserve Board's US model (FRB/US) to provide quantitative evidence on the possible macroeconomic impacts of the IRA. Consistent with this, we show that new investment under the IRA, while large relative to the current level of investment in the energy sector, is comparatively small as a share of both overall investment and overall economic activity. Increases in clean power investment and household transfer income for electric vehicles and other household equipment initially increase demand before raising the capital stock and output. The movements in interest rates and unemployment are very small owing to the small size of electric power investment relative to the overall economy. Although we find that IRA investments in the baseline case are likely not large enough to meaningfully influence macroeconomic aggregates, section VII quantifies how the macroeconomic environment—including higher interest rates and rising costs of labor and materials—could have meaningful negative impacts on clean energy investment.

I. Summary of the IRA's Climate Provisions

Table 1 summarizes the major energy- and climate-related provisions in the IRA and the accompanying fiscal score (CBO 2022).[2] The fiscal score reflects estimates made by the CBO and JCT of the costs to the US government over the ten-year budget window, 2022–2031. The top panel of the table reflects tax credits, which the CBO/JCT estimate will account for about $271 billion in lost tax revenues in total through 2031. The bottom panel reflects direct expenditures, which are estimated to be $121 billion.[3] As discussed in section II, the CBO/JCT score is an initial estimate of budgetary effects of the IRA, and actual tax expenditures could be significantly larger, given how many of the tax credits are uncapped.

I.A. Tax Credits

PRODUCTION AND INVESTMENT TAX CREDITS The production and investment tax credits for clean electricity and energy storage account for about one-third of the estimated costs of the IRA's climate provisions (table 1). The production tax credit (PTC) is awarded per megawatt-hour of electricity output for the first ten years of production from qualifying low-emitting resources, while the investment tax credit (ITC) is awarded as a percentage of the investment cost.

There are two phases to each tax credit. For the first several years, until January 1, 2025, the law lists tax credit amount by type of resource (e.g., over $5/MWh for wind and solar renewable projects that do not meet labor requirements).[4] For projects that are placed into service after December 31, 2024, the law is broader and compensates any clean electricity generation

2. For more details on the climate-related provisions of the IRA, see *Building a Clean Energy Economy: A Guidebook to the Inflation Reduction Act's Investments in Clean Energy and Climate Action*, produced by the Biden administration (White House 2023a). See also Congressional Research Service (2022a).

3. Much of the reporting on the IRA has cited a total figure of $369 billion for the climate provisions, which is apparently from the initial press release on the IRA issued by the offices of Senate Democratic Leader Chuck Schumer and Senator Joe Manchin; see "Joint Statement from Leader Schumer and Senator Manchin Announcing Agreement to Add the Inflation Reduction Act of 2022 to the FY2022 Budget Reconciliation Bill and Vote in Senate Next Week," July 27, 2022, https://www.democrats.senate.gov/newsroom/press-releases/senate-majority-leader-chuck-schumer-d-ny-and-sen-joe-manchin-d-wv-on-wednesday-announced-that-they-have-struck-a-long-awaited-deal-on-legislation-that-aims-to-reform-the-tax-code-fight-climate-change-and-cut-health-care-costs.

4. All values are shown in 2022 US dollars unless otherwise noted. The base PTC level is listed in the bill text as 0.3 cents per kilowatt-hour, which is expressed in nominal terms from when the wind PTC was first applied to projects built in 1993. Many IRA tax credits include inflation adjustments over time.

Table 1. Fiscal Score of the Climate-Related Provisions of the IRA by Major Category

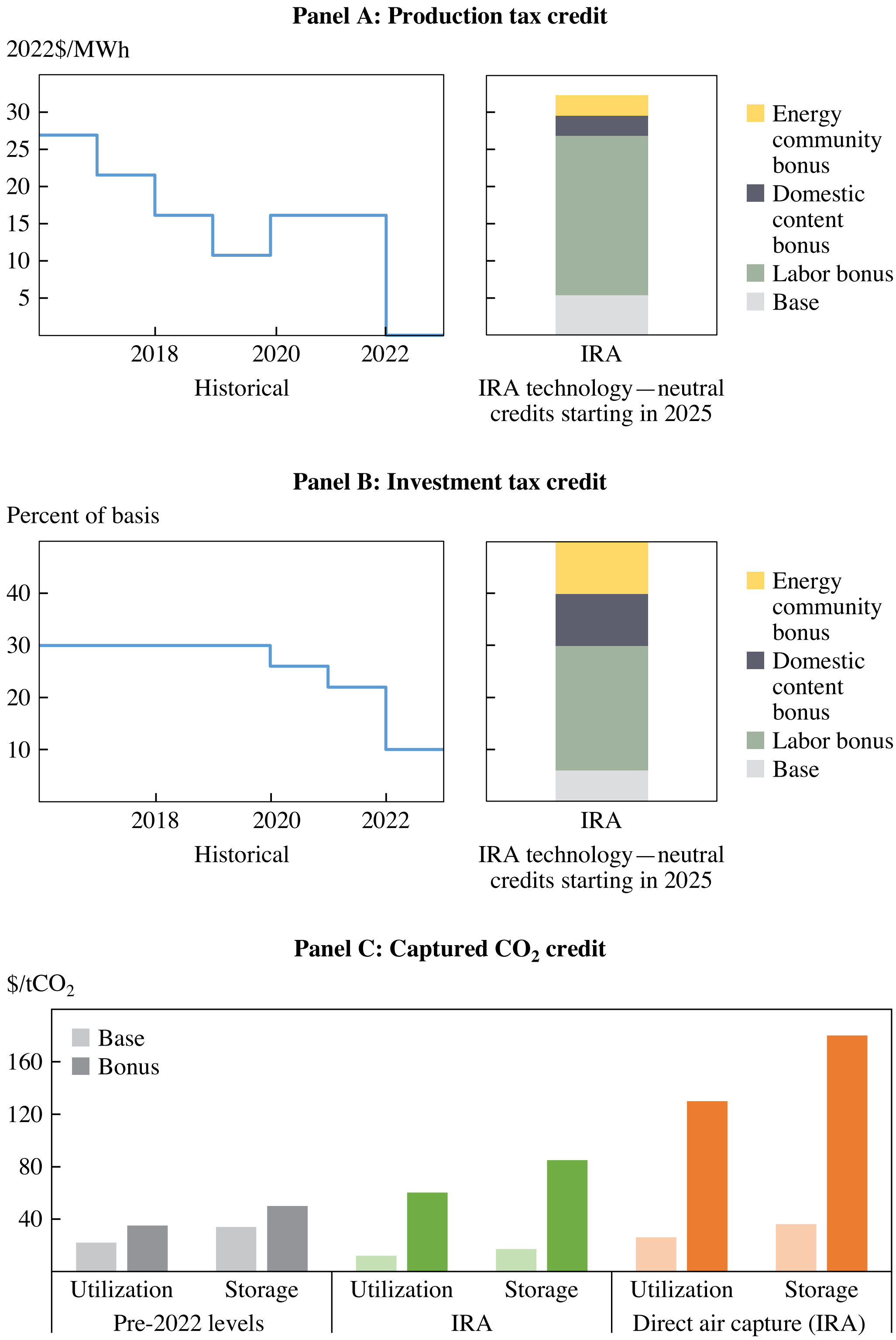
	Fiscal score ($ billions)
Tax credits	
Investment and production tax credits for clean electricity generation and storage	131
Production tax credit for carbon capture and sequestration	3
Nuclear power production tax credit	30
Clean fuels	19
Clean energy and efficiency incentives for individuals	37
Clean vehicles	14
Clean energy manufacturing	37
Subtotal	271
Direct expenditures	
Agricultural and forestry conservation and sequestration projects	21
Energy loans	17
Energy efficiency	11
Industrial decarbonization	5
Other (e.g., Green Bank)	66
Subtotal	121
Total	392

Sources: CBO (2022) and authors' calculations.
Note: Values are based on the CBO's September 7, 2022, estimates. Numbers may not sum due to rounding.

capacity, defined as one with zero GHG emissions. The tax credit is five times higher (about $27.5/MWh) for projects that meet certain labor requirements on prevailing wages and apprenticeships, as shown in figure 1. There is also a 10 percent increase in the PTC and a 10 percentage point boost to the ITC for projects that use domestically produced steel and other materials, assuming they comply with the labor requirements. Similar bonuses are available for projects that are sited in energy communities that meet specified criteria. Many of the provisions include incentives to meet similar labor, domestic content, and location-based requirements, so we describe the specifics below.

Qualifying electricity facilities are allowed to choose whether to take the PTC or the ITC, and the relative value of each credit could vary by location (e.g., due to variation in wind and solar resource quality), technology, bonus credit eligibility, and assumed capital costs. In many locations, land-based wind and solar photovoltaic (PV) have higher lifetime credit values with the PTC with the labor bonus, while offshore wind and new nuclear have higher values with the ITC (Xu and others 2022). However, if a project is eligible for both the energy community and domestic content bonuses, then the ITC could be more valuable for developers, given the higher incremental value of these bonuses under the ITC.

Figure 1. Production, Investment, and Carbon Capture Credits under the IRA Relative to Pre-IRA



Sources: Davis and others (2020); Inflation Reduction Act.

Note: The right-hand side of panels A and B reflects the technology-neutral credits starting in 2025, but the wind- and solar-specific credits available in 2023 and 2024 are identical.

PRODUCTION TAX CREDIT FOR CARBON CAPTURE AND SEQUESTRATION The IRA also expands the tax credit available since 2008 to facilities that capture carbon dioxide (section 45Q of the US Internal Revenue Code). With the IRA, facilities above a minimum size threshold that meet labor requirements are eligible for \$85/tCO_2 stored or \$60 for CO_2 utilization (figure 1, panel C). The provision applies for industrial or power-generating facilities that capture carbon dioxide from their production processes, as well as direct air capture plants built solely to capture and sequester carbon, which receive \$180 per ton of captured and stored CO_2.

Although the CBO estimates that the tax credit for carbon capture and sequestration (CCS) will cost the government only \$3.2 billion over the budget window (i.e., about 1 percent of the tax expenditures in table 1), some external modelers see substantial investment (Jenkins and others 2022; Zhao and others 2022; Bistline, Roney, and others 2023). Among those modelers that project investments in CCS, major applications include both the industrial sector and the electric power sector, though relative sequestration in each varies by model.

NUCLEAR POWER PRODUCTION TAX CREDIT The IRA adds a production tax credit through 2032 for existing nuclear power plants that meet labor and wage requirements. This credit provides up to \$15/MWh, though the magnitude of the subsidy depends on electricity revenues and whether plants already receive credits from other federal or state zero-emission credit programs. For example, the Infrastructure Investment and Jobs Act, signed into law in November 2021, created a \$6 billion program to auction grants to nuclear power plants that remain in service.

CLEAN FUELS The IRA also extends and expands credits for clean transportation and industrial fuels. As with the PTC and ITC, the legislation extends targeted tax credits for biodiesel, renewable diesel, and alternative fuels for the first several years and then replaces those with a technology neutral credit. The technology neutral credit begins in 2025 and is available through the end of 2027. The credit value is \$1/gallon if labor requirements are met, and can be increased depending on the emissions intensity of the fuel. The CBO projects the largest expenditures in this category will be a new credit for clean hydrogen (section 45V in the IRA), which can be used in transportation, industrial, and power generation applications, and the magnitude of these hydrogen subsidies depends on the emissions intensity of production.[5] The IRA also adds a tax credit for sustainable aviation fuels

5. Credits for electrolytic hydrogen may be combined with PTC and ITC incentives for clean electricity production, which is an input to hydrogen production.

of \$1.75/gallon with the labor bonus, although CBO estimates, consistent with those of outside modelers, reflect relatively low take-up of this credit (Bistline, Blanford, and others 2023). Unlike the power sector PTC, the tax credits apply to all qualifying fuels produced that year, whether they are from a new facility or not.

CLEAN ENERGY AND EFFICIENCY INCENTIVES FOR INDIVIDUALS The CBO estimates that individuals will make use of almost \$40 billion in tax credits for clean energy and energy efficiency investments (table 1).[6] Individual taxpayers can receive credits for their investments in equipment, including home solar; battery storage; solar water heating; small wind energy; energy efficient insulation, windows, and doors; electric heat pumps; and home energy audits and electric panel upgrades necessary for other efficiency improvements. The amount of rebate can vary based on the energy savings, building type, and household income. There are caps on the amounts an individual taxpayer can claim for specific investments (e.g., \$150 for a home energy audit and \$2,000 for a heat pump) and on total annual credits, but there are no caps on the total amount of credits. Unlike the more commercially oriented credits discussed thus far, these credits do not offer bonuses for using a particular category of labor.

CLEAN VEHICLES The IRA allows taxpayer credits up to \$7,500 for the purchase of a new electric or hydrogen fuel cell vehicle if several conditions are met. The conditions include the following: the final assembly of the vehicle must take place in North America; a share of both the critical minerals and the battery components must come from North America (or, in the case of critical minerals, a country with which the United States has a free-trade agreement), and the share escalates over time after 2024; and both the vehicle manufacturer's suggested retail price (MSRP) and the taxpayer's income must be below specified limits. Of the total credit, \$3,750 is tied to meeting the battery components requirement and \$3,750 to the critical minerals requirement. Treasury guidance issued in March 2023 confirmed that companies leasing vehicles to consumers may claim the commercial clean vehicle credits, which can provide \$7,500 without stringent requirements on battery sourcing or caps on MSRP or income eligibility (US Department of the Treasury 2023a). More broadly, the commercial clean vehicle tax credits provide up to \$7,500 for vehicles less than 14,000 pounds and \$40,000 for larger vehicles (or 30 percent of the purchase price or incremental cost of an internal combustion engine replacement, whichever is lower).

6. Less than \$0.5 billion of this line item is for energy efficiency investments in commercial buildings.

The IRA also introduces a $4,000 credit (or 30 percent of the vehicle price, whichever is smaller) for the purchase of a previously owned electric vehicle as long as the vehicle is more than two years old, the buyer meets income requirements, and the selling price is below $25,000. Both the income and selling price thresholds are considerably lower than those for new electric vehicles. Finally, the IRA extends tax credits for individual taxpayers, who can, regardless of income, deduct up to 30 percent or $1,000 for home charging. Businesses can also claim tax credits for electric vehicle charger installations of 30 percent or (as long as they satisfy labor requirements) up to $100,000.

CLEAN ENERGY MANUFACTURING The IRA extends and expands tax credits for retrofits or new construction of certain energy manufacturing facilities, such as facilities that produce energy storage systems or electrolyzers. It features a 30 percent credit capped at $10 billion that applies to a range of clean energy technologies and an uncapped credit per unit of production for several specific wind, battery, and solar components (for example, $12 per square meter of photovoltaic wafer or $3 per kilogram of solar-grade polysilicon). The CBO estimates that the bulk of the tax expenditures will be through the uncapped provision, though analysis by Credit Suisse indicates that manufacturing credits could be many times the CBO/JCT estimate (Jiang and others 2022).

I.B. Common Features of the Tax Credits

Most of the IRA tax credits are not capped, so the CBO/JCT estimates summarized in table 1 are subject to considerable uncertainty. In section II, we present examples of models that have come up with widely varying estimates of the fiscal costs of the credits. In some cases, such as production-based credits for low-carbon electricity, carbon capture, and clean hydrogen, lower fiscal costs would be driven by lower than anticipated deployment, meaning that emissions would not come down as quickly as hoped. For the ITC, however, lower budgetary effects could also be driven by lower than expected investment costs—for example, if the costs of renewable or storage technologies fell faster than expected. Budgetary effects of the tax credits also could be lower if bonus credit uptake is limited.

The IRA does two things to make the tax credits easier to use: it makes some of them direct pay and some of them transferable.[7] Direct pay

7. Some credits are transferable but not eligible for direct pay, such as the personal electric vehicle credit. Some are eligible for direct pay but not transferable, such as the credit for commercial clean vehicles. Many are both, including the PTC and ITC for renewable electricity. Credits for alternative fuels are neither eligible for direct pay nor transferable.

essentially transforms the tax credit into a grant and means that entities such as nonprofits and state and local governments are eligible to receive them. If a tax credit is transferable, a taxpayer can transfer the credit to an unrelated party in exchange for cash. This means that if a provider (e.g., a solar power project developer) has a tax bill that is too small to absorb the credits, it can transfer the credits to a taxpayer who can use them, that is, one whose tax bill is larger than the value of the credits. This transferability provision did not exist before the IRA; so, for example, renewable developers had to form partnerships with taxpayers who had the ability to absorb the credits (so-called tax equity investors). As another example, the IRA specifies that beginning in 2024, the taxpayers may elect to transfer the electric vehicle credit to the dealer, meaning that the credit works like a point-of-sale rebate.

Almost all the credits include substantial bonuses for projects that use domestic content, are located in low-income or energy communities, and meet certain labor requirements (figure 1). Companies can comply with the labor requirements if they pay prevailing wages during construction and repair and if qualified registered apprentices provide more than a threshold share of labor hours, where the threshold increases over time. This bonus is lucrative for projects eligible for the PTC and ITC, increasing values by five times relative to the base rate. The domestic content provisions typically increase over time, presumably to allow US manufacturers the opportunity to scale production capacity.

The energy communities bonus provides an additional 10 percent for the PTC or 10 percentage points for the ITC if any of three criteria are met related to brownfield sites, employment and tax revenue from fossil fuels, or coal mine or plant closures.[8] Eligibility for energy community bonuses could affect bonus uptake, siting decisions for projects, and the ability to direct IRA funds toward areas experiencing the most acute impacts from lower fossil fuel consumption and production. The broad geographical coverage of statistical areas and census tracts under energy communities definitions likely means that large land areas may be eligible for these bonuses,

8. The IRA specifies a "0.17 percent or greater direct employment or 25 percent or greater local tax revenues related to the extraction, processing, transport, or storage of coal, oil, or natural gas" and an "unemployment rate at or above the national average unemployment rate for the previous year" (Inflation Reduction Act of 2022, H.R. 5376, 117th Cong. (2021–2022), Pub. L. 117–169 (August 16, 2022), https://www.congress.gov/bill/117th-congress/house-bill/5376/).

covering 42–50 percent of US land area according to initial estimates (Raimi and Pesek 2022), which is consistent with Treasury and Internal Revenue Service (IRS) guidance. Even areas that are geographically distant from communities that are dependent on fossil fuels for employment and government revenue may be eligible (US Department of the Treasury 2023b). This coarse geographical targeting means that IRA benefits also go to regions with limited fossil fuel dependence, while at the same time, the unemployment criterion may exclude areas with some of the highest dependence on fossil fuels, including Colorado, Louisiana, North Dakota, West Texas, and Wyoming (Raimi and Pesek 2022). Additionally, the binary eligibility rule for the energy communities bonus ignores the heterogeneity of fossil fuel dependence, which lowers the cost-effectiveness of these provisions in achieving "just transition" objectives. The modeling in section II illustrates that the eligibility for the energy communities bonus can increase the deployment of wind, solar, and other IRA-qualified resources, though the geographical allocation of this capacity does not necessarily align with communities dependent on fossil fuel.

The credits are available over different time periods. The production and investment tax credits begin to phase down either in 2032 or at the point when power sector emissions reach 25 percent of their 2022 emissions, whichever is later. This emissions-based eligibility threshold is a novel feature of the IRA and could imply that qualifying clean electricity resources may receive tax credits well into the 2030s and potentially longer, which has associated budgetary impacts. Production-based tax credits for hydrogen and electricity apply to projects placed in service through at least 2032 and continue for ten years after the project begins claiming the credit. Credits for CO_2 capture continue for twelve years after the project begins claiming the credit. The electric vehicle tax credits are generally available through 2032, which is the end of the ten-year budget reconciliation period.

I.C. Direct Expenditures

AGRICULTURAL AND FORESTRY CONSERVATION AND SEQUESTRATION PROJECTS

The IRA provides more than $20 billion for agricultural and forestry conservation programs. Much of the agricultural funding flows through existing conservation programs, though the IRA expands funding for them significantly. For instance, $8.45 billion is directed to the Environmental Quality Incentives Program (EQIP) for practices that improve carbon storage in soil or decrease GHG emissions. Funding for forestry programs would target hazardous fuel reduction projects, vegetation management projects, inventories of old-growth forests, and other measures.[9]

ENERGY LOANS The IRA increases existing loan program authority of the US Department of Energy's Loan Programs Office by about $100 billion and creates a new Energy Infrastructure Reinvestment Program, which aims to accelerate retooling and replacing emissions-intensive energy infrastructure. The IRA also increases funding for several existing programs that aim to encourage farmers and rural landowners to purchase renewable energy systems. It also provides almost $10 billion to encourage rural electric cooperatives to invest in renewables and other low-carbon energy projects.

ENERGY EFFICIENCY The IRA includes over $10 billion in direct expenditures for energy efficiency programs, including a new Department of Energy program to award grants to state energy offices to develop whole-house energy-saving retrofit programs.[10] It also increases funding for energy efficiency under an existing Department of Housing and Urban Development affordable housing program.

INDUSTRIAL DECARBONIZATION The law funds a new program at the Department of Energy to support industrial facilities in emissions-intensive industries that complete demonstration and deployment projects to reduce emissions. Although projections before the IRA suggest that the industrial sector will be responsible for over one-quarter of emissions by 2030, the IRA allocates only $5 billion for emissions reductions in the sector. Some models suggest that clean hydrogen and CCS will be useful in the industrial sector, so the total subsidies for the sector may be larger than $5 billion, but still considerably smaller than subsidies for the electric power and transportation sectors (Bistline, Blanford, and others 2023).

OTHER Notable expenditures in the "Other" category in table 1 include $27 billion for the Environmental Protection Agency (EPA) to run the Greenhouse Gas Reduction Fund, which will award competitive grants with an emphasis on clean energy projects that benefit low-income and disadvantaged communities. (This is sometimes described as the US government's "green bank," as much of the funding will support nonprofit organizations that provide financial or technical assistance to local clean energy projects.)

9. See Mahajan and others (2022) for analysis of these provisions. They project that these provisions lead to CO_2 emissions from land use change and forestry in 2030 of –744 $MtCO_2$ equivalent/year (i.e., net removals) instead of –707 $MtCO_2$ equivalent/year in the counterfactual reference without the IRA. See Congressional Research Service (2022a) for more details on the agricultural and forestry programs.

10. US Department of Energy, "About the Home Energy Rebates," https://www.energy.gov/scep/home-energy-rebate-programs.

The IRA includes a Methane Emissions Reduction Program to establish a charge on methane emissions from specified sources, beginning at $900 per metric ton of methane and increasing to $1,500 after two years. This fee equates to about $36 and $60 per $MtCO_2$ equivalent, although the precise number depends on the assumed CO_2 equivalence of methane (Congressional Research Service 2022b). The fee will not be assessed if states adopt EPA regulations.

I.D. Comparing the IRA to Pre-2022 Programs

In many cases, the IRA extended and expanded existing programs. In some cases, the IRA introduced entirely new programs.

As an example of enhancements to existing tax credits, figure 1 depicts the production and investment tax credits that existed for wind, solar, and CCS before the IRA. Panel A summarizes the credits available to wind generators through the production tax credit, which had been as high as $27/MWh in 2016 (2022$) but expired on December 31, 2021. Before the IRA, solar projects were eligible for the ITC but not the PTC. The bars on the right break down the IRA credits, showing the large bonus credits available for plants that meet the labor requirements. Panel B of figure 1 compares historical ITC values with IRA ones. Finally, panel C summarizes credits available for captured CO_2. Before the IRA, industrial and power-generating facilities were eligible for $50/$tCO_2$ for CO_2 storage and $35/$tCO_2$ for utilization. The updated IRA credits for CO_2 capture also include higher credit levels for direct air capture, which can be up to $180/$tCO_2$ for projects with the labor bonus.

The longevity of the tax credits under the IRA also provides renewable project developers with more certainty than they had in the past. For example, the Union of Concerned Scientists noted in 2015 that, since its inception with the Energy Policy Act of 1992, the production tax credit expired six times. Though it was subsequently extended by Congress each time, they conclude that "this 'on-again/off-again' status has resulted in a boom-bust cycle of development. In the years following expiration, installations dropped between 76 and 93 percent."[11] Timing projects to ensure that they qualify for tax credits may increase costs and risk for renewables developers.

Examples of expansions under the IRA include extending the investment tax credit to stand-alone energy storage projects, which previously were only eligible if they were colocated with solar power facilities.

11. Union of Concerned Scientists, "Production Tax Credit for Renewable Energy," July 15, 2008, updated February 9, 2015, https://www.ucsusa.org/resources/production-tax-credit-renewable-energy.

In some cases, the IRA introduced brand new programs, including the EPA's Greenhouse Gas Reduction Fund, tax credits for advanced manufacturing of clean energy inputs, and tax credits for commercial vehicles. And many of the labor market, domestic content, and energy community credits are new.

II. Fiscal Implications

II.A. Initial CBO/JCT Score

Initial estimates by the CBO and JCT (CBO 2022) indicate that the entire climate and non-climate provisions of the IRA would increase federal tax revenue by $58 billion on net over the ten-year budget window (i.e., through 2031).[12] Increases in fiscal costs from tax credits and direct spending would be more than offset by increases in revenues from alternative minimum taxes on large corporations, excise taxes on stock buybacks, and increased enforcement of extant taxes. According to this CBO/JCT estimate, costs to the US government for energy- and climate-related tax credits are $271 billion and $121 billion for direct expenditures through 2031 (table 1).

As discussed in section I, large shares of spending are allocated for IRA provisions where tax credits are uncapped, which are investment- or production-based. This means that actual federal tax expenditures and budgetary effects might be significantly more than initially estimated.

II.B. US-REGEN Score

Here, we use the energy-economic model US-REGEN to estimate the budgetary effects of core energy-related IRA provisions.[13] US-REGEN

12. For a summary of CBO/JCT estimates, see CBO (2022). For an overview of the CBO's general approach to preparing cost estimates, see CBO (2018); for the JCT's approach, see JCT (2019). These quick turnaround analyses of proposed legislation estimate changes to federal spending and revenues for most bills approved by committee in the House or Senate. For the IRA's power and transport provisions, JCT revenue estimates come from baseline projections, often based on US Energy Information Administration projections, combined with tax data and assumed elasticities.

13. EPRI's US Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model features regional disaggregation and technological detail of the power sector and linkages to other economic sectors. Recent peer-reviewed articles and reports can be found at EPRI, "Models," https://esca.epri.com/models.html, and detailed model documentation at "US-REGEN Documentation," https://us-regen-docs.epri.com/. For descriptions of IRA implementation, see Bistline, Roney, and others (2023). The analysis was conducted in February 2023 and does not consider changes in policy or guidance after that time.

brings technological, temporal, spatial, and cross-sector detail, which can influence the economics of supply- and demand-side resources in the energy system and consequently the budgetary effects of IRA provisions. The electric sector model is an intertemporal optimization of capacity planning and dispatch with simultaneous investments in generation, energy storage, transmission, hydrogen production, and carbon removal.[14] Demand for electric vehicles, heat pumps, and other building equipment comes from separate logit choice models that translate relative costs of ownership across technologies into equilibrium market shares.[15]

This analysis suggests that government expenditures under the IRA may be significantly larger than initial estimates based on higher tax credit uptake and deployment of clean electricity, carbon capture, and electric vehicles. Total fiscal costs of tax credits in US-REGEN are estimated to be over $780 billion by 2031—nearly three times the CBO value for comparable credits. Figure 2 compares total fiscal costs (i.e., cumulative expenditures) of IRA tax credits in the US-REGEN analysis with the CBO/JCT score for select IRA provisions over time. When these tax credits are combined with direct expenditures, total budgetary effects of the IRA's climate provisions total $901 billion through 2031.

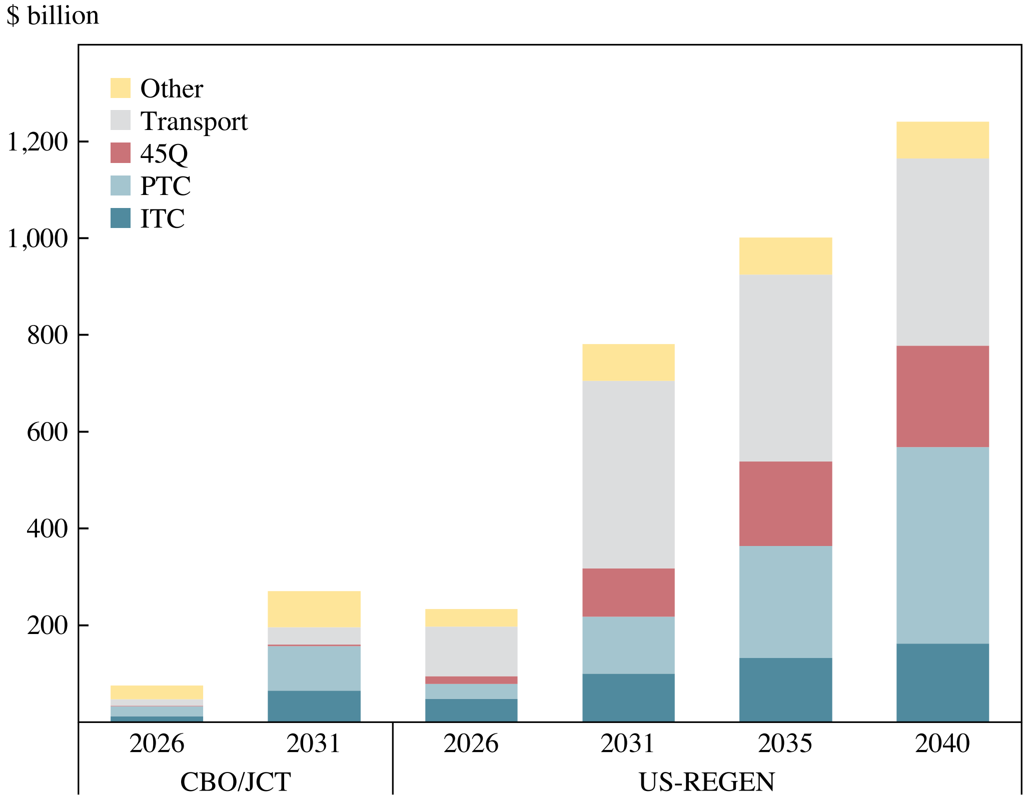
Tax credits in the electric sector are projected to be $320 billion cumulatively through 2031 by US-REGEN. One of the largest differences between CBO/JCT and US-REGEN estimates is 45Q credits for captured CO_2. The CBO/JCT score indicates a total of $3.2 billion in 45Q credits through 2031 (and just $0.3 billion annually in 2031). In contrast, credits for captured CO_2 in US-REGEN total $100 billion through 2031.[16] US-REGEN estimates could be conservative, since they reflect only credits used in the power sector. BloombergNEF estimates cumulative 45Q credits could be

14. US-REGEN uses a unique approach for selecting intra-annual segments to more accurately characterize the economics of variable renewables, energy storage, and dispatchable capacity (Blanford and others 2018). This algorithm allows the model to capture features such as diminishing marginal returns for higher wind and solar deployment, the value of firms' low-emitting technologies under deep decarbonization, and chronological system operations for short- and long-duration energy storage options.

15. The model includes segmentation of firms and consumers to capture differences that are relevant to technology choice, including household location, vehicle ownership, driving intensity, building type, and charging access for passenger vehicle decisions. Hourly electricity profiles for vehicle charging are based on exogenous charging patterns that vary by driver type, day type, temperature, and location and include flexibility through deferrable charging (Bistline, Roney, and others 2021). US-REGEN assumes perfectly competitive markets, meaning that tax credits and taxes are passed through to consumers.

16. Note that US-REGEN is typically run in five-year time steps. However, for comparability with the CBO/JCT score, we interpolate results to show 2026 and 2031 values.

Figure 2. Estimates of Cumulative (Undiscounted) Fiscal Costs from IRA Tax Credits by Provision



Sources: CBO (2022) and authors' calculations.

Note: CBO/JCT scores are based on September 7, 2022, estimates and look at budgetary effects from 2022 to 2031. Values are shown in nominal terms. The "Other" category includes additional end-use incentives (e.g., credits for heat pumps) and manufacturing. The 45Q credits are for captured CO_2.

over $100 billion, as carbon capture and sequestration (CCS) could become economical for several point-source CO_2 applications outside of the power sector, including natural gas processing, ethanol, ammonia, and cement (Attwood 2022).

Note that the CBO/JCT score examines effects only across a ten-year budget window, and most IRA incentives are available for ten years from their construction date (i.e., a project constructed in the early 2030s may receive credits into the 2040s). US-REGEN estimates that the electric sector tax credits will sum to $780 billion through 2040, 63 percent of the total (figure 2). Cumulative credits for captured CO_2 are estimated to be $210 billion by 2040. For a hypothetical budget window from 2031 to 2040, electric sector tax credits would be $460 billion, nearly three times the comparable CBO/JCT values for the initial ten-year period (about $160 billion).

Fifty-nine percent of aggregate spending through 2031 in US-REGEN comes from demand-side credits for electric vehicles, heat pumps, and energy efficiency upgrades. In particular, subsidies to promote electric vehicle sales dominate end-use credits and are significantly higher than initial estimates. Total fiscal costs of clean vehicle credits in US-REGEN are $390 billion through 2031, which is more than an order of magnitude greater than CBO estimates of $14 billion. If the US Energy Information Administration's (EIA) estimates are used for electric vehicle deployment, the CBO/JCT score suggests that the average eligible share of vehicles for the full credit is 12 percent.[17] On the other hand, if all new electric vehicles in 2030 are assumed to be eligible for the full credit, the CBO/JCT score implies an electric vehicle sales share of 1 percent.

Because electric vehicles can have lower total costs of ownership for many households before tax credits (Burnham and others 2021), 73 percent of electric vehicles sold in 2030 would have occurred in the counterfactual without IRA incentives in US-REGEN, reducing the efficiency of these tax credits.[18] Figure 3 indicates that the IRA increases the electric vehicle share of new vehicle sales by 12 percentage points in 2030, from 32 percent to 44 percent. There is considerable uncertainty about the fiscal cost of consumer tax credits for electric vehicles since, as section I.A describes, magnitudes of these credits are tied to battery components and critical minerals requirements, various eligibility restrictions, and domestic manufacturing incentives. These factors depend on Treasury guidance, firms' responses to passenger clean vehicle credits and manufacturing tax credits, and consumer purchasing decisions.[19]

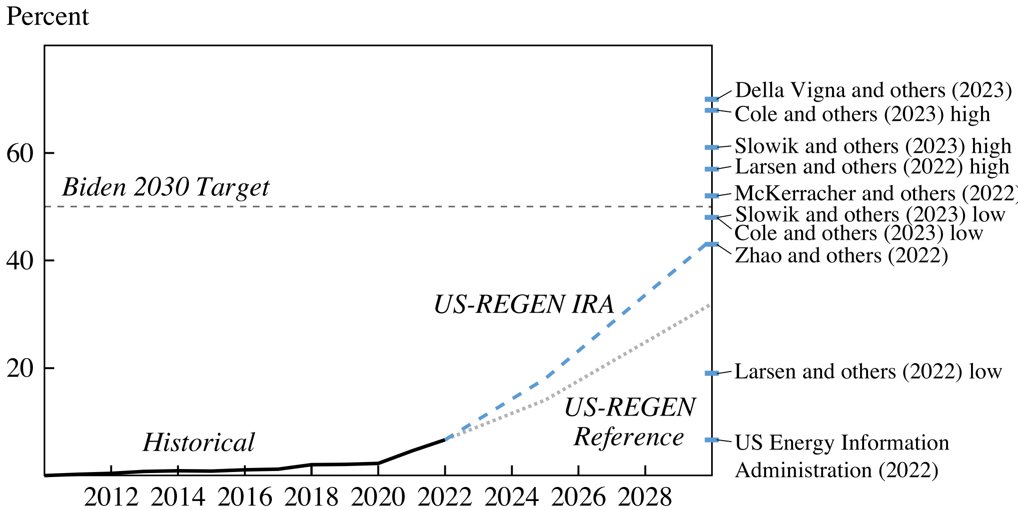
Tax expenditures increase over time, especially in the electric sector. Figure 2 illustrates how fiscal costs of tax credits in 2031 total $781 billion but reach over $1.2 trillion by 2040. End-use incentives are larger in 2031,

17. The US Energy Information Administration (2022) projects that electric vehicle sales shares are 6.6 percent in 2030, declining from a 6.7 percent sales share in 2022 (see figure 3).

18. Electric vehicle shares account for range anxiety, household heterogeneity, preferences for internal combustion engine vehicles, and other factors in US-REGEN's logit choice model of passenger vehicles, as described in the model documentation at EPRI, "Transportation," https://us-regen-docs.epri.com/v2021a/assumptions/transportation.html.

19. For US-REGEN scenarios, new light-duty vehicle sales are assumed to have an increasing average incentive value for clean vehicle credits (section 30D in the Internal Revenue code) and advanced manufacturing production credits (section 45X) over time. Assumptions about battery assembly, critical materials sourcing, income and sales price eligibility, final vehicle assembly, and battery manufacturing credits lead to an average incentive value for new electric vehicles of $3,750 in 2025 and $7,500 in 2030, which are similar to the moderate scenario in Slowik and others (2023).

Figure 3. Electric Vehicle Share of New Passenger Vehicle Sales



Sources: International Energy Agency (2022; historical data) and authors' calculations.
Note: Electric vehicles include battery and plug-in hybrid vehicles. US-REGEN scenarios with and without the IRA are compared with recent estimates of electrification shares of new vehicle sales under the IRA.

but since these credits generally expire around 2031, power sector credits lead cumulative spending by 2040. The power sector PTC and ITC could last longer, until electricity emissions reach 25 percent of 2022 levels, which could mean that credits could remain in place for over two decades and that fiscal implications of IRA credits are largest after the initial ten-year window.[20] Projections for tax expenditures over time can vary based on uptake of ITC vis-à-vis PTC (i.e., where the former are front-loaded and the latter are payouts over time), bonus eligibility, and timing of investments.

II.C. Comparisons with Other Estimates of the IRA's Fiscal Costs

This finding that fiscal costs under the IRA are uncertain and may be much larger than initial CBO/JCT estimates is reflected in other studies.

An analysis by Credit Suisse points to greater climate spending in several areas, especially for advanced manufacturing credits. The authors of the report project tax expenditures of $250 billion for these credits supporting solar, wind, and battery supply chains, which is eight times higher than CBO estimates (Jiang and others 2022).

20. This threshold is approximately 380 $MtCO_2$ equivalent/year, based on preliminary estimates of 2022 emissions by the Rhodium Group (Rivera and others 2023). IRA scenarios in US-REGEN generally do not reach emissions levels below this threshold until after 2040.

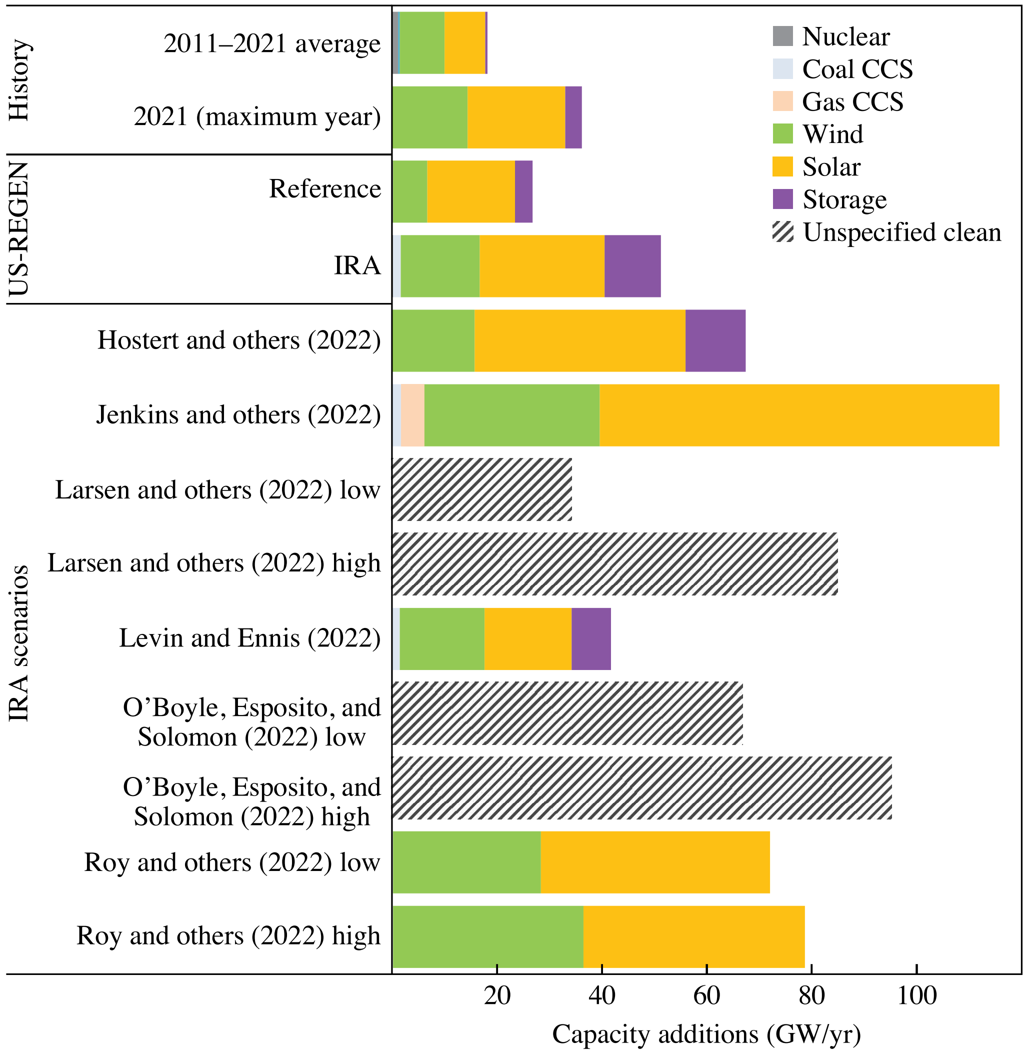
An analysis by Goldman Sachs (Della Vigna and others 2023) estimates that government spending could be nearly $1.2 trillion over the next decade, including $393 billion for transport electrification and $274 billion for clean electricity.

Cole and others (2023) estimate cumulative federal tax expenditures for light-duty vehicles to be $451 billion through 2031, comparable to the $390 billion in US-REGEN, which is more than an order of magnitude greater than the $14 billion CBO value. They also estimate that 40–57 percent of this spending would be inframarginal transfers to consumers who would have purchased in the counterfactual without IRA incentives. Figure 3 compares the estimates by Cole and others (2023) for new sales of electric vehicles under the IRA with US-REGEN values and several other estimates from the literature (Slowik and others 2023; Zhao and others 2022; McKerracher and others 2022; Larsen and others 2022). These shares span a wide range—from 19 to 70 percent—though many are above the US-REGEN value of 44 percent, suggesting that the budgetary effects in figure 2 could be conservative.

Power sector capacity additions vary based on IRA implementation and scenario assumptions (e.g., projections of capital costs, fuel prices, and other policies and incentives). Figure 4 compares US-REGEN additions of low-emitting capacity (including renewables, nuclear, CCS-equipped fossil fuels, and energy storage) with other public estimates of the IRA's impacts (Roy and others 2022; Levin and Ennis 2022; Hostert and others 2022; O'Boyle, Esposito, and Solomon 2022; Jenkins and others 2022; Larsen and others 2022). Average annual capacity additions under the IRA range from 34 GW/year to nearly 120 GW/year, which suggests that the US-REGEN estimates in earlier sections could underestimate fiscal costs of IRA provisions.

The comparison of electric sector additions in figure 4 also illustrates how although IRA tax credits accelerate clean electricity deployment, there are still considerable additions of solar, wind, and energy storage in the counterfactual without the IRA. Technological change has led to rapid cost declines for solar power, wind power, and battery storage over the past decade (see figure 18), and the expectation of future declines in costs of these resources (see figure 8) implies that a portion of the power sector tax credits will be inframarginal transfers to firms that would have adopted these technologies even without the IRA (similar to clean vehicle credits), which aligns with qualitative insights from earlier tax credit analysis (Stock and Stuart 2021). Average annual additions of low-emitting capacity in US-REGEN is 51 GW/year with the IRA and 27 GW/year in the counterfactual reference,

Figure 4. Average Annual Capacity Additions by Low-Emitting Generation and Energy Storage Technologies



Sources: US Energy Information Administration and authors' calculations.

Note: Historical values come from US Energy Information Administration, "Form EIA-860 Detailed Data with Previous Form Data (EIA-860A/860B)," https://www.eia.gov/electricity/data/eia860/, and show average additions over the past decade and the year of maximum deployment to date (2021). US-REGEN model outputs show build rates with and without the IRA through 2035. These scenarios are compared with estimates in the literature for deployment under the IRA through 2035, where available. Note that several studies do not report energy storage capacity or technology-specific capacity additions (aggregate values are shown in stripes).

indicating that over half of these additions would have occurred without IRA tax credits. Nonetheless, US-REGEN modeling suggests that the IRA incentives are highly cost-effective, as we discuss below.

Figure 4 also illustrates the broad range in possible electric sector additions under the IRA, even across models with similar IRA implementations (Bistline, Blanford, and others 2023). These cross-model differences in power sector outcomes are tied to model structure, input assumptions, and IRA representations. In particular, temporal resolution (i.e., the number of intra-annual periods represented for investment and dispatch decisions) and assumed discount rates (section III.A) alter the economics of low-emitting resources (Bistline 2021; Lonergan and others 2023).[21]

II.D. IRA Emissions Impacts and Implied Abatement Costs

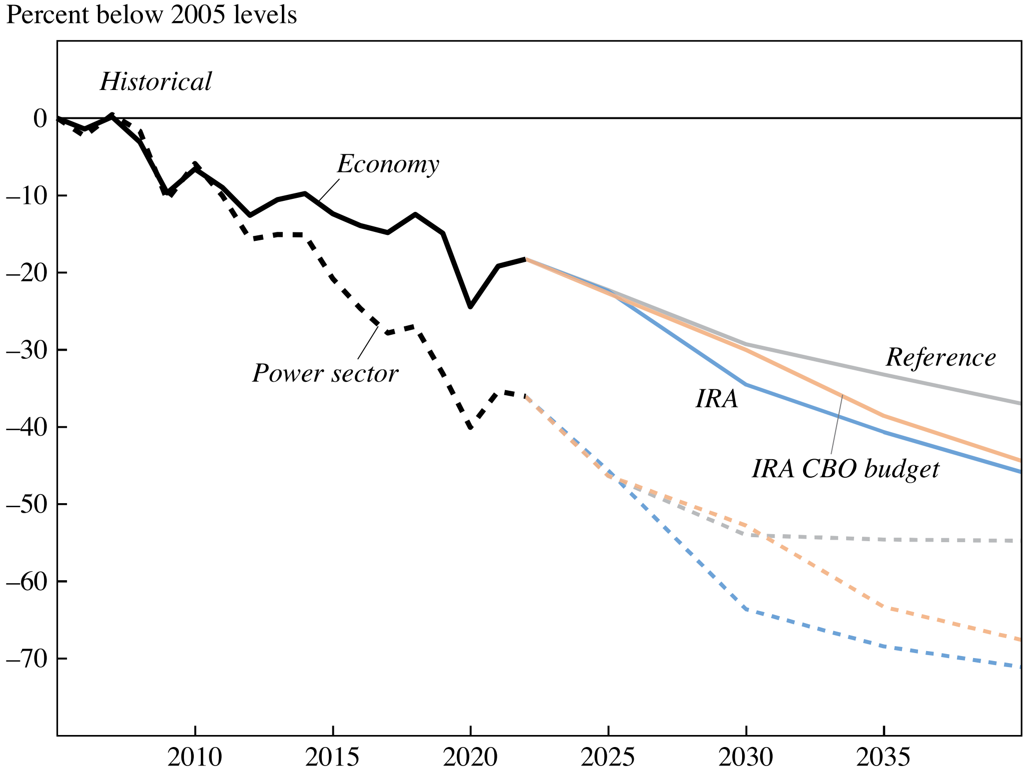
Although the CBO/JCT score does not provide carbon reduction estimates, the initial announcement of the IRA indicated that it would "reduce carbon emissions by roughly 40 percent by 2030" (Senate Democrats 2022). Figure 5 shows CO_2 emissions over time for the US-REGEN scenarios, indicating economy-wide reductions with the IRA of 35 percent by 2030 (from 2005 levels) and 41 percent by 2035 (compared to 29 percent and 33 percent, respectively, in the reference scenario without the IRA).[22] Large shares of IRA-induced emissions reductions beyond reference levels come from the electric sector, which decreases its emissions 64 percent by 2030 (compared to 54 percent in the reference). If a 40 percent reduction in economy-wide emissions were reached by 2030, fiscal costs of the tax credits would exceed the US-REGEN estimates in figure 2, making them even higher than initial CBO estimates (the sensitivity in the next subsection indicates that tax credit expenditures would be nearly $1,100 billion through 2031 if a 40 percent reduction is reached).

We also conduct a sensitivity in US-REGEN to evaluate emissions reductions if fiscal costs over the ten-year budget window are constrained to the CBO/JCT score values for power sector tax credits (table 1). Figure 5

21. For instance, US-REGEN has one of the highest temporal resolutions of the models represented in figure 4 but lower deployment, whereas one of the models with highest deployment has a single annual time slice (Energy Innovation 2021).

22. This 6 percentage point reduction in energy CO_2 emissions is comparable to the US Energy Information Administration's reduction between its reference case with the IRA and its no-IRA scenario, which is 7 percentage points—from 26 percent below 2005 by 2030 to 33 percent with the IRA (US Energy Information Administration 2023).

Figure 5. Economy-Wide and Electric Sector CO_2 Emissions over Time



Sources: Environmental Protection Agency; CBO; and authors' calculations.

Note: Values are based on US-REGEN modeled scenarios with IRA incentives, a counterfactual reference without the IRA, and an IRA scenario with a constraint that fiscal costs match CBO values through 2030. Historical values come from the US Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks," https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

shows how economy-wide emissions reductions reach 30 percent below 2005 only by 2030 in that case.[23]

We calculate emissions reductions in the US economy and do not model impacts on the rest of the world. All of the models summarized in figure 4 take a similar approach. This implicitly assumes that reductions in the United States will not lead to increased emissions outside the United States (i.e., that there will not be meaningful emissions "leakage"). The existing empirical estimates and model-based studies suggest that emissions leakage is limited (Grubb and others 2022), and these studies are based on climate mitigation approaches that impose costs on domestic industry, such

23. Power sector emissions in a scenario with IRA incentives that are capped at the CBO values exceed reference levels, since renewables and CCS deployment are lower than in the IRA scenario but overall generation is higher than the reference case due to the additional end-use electrification from IRA incentives.

as carbon pricing. Since the IRA will subsidize clean production, emissions leakage is likely to be even more limited. We discuss possible technological and policy spillovers to the rest of the world below.

Our estimated emissions reductions can be used to calculate implied abatement costs associated with IRA tax credits. In particular, the cost per metric ton of CO_2 reduced from IRA tax credits in the power sector is based on changes in total system costs over time (including all private sector and government costs that would not have been borne without the IRA) divided by emissions impacts from the IRA (which is the difference between the IRA and reference scenarios in figure 5).[24] Cumulative incremental costs under the IRA are $420–570 billion across the model's time horizon, depending on the discount rate—ranging from 1.5 percent to 3 percent—with cumulative reductions of 9.4 billion metric tons of CO_2. As shown in figure 6, IRA tax credits reduce CO_2 emissions at an average abatement cost of $45–61 per metric ton for the power sector—considerably less than recent estimates of the social cost of CO_2—with mean values between $120–400/t$CO_2$ in 2030 (Rennert and others 2022), depending on the near-term discount rate, even before accounting for avoided air pollution damages and other co-benefits.[25] The finding that the IRA's average abatement costs are likely below updated social cost of carbon estimates holds even with the higher abatement costs used in section II.E and inframarginal transfers noted in section II.C.

II.E. Lower and Higher Fiscal Cost Sensitivities

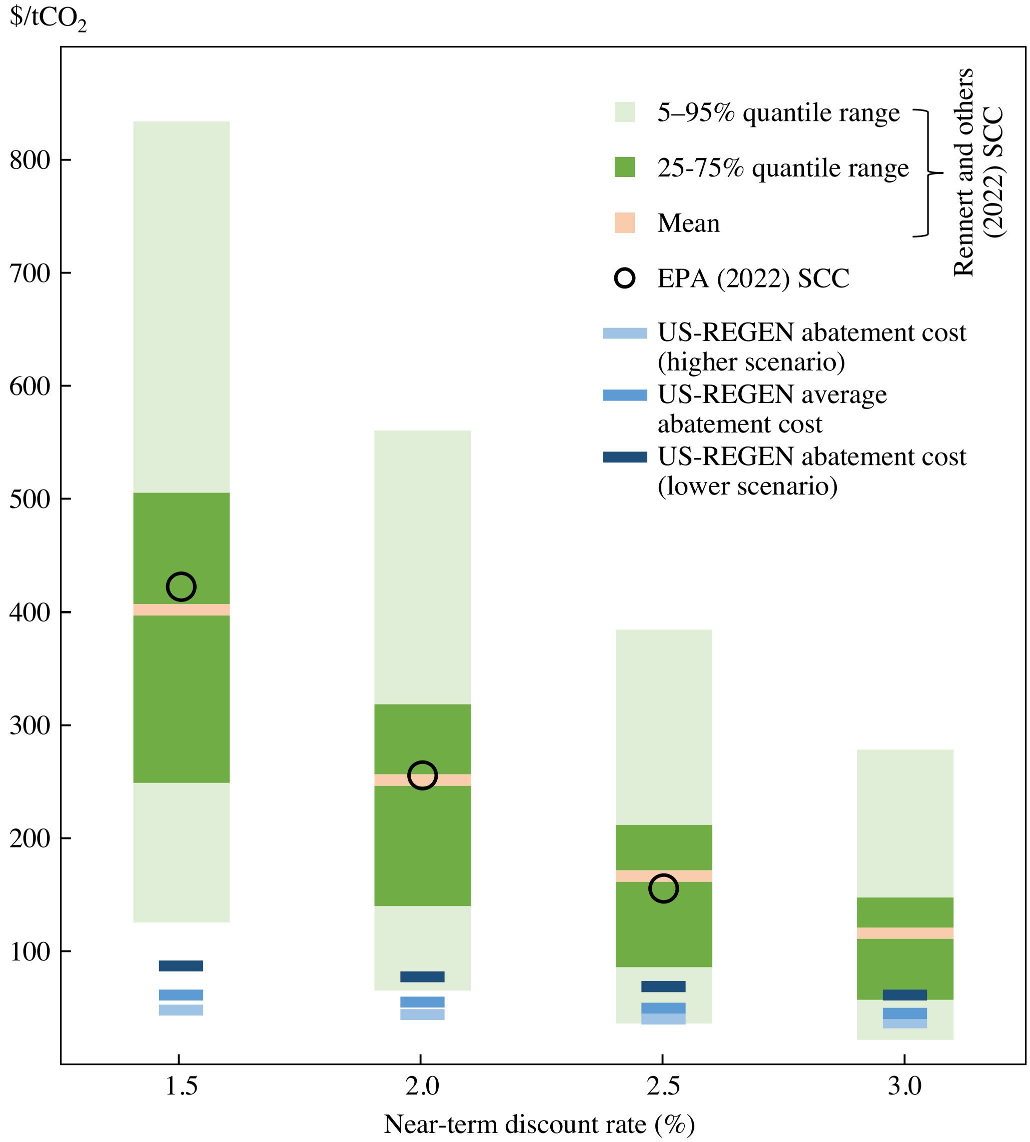
Given uncertainties in the planning environment, we include two sensitivities to investigate the potential range of the IRA's fiscal costs, in addition to the central case presented earlier.[26] A *lower fiscal costs* scenario

24. Similar to the definitions used by Stock and Stuart (2021) and Greenstone and others (2022), this definition includes incremental expenditures on capital costs (including generation, energy storage, transmission, and distribution), fuel costs, and maintenance costs, and includes both public and private expenditures. Abatement costs include changes in cost and emissions through the model horizon of 2050, since incentives can shift cash flows far into the future, given the long-lived nature of many assets and the potential for capital-intensive, low-emitting resources to lower operational costs over time. Comparisons use discounted costs and undiscounted emissions, due in part to the comparability with emissions-equivalent carbon price in section V.E, where the shadow price on the annual emissions cap constraint is implicitly using discounted costs (since the objective function is the net present value of system costs) and undiscounted emissions. If both costs and emissions are discounted, average abatement costs are $88–94/t$CO_2$.

25. Note that average abatement costs would be higher if distortions associated with financing the incentives were included (Finkelstein and Hendren 2020).

26. These illustrative scenarios should not be interpreted as bookends of possible scenarios or as predictions of likely outcomes.

Figure 6. Comparison of Social Cost of CO_2 Estimates and Average Abatement Cost of IRA Tax Credits in the Power Sector from US-REGEN



Sources: Environmental Protection Agency (2022); Rennert and others (2022); and authors' calculations.

Note: Social cost of CO_2 values come from EPA (2022) and Rennert and others (2022), which reflect damages only from sea-level rise, building energy expenditures, temperature-related mortality, and agriculture. Scenario results from US-REGEN are summarized in table 2.

Table 2. Comparison of Key Metrics across Lower, Central, and Higher Fiscal Cost Sensitivities in US-REGEN

Metric	*Lower*	*Central*	*Higher*
Total tax credit expenditures to 2031 ($ billion)	$244	$781	$1,070
Expenditures relative to CBO/JCT	0.9	2.9	4.0
Total fiscal costs to 2031 ($ billion)	$365	$902	$1,190
Economy-wide CO_2 in 2030 (% from 2005)	–28%	–35%	–40%
Power sector CO_2 in 2030 (% from 2005)	–51%	–64%	–75%
Abatement cost ($/t$CO_2$)	$61–87	$45–61	$36–49
Electric vehicle sales share in 2030 (%)	33%	44%	60%
Clean capacity additions to 2035 (GW/year)	34.7	51.3	75.9

Source: Authors' calculations.

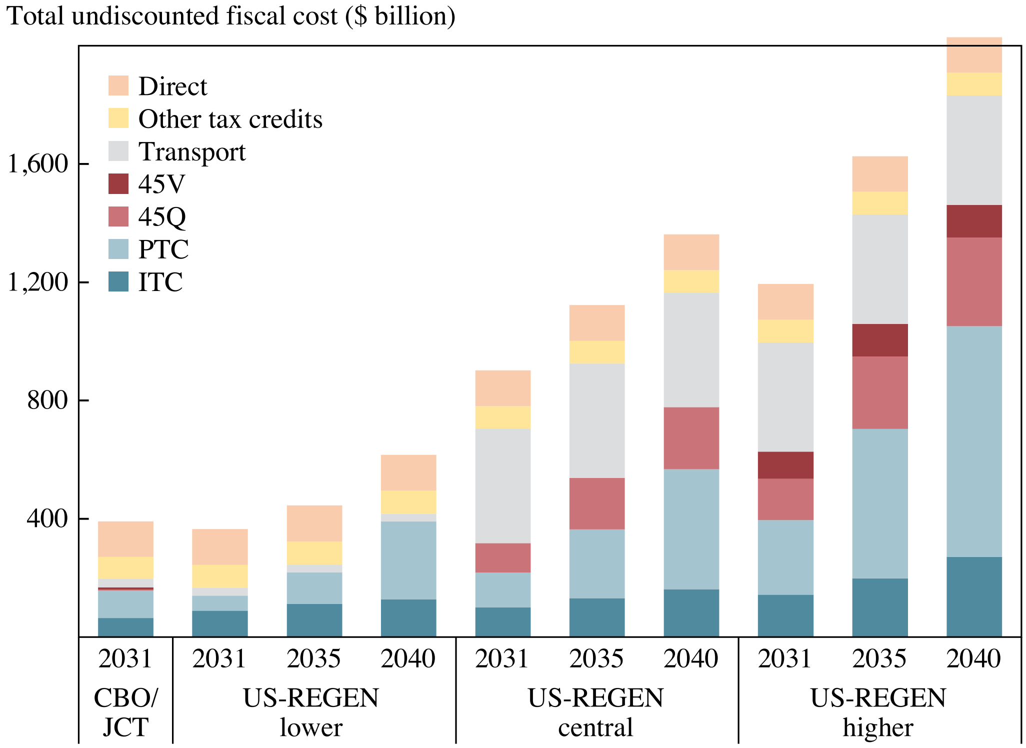
Note: Total fiscal costs include all tax credits and direct expenditures. Abatement costs show ranges across different discount rates (1.5 percent to 3 percent).

assumes higher supply-side costs, higher interest rates, and lower eligibility of electric vehicles for credits. Scenario assumptions are discussed in section VII, which provides a deep dive into how the assumed macroeconomic environment can alter the effects of the IRA. A *higher fiscal costs* scenario uses the same technology and market assumptions as the central case but adds additional policies, including higher credit values for clean hydrogen under the IRA, IRA bonus credits for energy communities and domestic content for all power sector projects, and new and existing source performance standards for power plants.[27]

These sensitivities expand the range of tax expenditures through 2031 from $781 billion in the central case to $244 billion to $1,070 billion, which is similar to the tax credits CBO/JCT score at the low end of the range and four times higher than the CBO/JCT estimate at the high end (table 2). Total fiscal costs of the IRA's climate provisions, inclusive of tax credits and direct expenditures, range from $365 billion to $1,190 billion through 2031 (compared with $902 billion in the central case). This sensitivity with lower fiscal costs also leads to more limited emissions reductions (similar to reference levels in figure 5) because of lower electric vehicle and clean electricity capacity deployment. The higher fiscal costs sensitivity reaches

27. IRA hydrogen credits are assumed to provide $3/kgH$_2$ for all electrolytic hydrogen in this scenario (unlike the central scenario, which assumes more stringent implementation guidance). The central case assumes that only a fraction of projects receive the energy communities bonus for the PTC and ITC; this assumption is consistent with updated Treasury and IRS guidelines, though this guidance is not explicitly modeled (White House 2023b). Model implementation of the new and existing source performance standards for power plants under sections 111(b) and 111(d) of the Clean Air Act comes from the analysis in Bistline (2023)—specifically, the scenario with plant-level cofiring-based standards for coal and natural gas combined cycle units.

Figure 7. Estimates of Cumulative (Undiscounted) Fiscal Costs from IRA Tax Credits by Provision across Low, Central, and High Fiscal Cost Sensitivities in US-REGEN



Sources: CBO and authors' calculations.

Note: CBO/JCT scores are based on September 7, 2022, estimates. Values are shown in nominal terms. "Other tax credits" includes additional end-use incentives (e.g., credits for heat pumps) and manufacturing; 45Q credits are for captured CO_2, and 45V credits are for clean hydrogen.

40 percent economy-wide CO_2 reductions by 2030 relative to 2005 levels and 75 percent reductions in power sector CO_2, which entails power sector investments increasing by almost 50 percent over the central case.

Figure 7 shows IRA fiscal costs by provision across these three sensitivities. Tax credit expenditures quadrupling through 2031 under the higher fiscal costs scenario are due to higher power sector credit uptake vis-à-vis the central case and about $100 billion in hydrogen credits. Fiscal costs of these tax credits approach $2 trillion through 2040 in the higher scenario.

II.F. Caveats

There are several uncertainties associated with the fiscal implications of the IRA. First, specific guidelines about IRA provisions still await clarifications from Treasury and the IRS, including those about bonus credit eligibility, qualifying resources for technology-neutral PTC and ITC in the power sector, emissions accounting for several credits, and others. Second, forthcoming policy and regulatory changes may affect uptake of tax credits, especially since the timing and stringency of such policies could be influenced by the presence of IRA incentives. For instance, the EPA released proposed performance standards for new and existing power plants under sections 111(b) and 111(d) of the Clean Air Act in May 2023. Since these standards are based on carbon capture and hydrogen at coal- and gas-fired plants, increased deployment of these IRA-subsidized resources could increase and accelerate fiscal impacts (Bistline 2023). Third, there are general uncertainties, as with any projection. For example, US-REGEN assumes that the levelized cost of electricity from utility-scale solar will decline by about 44 percent with the IRA, relative to current unsubsidized levels (see figure 8), though there is considerable uncertainty about the pace of future technological change (Bistline and others 2022; Way and others 2022). These unknowns about technologies, markets, and policies mean that IRA incentive uptake (shown in figure 4) and budgetary impacts are uncertain.

III. Energy Production Analysis

This section describes results from the US-REGEN model (described in section II) that shed light on costs and market implications of the IRA. Our focus here is on the impact of the IRA on the cost of different generating technologies and implications for the price of electricity.

III.A. Levelized Cost of Electricity

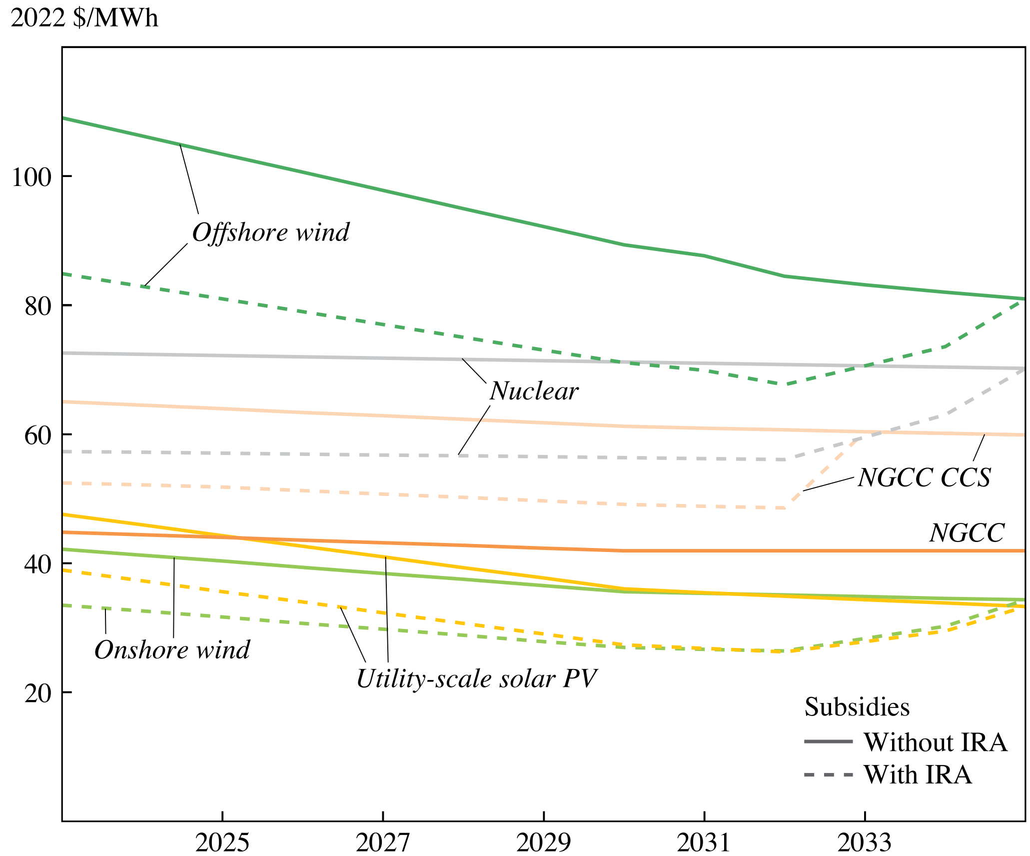
Analysts often reference the levelized cost of electricity (LCOE) for different types of electricity generation. The LCOE is the discounted sum of costs associated with building and operating a power plant over its lifetime divided by the discounted sum of future electricity production:

(1) $$LCOE = \frac{\sum_{t=1}^{T}\left(I_t + OM_t + FC_t\right) \Big/ \left(1+r\right)^t}{\sum_{t=1}^{T} E_t \Big/ \left(1+r\right)^t},$$

where I is investments in period t (including financing costs, minus subsidies), OM is operations and maintenance costs, FC is fuel costs, r is the discount rate, and E is electricity production.

Figure 8 plots estimates of the levelized costs of electricity through 2035 for several prominent generating technologies. The estimates are

Figure 8. Levelized Cost of Electricity by Technology over Time without and with IRA Subsidies



Sources: Bistline, Roney, and others (2023) and authors' calculations.

Note: Capital costs underlying these estimates are based on Bistline, Roney, and others (2023). Estimates assume thirty-year financial lifetimes and 7 percent discount rates (weighted average cost of capital). Onshore wind and utility-scale solar PV are assumed to take the PTC under the IRA, nuclear and offshore wind take the ITC, and natural gas combined cycle with CCS (NGCC CCS) takes CO_2 capture credits. Labor bonuses are included but not bonuses for energy communities or domestic content.

based on capital cost assumptions from the EPRI's US-REGEN model used for the analysis in other sections.[28] Without the IRA, costs for renewable technologies, including solar and wind, are generally projected to decline (24 percent for solar, 16 percent for onshore wind, and 18 percent for offshore wind by 2030). These projections are based on a combination of factors, including assumptions about learning curves, technological

28. Values are discussed in Bistline, Roney, and others (2023). Capital cost assumptions in 2030 are similar to the National Renewable Energy Laboratory's Annual Technology Baseline (moderate technology innovation scenario), which is the primary source for many models that have informed policy discussions about the impacts of the IRA (see Bistline, Blanford, and others 2023); however, near-term costs have been adjusted to reflect observed 2022 costs.

progress (e.g., larger rotors for onshore wind), and estimates from the literature.[29]

Figure 8 also highlights the impact of IRA subsidies on the estimated costs for all the eligible technologies. Only the natural gas combined cycle without CCS is ineligible for subsidies. The calculations behind figure 8 assume that the technology-neutral production and investment tax credits begin to phase down in 2032 for illustrative purposes, though these could continue afterward if power sector CO_2 emissions have not reached 25 percent of their 2022 levels.

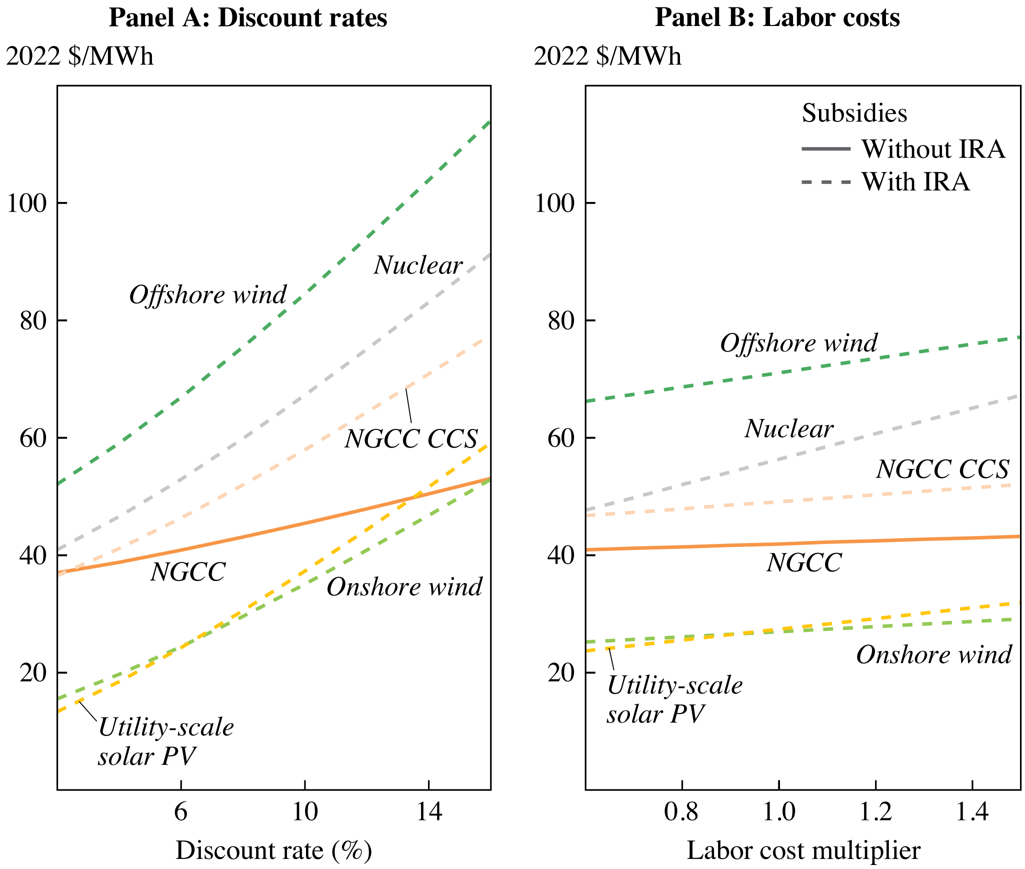
While LCOE estimates can be a useful summary statistic to make high-level comparisons, especially for time trends of individual technologies, they also have well-known limitations. The statistic does not account for the value of the electricity provided to the grid. LCOE does not distinguish between resources that produce electricity primarily when demand and wholesale prices are low and resources whose output aligns with higher-priced periods, including dispatchable resources. Joskow (2011) details these issues, highlighting the extent of the problem by noting that "the difference between the high and the low hourly prices over the course of a typical year, including capacity payments for generating capacity available to supply power during critical peak hours, can be up to four orders of magnitude" (239). The value to production at different times of the day and over the course of the year will also vary as more renewable resources are added to the system.[30] Models that minimize system costs (such as US-REGEN) simultaneously account for power system investments and operational dynamics, including endogenous representations of how the costs and value of different resources change as the system evolves (Bistline, Blanford, and others 2021).

With those limitations in mind, figure 8 highlights how, particularly with IRA tax credits, the LCOE of onshore wind and solar PV installations is below that of other resources. Firms will have strong incentives to build these resources. Offshore wind, even with IRA subsidies, is considerably more expensive than other resources, but several states have resource-specific

29. This figure does not show variability in LCOE estimates based on regional labor costs, resource quality (e.g., for wind and solar generation), or capacity factors (which can vary by scenario and time period), though these features are accounted for in the US-REGEN modeling in other sections.

30. In particular, wind, solar, and other resources exhibit diminishing marginal returns, where the economic value of additional capacity decreases as their deployment increases (Bistline 2017; Hirth 2013). Metrics like LCOE neglect declining value and increasing system costs.

Figure 9. Levelized Cost of Electricity by Technology in 2030 for Various Assumptions about Discount Rates and Labor Costs



Source: Authors' calculations.

Note: All other parameters are held constant from the comparisons in figure 8. Costs for technologies are shown after accounting for IRA subsidies, except for NGCC capacity, which is not eligible for tax credits.

mandates for these resources, which are represented in many models, including US-REGEN. Finally, the impact of tax credits on the LCOE is a function of the assumptions about how long the subsidies will persist. As discussed above, we illustrate LCOEs with credits that begin declining in 2032, but extended tax credits would reduce LCOEs across longer horizons, potentially across multiple decades.

LCOE estimates, including those reflected in figure 8, incorporate assumptions about the interest rate faced by a project developer. Figure 9, panel A, plots LCOEs under different discount rates, highlighting how various technologies respond to increases in the cost of borrowing (across an illustrative range of rates). Low-carbon technologies are all more sensitive to increases in interest rates, reflecting the large upfront investments required and relatively low operating costs, including a lack of fuel costs (except in the case of CCS-equipped capacity). Figure 9, panel B, plots LCOEs under different assumptions about labor costs. Nuclear plants are the most sensitive to increases in labor inputs, and labor's share of total plant costs ranges from 17 percent (for onshore wind) to 44 percent (nuclear). Section VII below explores the sensitivity of IRA fiscal costs and emissions impacts under different assumptions about interest rates and other input costs.

III.B. Electricity Market and Price Impacts of Tax Credits

In addition to encouraging the construction of new electricity generating resources, IRA tax credits will have an impact on how new and existing resources are operated. IRA incentives can have large impacts on electricity markets, since credits can lower wholesale prices and increase the prevalence of negative-priced periods. Generation technologies that collect production-based tax credits will have strong incentives to operate even when wholesale prices are low and even negative (which is more common during hours when output from these resources is highest) to collect credits.[31] For example, the variable costs of operating a wind turbine are negligible, and the operator could receive as much as \$33/MWh in subsidies. As long as wholesale prices are above –\$33/MWh, it is profitable for the wind plant to generate electricity.[32] Negative prices alter economic signals for market entry and exit of generators, shift incentives for locational decisions and balancing resources (e.g., energy storage, transmission), affect system operations, and change the economics of end-use electrification and new loads (e.g., hydrogen production, cryptocurrency mining).

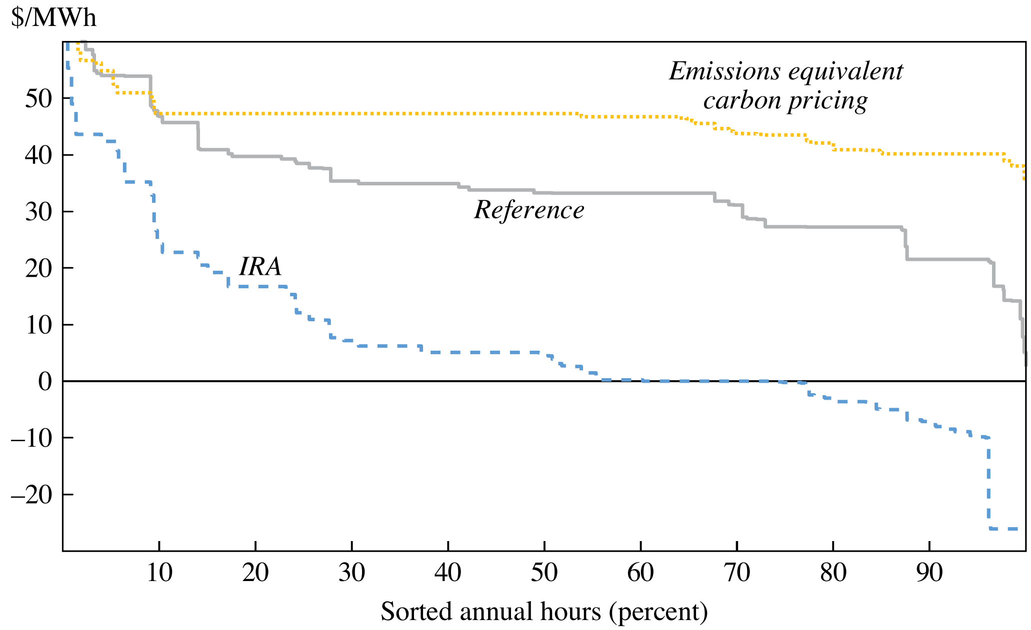
Electricity markets have already experienced periods of negative wholesale prices, driven in large part by subsidized renewables.[33] For example, California and Texas, areas with significant renewable capacity, experienced the most periods with negative wholesale electricity prices in 2021 and the first half of 2022 (Malik 2022). Energy storage can play an important role in shifting electricity from periods with low prices to periods with higher prices. Since the IRA extends tax credits to stand-alone energy

31. Output-based tax credits under the IRA include the technology-neutral PTC, credits for captured CO_2, and credits for clean hydrogen.

32. These negative offer prices can be as low as –\$70–90/MWh for coal with CCS taking 45Q credits for captured CO_2 (Bistline, Roney, and others 2023).

33. Negative bids from subsidized resources are not the only cause of negative prices in current markets. Local transmission congestion and system-wide oversupply (e.g., due to flexibility constraints) also play roles (Seel and others 2021).

Figure 10. Wholesale Electricity Price Duration Curves for the Reference, IRA, and Carbon Price Scenarios



Source: Authors' calculations.

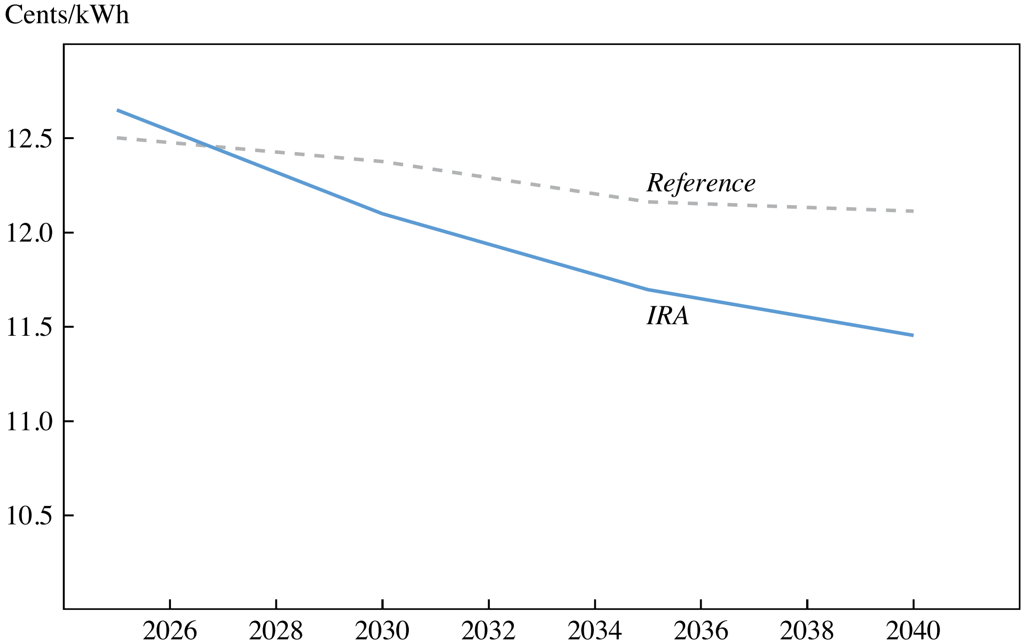
Note: Curves are shown for the Southwest Power Pool (SPP) region in 2050, which includes South Dakota, Nebraska, Kansas, and Oklahoma.

storage, deployment of these resources could be significant: comparisons in section II illustrate how deployment of storage technologies could total over 10 GW per year (compared with about 7 GW of energy storage installed cumulatively as of 2022).

Even with storage deployment, figure 10 shows how IRA tax credits increase the frequency of zero- and negative-priced hours, which comprise nearly half of all hours in the wind-dominant Southwest Power Pool (SPP) region. Ultimately, the frequency of negative-priced periods depends on (1) the fraction of generators taking different tax credits (since negative-priced periods are more likely the more generators take the PTC rather than the ITC), (2) the extent of generator entry and exit (which affects shares of IRA-subsidized resources), and (3) regional supply-demand balances (which influence supply curves and ultimately which technologies are on the margin).[34] In contrast, emissions equivalent carbon pricing (as presented

34. There are many hours with positive clearing prices, even with significant deployment of zero-marginal-cost resources—energy storage bids at its opportunity cost, gas-fired capacity is on the margin in many hours, and not all subsidized resources are incentivized to make negative bids (e.g., those electing to take the ITC).

Figure 11. **Load-Weighted National Average of Residential Retail Electricity Prices over Time**



Source: Authors' calculations.
Note: Values are based on US-REGEN modeled scenarios with IRA incentives and a counterfactual reference without IRA. Note the truncated vertical axis.

in table 3) increases wholesale prices relative to the reference. In terms of policy, there are different perspectives on the importance of wholesale and retail market changes for deeply decarbonized energy systems, which may be dominated by resources with zero or negative short-run marginal costs, energy-limited devices such as storage, and cross-sector interactions and subsidized resources, which may exacerbate "missing money" problems and out-of-market payments for resource adequacy and reliability (Ela and others 2021; Mays, Morton, and O'Neill 2019; Hogan 2019; Conejo and Sioshansi 2018).

While the analysis of price pressures has focused on the production-based incentives in the electricity market, similar incentives will exist in the manufacturing sector, where the IRA offers subsidies per unit produced (e.g., solar panels). These subsidies will put downward pressure on market prices for all suppliers.

Annual retail electricity price impacts of IRA incentives are shown in figure 11. Modeled prices in US-REGEN illustrate how IRA incentives lower national long-run retail prices by 2.2 percent in 2030 and 5.4 percent in 2040, relative to a counterfactual scenario without IRA incentives, which already indicates a trend of declining prices over time.[35] These changes are consistent with other studies of the IRA (Roy, Burtraw, and Rennert 2022), which also depend critically on assumed fuel price trajectories. Beyond lowering household and firm electricity costs, an advantage of retail electricity price declines is that they can further encourage end-use electrification, which is a central decarbonization strategy in many studies (DeAngelo and others 2021).

III.C. Distributional Implications

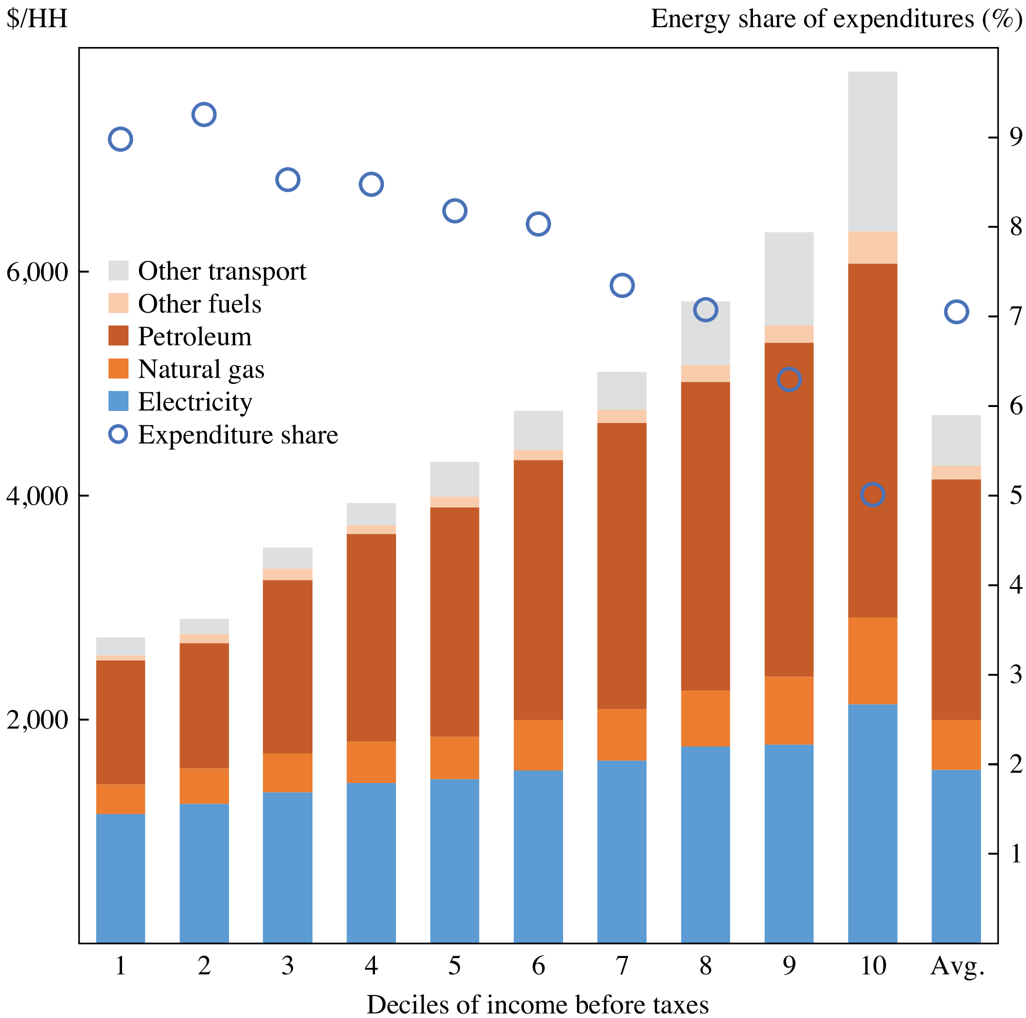
Households across the income distribution will experience different impacts from the IRA. Lower-income households spend a slightly larger share of their income on electricity than higher income households (figure 12), so by reducing the costs of electricity, the IRA will provide greater benefits for many lower-income households. The relationship between income and consumption shares is stronger for petroleum (primarily gasoline for transport), so the means-tested tax credits for electric vehicles in the IRA can help lower-income households that buy an electric vehicle reduce these expenditures. For example, Burnham and others (2021) find that even at gasoline prices of less than $2.63 per gallon, fuel costs for electric vehicles are about half the fuel costs for a comparably sized vehicle with an internal combustion engine. Impacts over the next decade or more will depend heavily on expected electricity and gasoline prices. Burnham and others (2021) also suggest that maintenance costs are significantly lower for electric vehicles. Finally, Linn (2022) describes how electric vehicle subsidies may lead to lower prices for gas-powered vehicles by interacting with existing fuel economy standards and state-level zero-emission vehicle programs. Since low-income households are more likely to buy gas-powered vehicles, this effect is progressive.[36]

The economic incidence of the tax credits will also factor into the distributional outcomes. US-REGEN assumes perfectly competitive markets, meaning that the tax credits are passed through to consumers. In electricity

35. Retail prices in US-REGEN are built up from modeled generation prices. These regional prices are calibrated to observed base year prices, including a markup to reflect sunk costs built into the rate base. Future retail markups are scaled based on projected changes to transmission and distribution costs as a function of the changing load and resource mix. Note that prices increase in 2025 under the IRA due to the assumption in the reference case that solar and wind tax credits maintained their previous step-down schedule, which leads forward-looking firms to front-load investment in these resources to take advantage of expiring credits.

36. US-REGEN captures many of these effects, and in ongoing work, we quantify the expected impacts of the IRA by region and income level.

Figure 12. Annual Household Energy Expenditures across Income Deciles



Source: US Bureau of Labor Statistics.

Note: Data are from the BLS 2022 Consumer Expenditure Surveys, table 1110, showing data for 2021 for deciles of income before taxes; https://www.bls.gov/cex/tables/calendar-year/mean-item-share-average-standard-error/cu-income-deciles-before-taxes-2021.pdf. Energy shares of expenditures on the secondary axis are based on average annual expenditures for consumer units within the decile.

markets, this assumption means that wholesale electricity buyers pass on the full benefits of the subsidies to end-use consumers. The second step involves assumptions about the political and regulatory processes that determine regional retail rates. Most other IRA analyses make the same assumption that the full values of the tax credits are passed through to consumers.[37] In reality, electric vehicle manufacturers, clean electricity

37. The analysis by Cole and others (2023), which presents several scenarios that vary the share accruing to the consumer, is the lone exception of which we are aware.

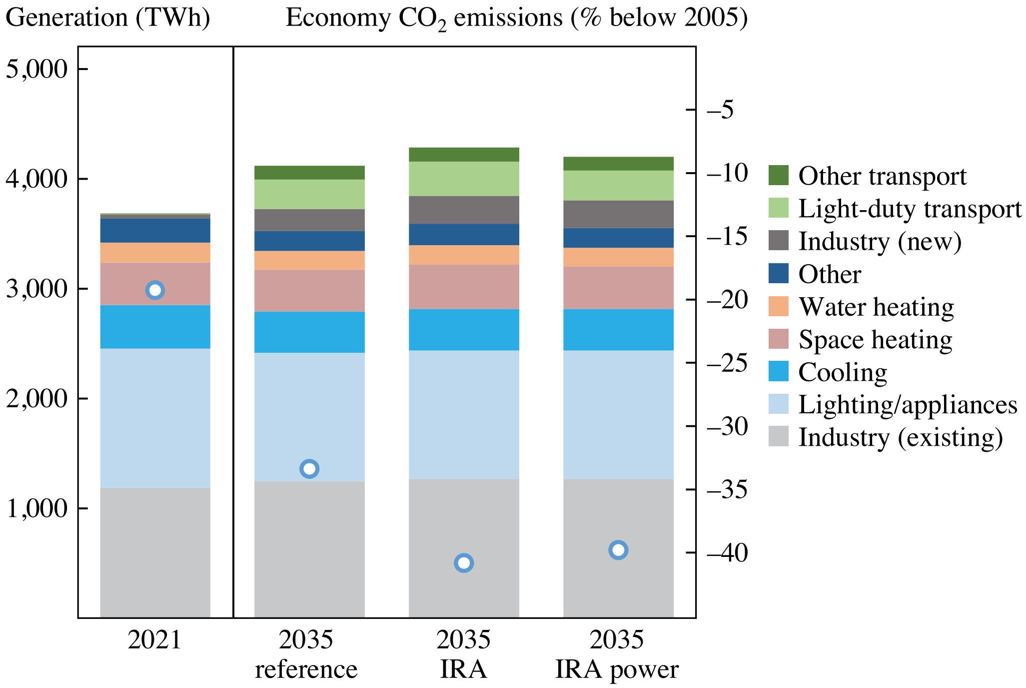
producers, and other firms and their shareholders may capture some of the tax credits. As described in online appendix B, an index of clean energy stocks fell relative to the market on December 19, 2021, when Senator Manchin, the pivotal fiftieth Democratic vote, went on television to say he was done negotiating on the bill then known as Build Back Better, which contained many of the same climate provisions as the IRA. It increased on July 27, 2022, when the Senate deal on the IRA was announced. These movements suggest that producers could gain from the tax credits and that they will not be fully passed through to consumers. Particularly if the domestic content and labor provisions change behavior (i.e., they are marginal), non-energy firms and their workers may also gain from the tax credits. In the case of electric vehicles, the incidence of the credits, and perhaps even the market structure for vehicle sales, will depend crucially on whether the Treasury guidance exempting leased vehicles from requirements on battery sourcing and eligibility caps stands. Sorting out the incidence of different IRA provisions and measuring it empirically will be useful tasks for future research.

III.D. Electrification Implications

The IRA alters electricity demand through two channels—by directly subsidizing the adoption of electric end-use technologies (e.g., the electric vehicle and heat pump tax credits discussed in section I.A) and by lowering electricity prices (as discussed in the section III.C). Technological change and consumer choice lead to transport, industrial, and buildings electrification and to a 12 percent increase in electricity demand by 2035 in the reference scenario without the IRA (figure 13). IRA incentives increase load growth by 4 percentage points to 16 percent from current levels by 2035.

To isolate the impact of lower prices on electricity demand, we include a scenario with only the IRA's power sector tax credits, which reach prices similar to those shown in figure 10. By 2035, demand for electricity increases in this scenario by 14 percent from current levels, which is midway between the reference without the IRA (12 percent) and the IRA scenario (16 percent), as shown in figure 13, with most of these increases relative to the reference coming from industry. Since there are more-limited IRA tax credits that directly incentivize industrial electrification, electricity growth in industry under the IRA is attributed primarily to lower electricity prices, which are reflected in high industrial electricity demand even with power sector IRA credits only (96 percent of growth in industrial demand under the IRA from the reference persists with only power sector credits).

Figure 13. Electricity Demand by End Use



Source: Authors' calculations.
Note: Values for 2035 are based on US-REGEN scenarios without IRA (reference), one with all IRA incentives (IRA), and one with power sector IRA incentives only (IRA power).

In contrast, incremental passenger vehicle electrification under the IRA is largely from the clean vehicle credits, as less than 2 percent of growth in passenger vehicle electricity demand from the reference occurs with power sector provisions alone. There are several reasons for this muted demand elasticity, even with lower wholesale electricity prices (see figure 10), including stock turnover dynamics, limited effects of fuel costs in purchase decisions, and wholesale electricity prices being only one component of retail prices (i.e., unsubsidized transmission and distribution costs could comprise large shares of retail prices).

IV. Macroeconomic Framework

In this section, we consider the macroeconomic impacts of the climate provisions of the IRA. We present a conceptual framework for understanding the macroeconomic impacts of clean power tax credits. Using a neoclassical growth model with clean energy capital, we show both the long-run and short-run macroeconomic impacts of investment and production tax credits on macroeconomic variables: interest rates, wages, output, and consumption. We show how macroeconomic outcomes vary depending on labor market conditions, bottlenecks in clean energy investment, reductions in the price of capital due to learning by doing, and domestic sourcing requirements. The model details are presented in online appendix A.

IV.A. Impact of Tax Credits

We start by characterizing how increases in clean energy tax credits impact macroeconomic aggregates. For simplicity, assume that household electricity demand is inelastic and fixed at $\overline{E}^h$. Then changes in power generation impact electricity prices and demand only via industrial demand. Model equilibrium can be reduced to the following three equations:

$$p_t^c\left(1-\tau_t^{inv}\right)u_c\left(C_t\right)=\beta u_c\left(C_{t+1}\right)\begin{bmatrix}\left(F_e\left(E_{t+1}^f,\overline{N}\right)+\tau_{t+1}^p\right)G_c\left(K_{t+1}^c\right)\\+p_{t+1}^c\left(1-\tau_{t+1}^{inv}\right)\left(1-\delta_c\right)\end{bmatrix}, \tag{2}$$

$$C_t=F\left(E_{t+1}^f,\overline{N}\right)-p_t^c\left(K_{t+1}^c-\left(1-\delta_c\right)K_t^c\right),\text{ and} \tag{3}$$

$$G\left(K_t^c\right)=E_t^f+\overline{E}^h, \tag{4}$$

which jointly determine the equilibrium path of electricity supplied to industry E_t^f, household consumption C_t, and clean energy power generation K_{t+1}^c as a function of underlying parameters and the exogenous path of capital prices p_t^c and fiscal policy.

In steady state, the level of clean energy capital is defined implicitly by the following condition:

$$p_c\left(\frac{1}{\beta}-1+\delta_c\right)\left(1-\tau_{inv}\right)=\left(F_e\left(G\left(K_{ss}^c\right),\overline{N}\right)+\tau_p\right)G_c\left(K_{ss}^c\right). \tag{5}$$

The left-hand side of this equation is just the steady-state user cost of capital, while the right-hand side is the marginal product of capital taking into account the effect of both power generation capital on electricity production and electricity production on overall output. Under mild conditions for the production function F and the power generation function G (see online appendix A), the steady-state level of capital K^c_{ss} is increasing in both the investment tax credit and the production tax credit. Figure 14 shows the user cost of capital and the marginal product of capital, which pin down the steady-state level of clean energy capital. The shift in user cost (left-hand side) and marginal product (right-hand side) under an investment and production tax credit are shown.

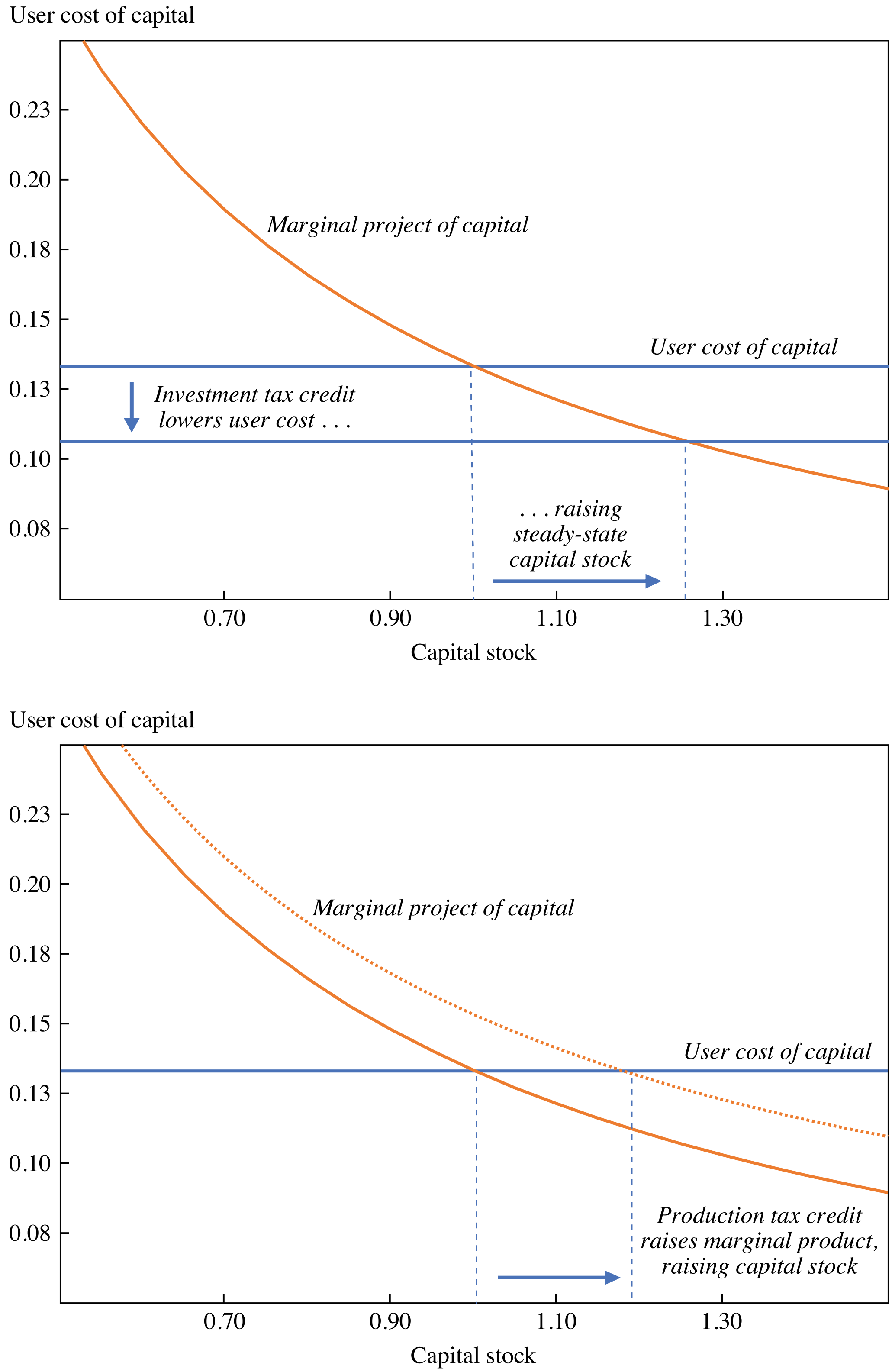
An increase in the clean energy capital stock increases other macroeconomic quantities in steady state; the increase in electricity supplied to industry raises output and investment. Labor productivity and wages also rise due to an increase in industrial electricity supply. Assuming that the subsidies are not too large, consumption also increases in steady state. On the price side, the price of electricity falls, while the real interest rate is unchanged ($r = 1/\beta - 1$).

Effectively, production and investment subsidies are a negative capital tax, raising the capital stock and productivity. To the extent that the weight of energy in the aggregate production function is low or the marginal product falls sharply with higher electricity supply, the tax credits have only marginal benefits in terms of productivity, output, wages, and consumption. However, the price of electricity would fall more sharply in this case. As with other supply-side tax policies with dynamic effects, the fiscal burden would be tempered somewhat by higher output (relative to a static analysis).

The transition path to this new steady state can also be characterized. An increase in the investment or production tax credit lowers consumption on impact while raising investment. The real interest rate rises initially before gradually falling back to its long-run level. Labor productivity, wages, and electricity prices inherit the dynamics of the capital stock, with wages and productivity rising gradually along the transition path to their higher steady state level. On the fiscal side, the increase in interest rates would raise debt-servicing costs on impact, with higher output mitigating the impact on the debt-to-GDP ratio over time.

Given that output, consumption, investment, wages, and productivity ultimately rise over the long run (and the price of electricity falls), a natural question to ask is if a strictly positive subsidy is welfare-improving. So far, we have not considered the impact of the policy on emissions or in mitigating damages from climate change, so the question is solely about whether the macroeconomic benefits are welfare-improving. The answer is no.

Figure 14. Steady-State Capital after an Increase in Investment Tax Credit and in Production Tax Credit



Source: Authors' calculations.

For the planner, the aggregate resource constraint holds, and the optimal allocation for clean energy capital would be implemented only if both the ITC and PTC are set to zero.

IV.B. Alternative Macroeconomic Conditions

In the baseline model, we assumed a fixed, inelastic supply of labor. Supporters of the Inflation Reduction Act have argued that by subsidizing construction and manufacturing, the legislation may help create jobs by increasing the labor force and by creating jobs in communities/regions that have seen structurally weaker labor markets (Williams, Zhavoronkov, and Madland 2022). Power generation would likely stimulate labor demand in less urbanized regions, and upstream labor demand for raw materials and equipment are also likely to be present in regions that have seen less robust labor markets.

One way to incorporate this channel is to assume that there exists a pool of labor that is currently outside the labor force but has a relatively low reservation wage. If aggregate labor supply is given by an upward-sloping labor supply curve (i.e., $w_t = N_t^{\varphi}$), then the investment or production tax credit increases employment as a higher capital stock boosts the marginal product of labor and labor supply adjusts to meet higher labor demand. In steady state, the increase in the clean energy capital stock is larger than in the case of an inelastic labor supply. Steady-state consumption, output, and labor productivity all increase by more than in the baseline case. This case also sees a larger level of subsidies, but a sharper decline in the price of electricity and possibly a decline in subsidy cost as a share of GDP.

However, a more elastic labor supply results in a *larger* increase in interest rates and decline in consumption (relative to the baseline case) as the initial demand impact dominates; an elastic labor supply implies a larger increase in investment given a larger increase in the desired capital stock. Along the transition path, as the capital stock rises, employment rises to keep the marginal product of labor from rising as much as in the baseline case, and the real interest rate gradually converges back to its long-run value $1/\beta - 1$.

Given supply chain disruptions and dislocations during the pandemic, another relevant departure to consider is the presence of bottlenecks that constrain the ability to ramp up construction of clean energy facilities or the manufacturing of equipment for those facilities. Domestic content requirements or delays in siting or transmission access could function to either raise the cost or outright prevent investment in new clean power generation despite the financial incentives provided in the IRA. Bottlenecks are classified as either "market" or "nonmarket"; the former shows up as an increase in the relative price of capital p_t^c when a (possibly time-varying) investment constraint is reached, while the latter is simply a constraint on investment that does not impact price. Market bottlenecks could be thought of as inelastic supply of a key material (like lithium or copper), while nonmarket bottlenecks could be thought of as prohibitions on the siting of new solar or wind projects.

Our model can be generalized to account for nonmarket bottlenecks by simply introducing a constraint on investment: $I_t^c \leq \overline{I}$. The intertemporal optimality condition for investment is now

$$p_t^c\left(1-\tau_t^{inv}\right)\lambda_t+\mu_t=\beta\lambda_{t+1}\left[\begin{array}{c}\left(F_e\left(E_{t+1}^f,\overline{N}\right)+\tau_{t+1}^p\right)G_c\left(K_{t+1}^c\right)\\ +\,p_{t+1}^c\left(1-\tau_{t+1}^{inv}\right)\left(1-\delta_c\right)\end{array}\right]+\beta\mu_{t+1}\left(1-\delta_c\right), \tag{6}$$

where μ_t is the Lagrange multiplier on the investment constraint in period t.

If the constraint is binding in steady state, then investment is constrained at its upper bound $\overline{I}$, and the user cost of capital is above the level that would obtain absent any bottlenecks. Relative to the baseline case, the capital stock is lower, as is output. The price of electricity is higher, and subsidies paid are lower. Even when the constraint does not bind in steady state, bottlenecks may constrain investment along the transition path. In this case, the path of investment is below the baseline case until the desired investment rate falls below the constraint. Since investment is lower initially, the rise in the interest rate and decline in consumption are muted in the case where bottlenecks initially bind. Bottlenecks mitigate the macroeconomic impact since the rise in investment is attenuated and the required decline in consumption to meet desired investment is lessened.

Market bottlenecks that manifest as a higher price of investment carry the same implications for the steady-state capital stock and transition dynamics. Indeed, the Lagrange multiplier in the nonmarket bottlenecks case is effectively a shadow price. For concreteness, assume that $p_t^c = p_c$ if $I_t^c < \overline{I}$—that is, the price of investment is constant at its steady-state value p_c so long as the investment constraint is slack. Then we can define a market price p_t^c when $I_t^c = \overline{I}$ that satisfies the investment Euler equation above:

$$p_t^c = p_c + \frac{\mu_t}{\lambda_t\left(1-\tau_t^{inv}\right)}. \tag{7}$$

Substituting for μ_t in the Euler equation above returns a Euler equation that delivers the same equilibrium path of consumption and investment as the nonmarket bottlenecks case. Likewise, the steady-state level of the capital stock would also be depressed (relative to baseline) because the tax credits are offset by a rise in the user cost of capital.

The distinction between market and nonmarket bottlenecks is not relevant for investment, but it does carry implications for the fiscal cost. With both types of bottlenecks, less clean energy investment is deployed, lowering fiscal cost. But market bottlenecks carry a counteracting effect on prices. Despite lower real investment, a higher price of investment may be sufficient to raise the fiscal cost of an investment tax credit. This issue is unique to the ITC since the PTC is tied to the quantity of clean energy produced. In the extreme case that investment is already against its constraint, the tax credit is fully offset by a rise in the price p_t^c, and the government subsidy generates no new investment. Indeed, there may a Laffer curve for ITC fiscal cost where fiscal cost is non-monotonic in the level of investment; with extreme bottlenecks no investment occurs, so fiscal expenditure is zero, but very high prices due to bottlenecks keep fiscal expenditure high even for low levels of real investment.

IV.C. Learning by Doing

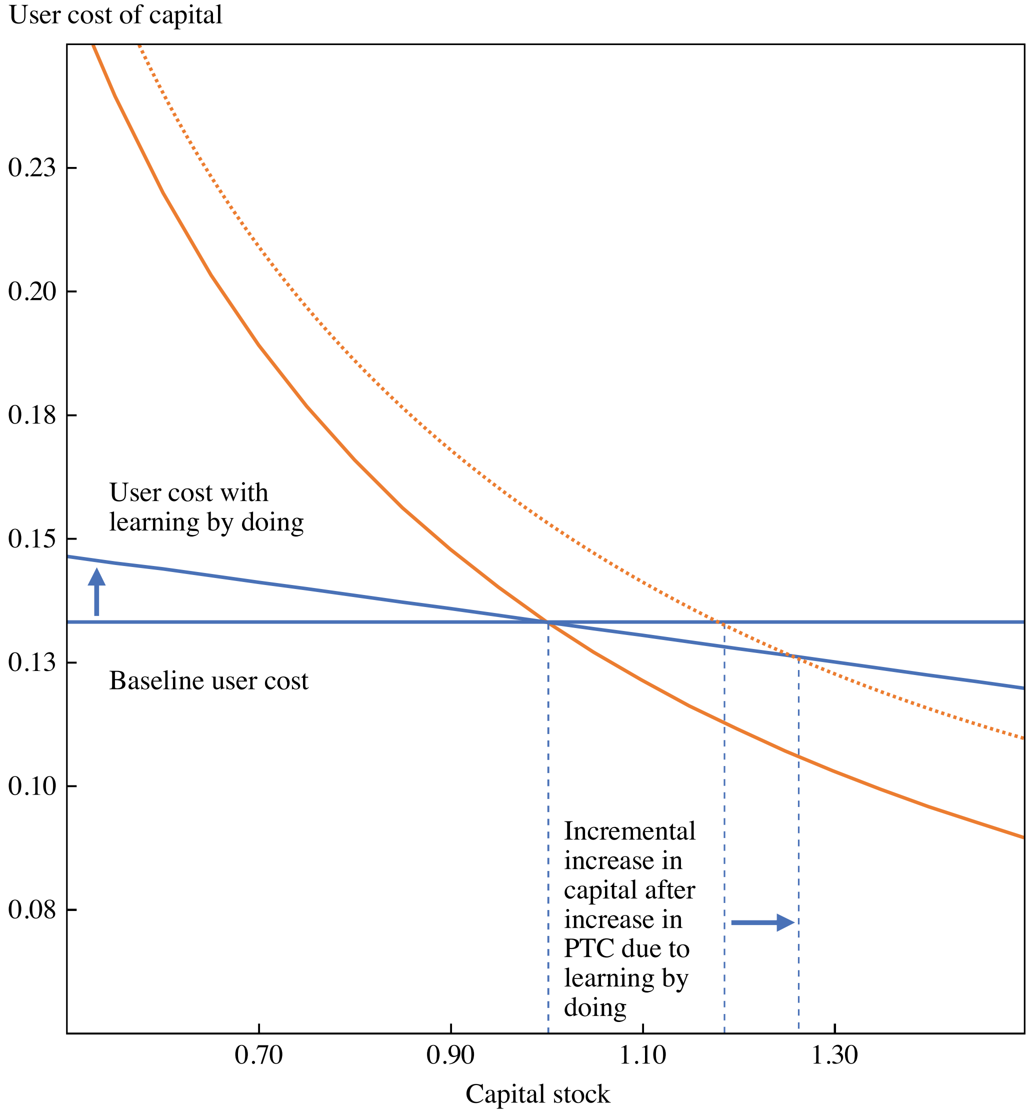
Proponents of the subsidies approach to clean energy transition have emphasized the dramatic decline in solar and wind production costs over the last decade and the potential for further declines in clean energy production costs. The Inflation Reduction Act includes a host of incentives to support the supply chain for clean energy and generous incentives for technologies that are not yet cost competitive, like carbon capture and clean fuels. To the extent that higher production spurs learning by doing and cost reductions, how might that impact the clean energy transition?

A classic formulation of learning by doing is Wright's law, which expresses marginal cost as a function of cumulative production (Wright 1936; Way and others 2022).[38] Accordingly, we model learning by doing by making the price of capital a decreasing function of the current stock of clean energy capital: $p_t^c = p_c\,(K_t^c)$.[39] For modest levels of learning by doing, the user cost of capital falls as more clean energy capital is produced.

38. The presence of credit constraints or locally increasing returns to scale would generate similar results.

39. Modulo of depreciation, which is low for power structures, the current capital stock is equal to cumulative production.

Figure 15. Learning by Doing Results in Larger Increases in Steady-State Capital after an Increase in PTC



Source: Authors' calculations.

Relative to the baseline model, this implies a larger increase in the clean energy capital stock in steady state for a given subsidy policy. Clean energy subsidies now lead to a larger increase in output, labor productivity, and wages and a larger decline in the price of electricity.[40] Figure 15 shows how the user cost becomes downward sloping with learning by doing, magnifying the impact of either the ITC or PTC.

40. If the price of capital is sufficiently sensitive to production, multiple steady states are possible. In particular, if over some region the price of capital drops faster than the marginal product of electricity, multiple steady states will obtain.

IV.D. Domestic Sourcing

As noted earlier, the IRA's investment tax credit is eligible for bonuses based on whether labor standards and domestic sourcing requirements are satisfied. The labor and domestic sourcing requirements have two distinct impacts on the equilibrium level of investment that is eventually realized. One way to model domestic sourcing is to assume two distinct prices for investment: $p_t^{c,low}$ and $p_t^{c,high}$, with associated investment tax credits of $\tau_t^{c,low}$ and $\tau_t^{c,high}$. The household's budget constraint becomes

$$(8) \qquad C_t + p_t^{c,low}\left(1-\tau_t^{c,low}\right)I_t^{c,low} + p_t^{c,high}\left(1-\tau_t^{c,high}\right)I_t^{c,high} = F\left(E_t, \overline{N}\right).$$

In steady state, the household chooses whichever option delivers the lowest user cost of capital. Importantly, the higher relative cost of investment may be chosen if the labor and domestic sourcing bonus is sufficiently generous. In this sense, the labor and domestic sourcing bonuses raise the clean energy capital stock, since the lowest user cost option (inclusive of the tax credit) is chosen in equilibrium. That the domestic bonus may lead to higher clean energy capital is a function of the generosity of the tax credit and does not mean it is optimal. Absent some other benefit or externality, the planner would always choose the lower cost investment $p_t^{c,low}$ to minimize the cost of achieving some given level of emissions.

Domestic sourcing has another distinct element—the use of imports to meet increased clean energy investment demand. Suppose that domestic and foreign producers both sell at a relative (domestic) price of p_t^c and are eligible for the same ITC. Then the absence of domestic sourcing would allow for a faster increase in investment with less crowding out of domestic consumption. The steady-state level of clean energy capital would be unchanged (relative to baseline), but the real interest rate would rise by less, and decarbonization of electricity production would be faster. From an emissions perspective and given conditions of full employment, the inability to import and slowdown in investment are likely to be the most important impact of domestic sourcing requirements.

IV.E. Crowding Out and Capital Taxation

Our model so far has abstracted away from the funding mechanisms of the IRA and possible impacts on the non-energy capital stock. It is straightforward to add non-energy capital to the production function and characterize the effect of the clean energy subsidies on non-energy capital. As was the case before, the subsidies increase the steady-state clean energy capital stock but also increase the non-energy capital stock. A lower price of electricity increases the rate of return and demand for non-energy capital in the same way that it increases labor demand. There is no long-run crowding out; private non-energy capital is *crowded in*. Output, consumption, wages, and labor productivity all rise in the long run by more than in the baseline model.

However, in the short run, investment in clean energy capital competes with non-energy capital and consumption. Depending on the elasticity of intertemporal substitution, non-energy investment and consumption may fall while clean energy investment crowds out these other uses. For sufficiently large crowding out of non-energy capital investment, it is possible, in the short run, that output, wages, and labor productivity initially decline before rising to their higher steady-state values.

The IRA is estimated to reduce deficits through a combination of reductions in prescription drug spending in Medicare, increased revenue from tax enforcement, and an increase in corporate taxation. So far, we assume that the tax credits in the IRA are funded via a lump sum tax levied on the representative household that does not distort behavior.[41] However, the corporate tax and tax enforcement provisions in the IRA may have an impact closer to a rise in the marginal tax rate on capital. In standard macroeconomic models, corporate tax increases can have substantial effects on investment and the capital stock.

Depending on the magnitude of the capital tax, the steady-state increases in output, wages, and labor productivity may be reversed if the long-run crowding out for non-energy capital is large enough. However, in the short run, the rise in capital taxation would mitigate the crowding out and interest rate effects of the clean energy subsidies. A higher capital tax, by lowering non-energy investment demand, would free output for consumption or clean energy investment, mitigating or reversing the increase in real interest rates. To the extent that the capital taxation effects dominate, output, consumption, and non-energy investment would gradually fall along the transition path to their lower steady-state values.

V. Clean Energy Subsidies versus Carbon Pricing

Subsidy-based approaches and emissions pricing are two widespread policy instruments to reduce emissions, each with trade-offs across economic, environmental, and political dimensions. While the United States does not

41. The macroeconomic impact would be identical if instead the policy were fully deficit financed (assuming that taxes eventually rise to stabilize the debt-to-GDP ratio).

have a federal price on carbon emissions, 55 percent of the greenhouse gas emissions in the rest of the Organisation for Economic Co-operation and Development (OECD) are subject to an explicit Pigouvian carbon price, in the form of either a carbon tax or cap-and-trade system (OECD 2022; Timilsina 2022). Several US states have carbon pricing covering varying shares of their carbon emissions, ranging from under 20 percent in Massachusetts to almost 75 percent in California. In total, explicit carbon pricing covers 6 percent of US GHG emissions.[42]

It is instructive to compare the subsidy-based approach to carbon pricing.[43] At a high level, both subsidies and carbon pricing change the relative prices of non-emitting and emitting fuels. Some of the provisions of the IRA are output-based credits, which directly subsidize production of zero-carbon energy. If every unit of subsidized production offset the same amount of carbon emissions (for example, if all nonsubsidized energy were generated by the same fossil fuel–fired technology with the same emissions per unit of energy), then the production tax credits would be identical to a carbon price. In other words, subsidizing a clean MWh of electricity at $10 per MWh would displace as much carbon from the electricity sector as taxing an emitting MWh of electricity at $10 per MWh, assuming inelastic demand.

V.A. Comparison to a Carbon Tax

To place more structure on the question of subsidies versus carbon pricing, we extend our macroeconomic framework from the previous section to allow for fossil fuel power generation. We now allow for both fossil fuel and clean energy capital, with relative price of investment p_t^f and p_t^c. Electricity generated from fossil fuel capital is given by the generation function $G^f(\cdot)$, with capital as the only factor of production; electricity generated from clean energy capital is given by the generation function $G^c(\cdot)$. Total electricity production is simply the sum of electricity generated from fossil fuel and clean energy capital (i.e., perfect substitutes). The details of the model extension are shown in online appendix A.

Relative to households in the baseline model, households now may invest in both clean energy and fossil fuel capital. Clean energy is eligible for both

42. The World Bank, "Carbon Pricing Dashboard," https://carbonpricingdashboard.worldbank.org/map_data.

43. Most sources describe policies as carbon pricing, although many of the policies cover GHG emissions in addition to CO_2. As noted above, the IRA introduces a price on methane emissions from specified entities in the oil and gas sector. These GHG emissions are not included in the 6 percent figure, which was based on programs through April 2022.

an investment tax credit and production tax credit. Fossil fuel energy instead faces a carbon tax where τ_t^f is a carbon tax and κ is a technological constant relating electricity generated from fossil fuels to carbon emitted. It is worth noting that a carbon tax is identical to an appropriately scaled negative production tax credit. Revenues raised from a carbon tax are rebated lump sum.

The household's optimal choice for clean energy and fossil fuel investment are now given by two Euler equations:

$$p_t^c\left(1-\tau_t^{inv}\right)\lambda_t = \beta\lambda_{t+1}\begin{bmatrix} G_1^c\left(K_{t+1}^c\right)\left(p_{t+1}^e+\tau_{t+1}^p\right) \\ +\,p_{t+1}^c\left(1-\tau_{t+1}^{inv}\right)\left(1-\delta_c\right)\end{bmatrix} \text{ and} \tag{9}$$

$$p_t^f\lambda_t = \beta\lambda_{t+1}\left[G_1^f\left(K_{t+1}^f\right)\left(p_{t+1}^e+\tau_{t+1}^f\kappa\right)+p_{t+1}^f\left(1-\delta_f\right)\right], \tag{10}$$

where λ_t is the household's marginal utility of consumption. In steady state, the fossil fuel and clean energy capital stocks are jointly determined by conditions equating the user cost of capital to its marginal product, analogous to the case with just clean energy capital:

$$p_c\left(1-\tau_{inv}\right)\left(r+\delta_c\right) = G_1^c\left(K_c\right)\left(p_e+\tau_p\right) \text{ and} \tag{11}$$

$$p_f\left(r+\delta_f\right) = G_1^f\left(K_f\right)\left(p_e+\tau_f\kappa\right). \tag{12}$$

If both generation functions G^f and G^c are constant return to scale, then the marginal increase in electricity production is constant for each unit of capital. In that case, only one of the steady-state conditions can hold in equilibrium (we are implicitly assuming that K_c and K_f are positive in steady state). In effect, a corner solution obtains in the long run, and only clean or fossil fuel technology is utilized. Increases in carbon tax and ITC/PTC would have an impact on this choice only if the unsubsidized (utilization-adjusted) user cost for fossil fuel generation was lower than the user cost and the carbon tax or ITC/PTC is large enough to make the relative utilization-adjusted user cost for clean energy lower. However, to the extent that clean energy has a lower user cost, further increases in the carbon tax or ITC/PTC do not have an impact on the steady-state level of capital stock. The level of capital stock is pinned down by the price of electricity p_e, which falls as the power generation capital stock rises.

If the generation functions G^f and G^c exhibit decreasing returns to scale, then both technologies may be utilized in steady state. In this case, incremental increases in either the carbon tax or the ITC/PTC will shift the energy mix toward clean energy. Nevertheless, the policies are not fully interchangeable so long as we rule out negative carbon taxes or negative subsidies. While either policy could achieve a given target for the mix of clean and fossil fuel generation, the overall level of electricity production rises under an ITC/PTC policy and falls under a carbon tax policy. The emissions reduction is, hence, greater under a carbon tax, but output, consumption, productivity, and wages all fall relative to those in the ITC/PTC policy.

The emissions difference between a clean energy subsidy policy and a carbon tax depends on the price elasticity of electricity demand. Relative to a carbon tax, subsidies encourage electricity consumption and discourage conservation. If household and industrial demand for electricity is sensitive to price, a carbon tax will have a relatively large effect on electricity consumed and hence emissions. By contrast, a subsidy policy—by encouraging electricity consumption—would partially undo the switch from fossil fuel to clean energy by raising overall electricity consumption (Holland, Hughes, and Knittel 2009).

One argument against carbon taxes is that these taxes have an adverse impact on poor households with inelastic energy consumption and whose energy consumption is a larger share of household expenditure. So long as *absolute* energy consumption is increasing in household income (see figure 12), a carbon tax recycled as a lump sum dividend provides poor households sufficient resources to both maintain their pretax energy consumption *and* increase non-energy consumption.

V.B. Optimal Policy

The difference in subsidy versus carbon tax policy in terms of electricity prices and electricity consumption begs the question of whether a subsidy policy is economically preferable to a carbon tax. Is there a case for a clean energy subsidy in lieu of a carbon tax? To address this question, we augment our baseline model to include damages from emissions and consider the planner's problem. As before, we assume only emissions from electricity production, ignoring transportation or land use. The details of the planner's problem are available in online appendix A.

The planner's choice from clean energy and fossil fuel capital are given by

$$p_t^c = \frac{1}{1+r_t}\left[p_{t+1}^e G_c'\left(K_{t+1}^c\right) + p_{t+1}^c\left(1-\delta_c\right)\right]$$

$$p_t^f = \frac{1}{1+r_t}\left[p_{t+1}^e G_f'\left(K_{t+1}^f\right) + p_{t+1}^f\left(1-\delta_f\right)\right] - \underbrace{\mu_{t+1}\kappa G_f'\left(K_{t+1}^f\right)}_{\text{time-varying carbon tax,}}$$

where μ_{t+1} is the multiplier that implicitly prices the damages from cumulative carbon emissions.

It is clear that the optimality condition for clean energy capital is the same as what would obtain with zero subsidies; that is, even in the presence of fossil fuel damages, the planner's allocation for clean energy capital is unchanged relative to the household. The condition that is distorted is the choice of fossil fuel capital, with the planner taking into account that additional fossil fuel capital increases damages from emissions. To implement the planner's allocation, the fiscal authority would need to levy a carbon tax that enters into the Euler equation for fossil fuel capital (the final expression in the equation). Note that we have made assumptions on neither the elasticity of electricity demand nor the relative price of clean versus fossil fuel capital.

Since emissions are cumulative and production exhibits diminishing returns in electricity, the (asymptotic) steady state features zero fossil fuel capital and a carbon tax high enough to ensure that only clean energy capital is utilized. The price of electricity will rise to incentivize increases in clean energy capital investment along with reductions in electricity demand.

Why does the planner rely exclusively on the price of electricity to incentivize a switch to clean energy power generation? The intuition is that subsidies do not change the underlying resource cost of clean energy capital. The incentive to choose power generation via clean versus fossil fuel capital depends only on the relative technological cost (i.e., p_t^c versus p_t^f). The only externality comes from damages generated by reliance on fossil fuel power generation. The main benefit of fossil fuels is power generation, and this benefit must be weighed against damages from emissions; a single instrument is sufficient for correcting that externality.

V.C. Learning by Doing Externality

In the context of our model, introducing a learning-by-doing externality can restore scope for a clean energy subsidy (in addition to a carbon tax). Households now do not internalize the impact of their investment on the price of capital and therefore underinvest relative to a social planner. This can be seen by comparing the household's Euler equation for clean energy investment (in the baseline case where the price of capital is exogenous) with that of the planner who internalizes that faster investment results in a faster decline in price of capital. Indeed, a subsidy could be warranted even if the unsubsidized price is low enough today or expected to be low enough in the future that clean energy capital is the only power generation source in the long run.

The Euler equation for investment from the planner now differs from the private optimality condition that does not take account of the learning-by-doing externality:

$$p\left(K_t^c\right)u_c\left(C_t\right) = \beta u_c\left(C_{t+1}\right)\begin{bmatrix} p_{t+1}^e G_c\left(K_{t+1}^c\right) + p\left(K_{t+1}^c\right)\left(1-\delta_c\right) \\ -\, p_c\left(K_{t+1}\right)I_{t+1}^c \end{bmatrix}. \tag{13}$$

Under learning by doing, there is an additional marginal benefit to an added unit of clean energy capital—a lower price of future investment (the final expression in the equation). The marginal benefits from increasing capital are the discounted sum of the added electricity generated, the market value of the undepreciated capital stock, and the decrease in the cost of new investment. This last term is given by the change in the price of the capital stock multiplied by next period expected investment. This last term does not appear in the household's private Euler equation and justifies a time-varying investment credit to internalize the learning-by-doing externality.[44]

V.D. Efficiency Impacts of Tax Credits versus Carbon Pricing

Our model abstracts from many dimensions of difference between subsidies and carbon pricing. One important difference is that pricing carbon, depending on how it is implemented, could generate revenue for the government. These revenues could be used to offset other distortionary taxes (Barron and others 2018; Goulder 1995), address equity concerns (Goulder and others 2019), or help achieve other policy objectives. A subsidy-based approach costs the government the subsidy amounts and imposes the marginal cost of raising government funds on the economy.

Our model also abstracts from differences in carbon emissions between unsubsidized energy resources. In practice, these can vary considerably, meaning a single clean energy subsidy does not reflect the fact that the benefits of zero-carbon power sources will vary depending on which

44. For a steady state to exist, it must be the case that $p_c\,(K) = 0$ for sufficiently large levels of capital (i.e., there must be some diminishing returns to learning).

unsubsidized energy resources they displace. For example, hydropower plants generate electricity without emitting CO_2, while coal plants emit about a metric ton of CO_2 per MWh, meaning that at a social cost of carbon of approximately $200 per ton, carbon emissions raise the cost of coal-fired electricity by several multiples. Coal and natural gas generation have different emissions intensities, and even within a fuel type, there is considerable heterogeneity in emissions rates (Kotchen and Mansur 2014). In the transportation sector, emissions are a function of vehicle fuel economy, which also varies considerably. Under the IRA, clean energy that displaces zero-carbon energy such as hydropower is subsidized at the same rate as clean energy that displaces the dirtiest resources.

In principle, this issue could be addressed by adjusting production tax credits based on regional or temporal characteristics that are correlated with the emissions rates of the unsubsidized energy (Abrell, Rausch, and Streitberger 2019). For example, EIA shows that the electricity grid produces emissions about eight times higher in Wyoming than Washington State (McArdle and Fasching 2022), so the PTC could be increased for clean energy producers that locate near Wyoming and reduced for producers in the Pacific Northwest. In practice, it may be difficult to legislate accurate adjustment factors given changing conditions on the electricity grid.[45] Further, it may be politically challenging to reward investments in some politicians' constituencies more than others.

Other provisions of the IRA subsidize the energy-using or energy-producing asset, irrespective of how much it is operated. The investment tax credit for zero-carbon electricity subsidizes the construction of the facility rather than its operation. Relative to the PTC, the ITC provides a lower incentive to produce clean energy once the facility is constructed and thus a lower incentive to locate in areas with the highest production potential (Aldy, Gerarden, and Sweeney 2018). With lower capital costs for relatively mature technologies like wind and solar that are expected to be deployed with the IRA, many developers could opt for the production tax credit, which could minimize such distortions. Similarly, the electric vehicle tax credits subsidize vehicle purchases without regard to how much electric vehicles are driven. Electric vehicles that are used as second cars and driven less will offset fewer emissions than vehicles that replace a household's only car.[46]

45. Note that efficiency gains from differentiated subsidies across technologies may be limited in practice (Abrell, Rausch, and Streitberger 2019).

46. Burlig and others (2021) use electric vehicle charging data to show that vehicles in California through 2019 were driven substantially less than vehicles with internal combustion engines.

Overall, a shortcoming of fixed tax credit rates for supply- and demand-side resources is that they are relatively inflexible as technology and market conditions change (Peñasco, Anadón, and Verdolini 2021).[47] Carbon pricing enables households and businesses to select their preferred approaches to lower emissions, which can help to reduce costs and account for other welfare-relevant considerations that vary across individuals and firms. Carbon pricing also can enable coordination across sectors and geographies. When policy stringencies differ across sources and locations, emissions leakage can occur, though there are several policy options to mitigate leakage when policies are not harmonized (Böhringer and others 2022).

Another potential rationale for policy instruments that lower electricity prices could be that retail prices exceed social marginal costs. Borenstein and Bushnell (2022) argue that residential electricity rates are higher than the full social marginal costs in many locations across the United States, including the Southwest and Northeast. However, their estimates for external marginal costs are based on older values of the social cost of carbon and marginal damages of criteria pollutants, which are considerably lower than more recent estimates (Rennert and others 2022; Shindell and others 2021). In addition, federal tax credits are relatively blunt instruments to correct for retail pricing distortions that dominate only in a few regions, especially since tax credit uptake and retail rate impacts are not necessarily correlated with areas with retail price distortions. Also, the analysis in Borenstein and Bushnell (2022) looks only at residential electricity rates, and marginal rates for other sectors are generally lower.

In addition to the negative externalities from emissions, climate change is also associated with positive innovation-related externalities, particularly since carbon emissions are unpriced in many parts of the world (van den Bergh and Savin 2021; Gillingham and Stock 2018; Acemoglu and others 2012; Popp, Newell, and Jaffe 2010). Both carbon pricing and subsidies are aimed at addressing not only negative externalities from emissions but also positive innovation-related externalities. Induced innovation, economies of scale, network effects, and learning-by-doing effects can be altered by subsidies, carbon pricing policies, and other instruments, which can lower costs of low-emissions technologies and of energy services more broadly, though impacts depend on policy design. For example, subsidies for nascent technologies, like electric vehicles, may push producers down a learning

47. On the other hand, features in the IRA such as the qualifying emissions threshold for the power sector PTC and ITC illustrate how dynamic elements could be incorporated into subsidy design.

curve. Or, with more electric vehicles on the road, the economics of installing and operating charging stations improve, and the number of mechanics with expertise working with electric vehicles will increase. Future research should elaborate on the advantages of subsidies versus those of carbon pricing for incentivizing innovation. It is plausible, for example, that subsidies involve less uncertainty for investors in clean technology and are therefore better at addressing liquidity constraints.

V.E. Estimates Comparing Tax Credits with Carbon Pricing

Several modelers have simulated the reductions achieved with a carbon price and compared them to tax credits. For example, Roy, Burtraw, and Rennert (2021) find that even relatively modest carbon fees reduce emissions more than the types of tax credits that were included in the IRA and that the two policies together can achieve greater emissions reductions at a lower fiscal cost, while also insulating households from increased costs.

Here, we use the energy-economic model US-REGEN to investigate how electric sector outcomes vary between a scenario with IRA incentives and another that matches annual electricity CO_2 emissions without the IRA (implicitly assuming a cap-and-trade policy approach). Table 3 compares electricity generation shares by technologies across these scenarios, along with emissions, electricity prices, and abatement costs. This comparison illustrates how carbon pricing leads to lower coal generation relative to a subsidy-focused approach, since the latter does not distinguish between the carbon intensity of unsubsidized generation, which has implications for associated air quality co-benefits. These lead to 68 percent reductions in power sector CO_2 emissions from 2005 levels by 2035. Average abatement costs in the CO_2 equivalent policy are relatively low (\$10/tCO_2), given the low incremental costs of coal-to-gas switching and renewables deployment at these levels.[48] Table 3 also confirms that tax credits lead to lower electricity prices, relative to carbon pricing with equivalent CO_2 emissions. These lower prices are due to the prevalence of subsidized resources that put downward pressure on electricity prices and shift costs from ratepayers to the federal government (i.e., taxpayers).

While these estimates pit the subsidies against an idealized alternative policy, another useful comparison is between the IRA subsidies and the social cost of carbon, which essentially measures whether the subsidies

48. Average abatement costs are presented for comparability between the IRA and carbon pricing scenarios. Marginal abatement costs under the carbon pricing scenario are \$12–15/tCO_2 between 2030 and 2035, which are the shadow prices on the emissions cap constraint.

Table 3. Comparison of Electric Sector Metrics in the IRA Scenario and Carbon Tax Scenario That Matches the IRA CO_2 Emissions Time Path

		IRA scenario		*Carbon tax*		*Difference (percentage points)*	
Metric (units)	*2021*	*2030*	*2035*	*2030*	*2035*	*2030*	*2035*
Generation share (%)							
Coal	22	11	8	7	4	–4	–5
Coal CCS	0	3	3	0	0	–3	–3
Gas	39	20	18	35	34	15	17
Gas CCS	0	0	0	0	0	0	0
Other	2	9	11	7	8	–2	–3
Nuclear	19	17	14	17	16	0	2
Hydro	6	6	6	6	6	0	0
Wind and solar	13	33	41	28	32	–6	–9
CO_2 (% drop from 2005)	35	64	68	64	68	0	0
Generation price ($/MWh)	$64	$56	$52	$65	$62	16%	20%
Abatement cost ($/t$CO_2$)	n/a	$45–61	$45–61	$10	$10	–85%	–82%

Sources: US Energy Information Administration; Environmental Protection Agency; and authors' calculations.

Note: Historical electricity generation shares come from the US Energy Information Administration, "Electric Power Monthly," https://www.eia.gov/electricity/monthly/. Historical emissions come from United States Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks," https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

pass a cost-benefit test. Several analyses estimate the cost-effectiveness of components of the IRA, permitting this comparison. Analyzing a suite of tax credits for the power sector like the ones included in the IRA (the credits that were included in the Build Back Better Act passed by the House in fall 2021), Greenstone and others (2022) estimate that the credits would reduce emissions at a cost of $33–50/t$CO_2$, substantially below the most recent estimates of the social cost of carbon of approximately $200/t$CO_2$ (EPA 2022). Similarly, Stock and Stuart (2021) compare a suite of electric sector policies to the social cost of carbon and find that extensions of the PTC, ITC, and subsidies for CCS (but not all of the credits eventually included in the IRA) have an average abatement cost of about $35/t$CO_2$, well below the social cost of carbon. Cole and others (2023) estimate that the electric vehicle tax credits, combined with the subsidies for charging stations included in the Infrastructure Investment and Jobs Act, would reduce emissions at a cost of approximately $95/t$CO_2$.

As shown in table 3, our estimates in US-REGEN indicate that IRA tax credits reduce CO_2 emissions at an average abatement cost of $45–61/t$CO_2$ for the power sector (discussed in section II.D). There may be an efficiency gap between IRA incentives and carbon pricing with equivalent CO_2 (with average abatement costs of about $10/t$CO_2$), but these incentives nevertheless pass the benefit-cost test for most of the updated ranges for the social cost of carbon (Rennert and others 2022), even before accounting for air pollution and other potential co-benefits.

V.F. Political Economy Considerations and Alternative Policy Instruments

The approach embodied in the IRA is motivated in part by political economy constraints on feasible policy instruments in the 117th US Congress, including legislative dynamics that led to climate policy via budget reconciliation, which is a procedure to pass budgetary legislation that can override filibuster rules in the Senate and hence can pass by a simple majority rather than a sixty-vote supermajority.

Although carbon pricing approaches can be efficient, effective, and equitable, their strengths can create political liabilities by raising costs of energy. Many Americans support government action to address climate change, but willingness to pay may be low (Jenkins 2014).[49] In contrast, tax credits can lower energy prices and hide policy costs, which may be one reason why subsidies tend to poll better in the United States, relative to carbon pricing (Krosnick and MacInnis 2020; Bergquist, Mildenberger, and Stokes 2020).

In addition to tax credits and carbon pricing, there are several additional policy instruments that have been used and proposed to reduce emissions and encourage adoption of clean energy technologies, including rate-based performance standards (e.g., the Clean Power Plan proposed by the US EPA in June 2014), portfolio standards (e.g., for renewables or broader clean energy), mandates (e.g., for offshore wind and energy storage in various US states), feed-in tariffs (e.g., for renewables in several European countries), and others. Each instrument has policy design elements such as stringency, timing, trading provisions, and eligible technologies that affect economic and environmental outcomes and that emphasize different abatement margins. The literature suggests that the relative performance of tax credits versus that of other policy instruments depends on several factors about the setting, including the regional energy system, level of decarbonization, renewable resource quality, and demand effects (Borenstein and

49. For instance, a poll by the AP-NORC Center and EPIC in 2019 indicated that 43 percent of US adults are unwilling to pay an additional $1 on their monthly utility bill; Energy Policy Institute at the University of Chicago, "Infographic: Where Americans Stand on Energy and Climate," https://epic.uchicago.edu/news/infographic-where-americans-stand-on-energy-climate/?_paged=4.

Kellogg 2022; Abrell, Rausch, and Streitberger 2019; Young and Bistline 2018; Paul, Palmer, and Woerman 2015; Fell and Linn 2013).

V.G. Industrial Policy Components

As discussed in section I.B, some of the tax credits include bonuses for using domestic content or are available only for domestically produced goods with stringent sourcing requirements, as is the case for the electric vehicle credits for purchases (not leases). There are also significant bonuses for certain labor practices. While the political economy benefits of the bonuses are clear, the economic implications depend on underlying conditions. One central question is how much the bonuses will lead to adjustments. For example, if most electricity plant construction workers and operators already receive prevailing wages and use apprentices, the bonuses serve as a political statement but will not meaningfully change practices or the economic costs. If the bonuses lead to behavioral adjustments, they may be solving market failures. For example, the literature on industrial policy suggests governments can use temporary protection to help local industries achieve economies of scale (Juhász 2018). Also, supply chain vulnerabilities may create externalities if individual buyers do not fully account for the broader economic harm created by disruptions in foreign supply. In the absence of market failures, the bonuses could raise costs more than is socially beneficial, undermining the climate benefits of the tax credits. Future work quantifying these possible externalities will be valuable.

Domestic content provisions also have implications for trade partners, as evidenced by the reaction to the IRA from European leaders. Some of the United States' most important trade partners have sizable carbon prices (e.g., the European Union and Canada), and those countries may feel pressure from industry to reduce those costs, lest they lose production to the United States. Such a scenario would undermine the climate benefits of the IRA.[50] Clausing and Wolfram (2023) discuss the possible dynamics when countries adopt asymmetric approaches to carbon mitigation.

VI. Quantifying the IRA's Macroeconomic Impacts

VI.A. Recent Trends in Electric Power Investment

As shown in section II (figure 4), the IRA has significant impacts on the level of investment in clean electricity generation, with 34–116 gigawatts

50. If the European Union or other countries respond by introducing clean energy subsidies rather than reducing carbon taxes, global climate benefits could be strengthened.

Table 4. Investment in Power Generation Structures and Equipment

	Nominal, 2018–2022 averages			*Growth, annualized rate*		*US-REGEN IRA impact*
				2012–2022		*Ten-year average*
	$ billion	*% of BFI*[a]	*% of GDP*	*Real output*	*Price level*	*$ billion (2022)*
Gross domestic product	22,350			2.2	2.5	
Nonresidential fixed investment	2,974		13.3	3.3	1.5	
Structures	633	21.3	2.8	–0.8	4.2	
Electric power structures (BEA estimate)	79	2.7	0.4	–3.1	4.2	21
Equipment	1,199	40.3	5.4	2.5	0.6	
Electrical transmission, distribution, and industrial apparatus	52	1.8	0.2	3.8	2.4	7
Electrical equipment, not elsewhere classified	9	0.3	0.0	1.2	2.1	

Sources: Bureau of Economic Analysis and authors' calculations.
a. Business fixed investment

of nameplate capacity added annually on average relative to 18 GW/year on average in the previous decade and 36 GW/year in 2021. Table 4 shows data from the Bureau of Economic Analysis (BEA) for investment in power generation and electricity distribution. Over the last five years, nominal investment in electric power structures averaged $79 billion, and nominal investment in electrical transmission and distribution averaged $52 billion. Investment in electric power structures accounts for about one-eighth of overall structures investment, but nonresidential structures investment is quite modest as a share of GDP. Likewise, electrical transmission and distribution account for about 4 percent of nonresidential investment in equipment. Total investment in electrical power generation, distribution, and transmission is about 5 percent of nonresidential fixed investment and less than 1 percent of GDP.

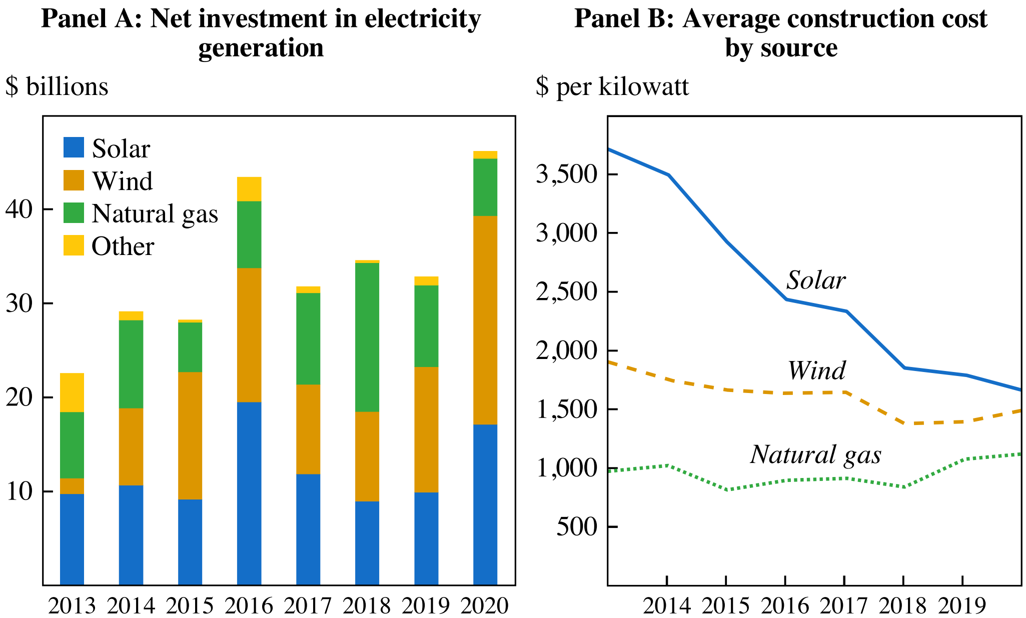
The US-REGEN model sees a boost (relative to 2022 levels) of approximately $21 billion per year over ten years in electric power generation and approximately $7 billion per year in transmission and distribution. These magnitudes are sizable relative to the current level of investment, but comparatively small as a share of both overall investment and overall economic activity. Even substantially larger increases in investment in power generation, transmission, and distribution (a doubling or more) would carry relatively modest macroeconomic impacts given the low share of power and electricity investment relative to overall investment. An apt comparison for the magnitude of the IRA impacts on electric power generation could be the shale oil revolution in the prior decade. Nominal investment in mining and wells rose from $98 billion between 2006 and 2010 to $152 billion between 2011 and 2015—an increase of more than 50 percent in a short period of time. Investment in mining and oil field machinery nearly doubled from $18 billion to $33 billion. The macroeconomic impacts from this investment boom appeared comparatively modest, however, with relatively limited macroeconomic impacts from the sharp slowdown in shale oil investment after 2015.[51]

The BEA data also suggest relatively high price growth over the past decade for investment in electricity generation. As table 4 shows, prices rose 4.2 percent (annualized rate) for investment in electric power generation structures, and real investment fell 3.1 percent (annualized) over the same period. Price increases were more in line with overall inflation for transmission and distribution, rising 2.4 percent at an annualized rate. In contrast to real investment in electric power structures, real investment in transmission and distribution rose over the past decade. Price increases for investment in structures have been particularly sharp over the last two years; the price index for electric power structures rose 12.3 percent year-over-year as of 2022:Q4. Negative real investment in electric power generation over this period is largely a function of flat nominal investment and surging price indexes.

The BEA investment data are mirrored by data collected by the US Energy Information Administration (EIA) on net additions to electricity generation and data on construction cost of new electric generation facilities. Figure 16 shows total construction expenditures for solar, wind, and natural gas electricity generation from 2013 to 2020. Total investment in power generation rose from $22 billion to $46 billion, with solar and wind rising from $10 billion and $2 billion to $17 billion and $22 billion, respectively, over this period. Nameplate capacity installed rose from 12 GW to 31 GW during this time—much faster than the level of real investment inferred from BEA data. Figure 16 also shows substantial drops in the

51. Bureau of Economic Analysis, "National Data: National Income and Product Accounts," tables 5.4.5 and 5.5.5; https://apps.bea.gov/iTable/?reqid=19&step=2&isuri=1&categories=survey. US GDP growth did decelerate in 2015, and nonresidential structures investment turned sharply negative (falling nearly 10 percent year-over-year). But the unemployment rate continued to fall, and core inflation appeared largely unchanged.

Figure 16. Trends in Electricity Generation Investment and Costs



Source: US Energy Information Administration.

average construction cost of solar power over this period, along with substantial declines for wind generation. The construction cost for natural gas remained largely stable over this period.

How do we reconcile the BEA and EIA data? The BEA reports gross investment in structures and equipment. The BEA's annual data on net investment from its fixed asset tables are quite close to the EIA's value for net investment in electricity power generation. In 2020, the BEA recorded gross investment of $83 billion in electric power structures and $41 billion in depreciation; the EIA's value for net investment in 2020 was $46 billion.[52] The EIA, however, does suggest materially different trends in both real investment and the price index for investment in electric power generation due to a sharp fall in construction costs for utility scale solar and wind.[53]

52. Bureau of Economic Analysis, "National Data: Fixed Assets Accounts Tables," tables 2.5 and 2.7; https://apps.bea.gov/iTable/?reqid=10&step=2&isuri=1.

53. The difference in price trends in BEA and EIA data may reflect that the BEA price index is weighted on a capital stock basis (i.e., disproportionately weighted toward coal and gas). The BEA uses indexes from Handy-Whitman and the Bureau of Reclamation to construct its price index for electric power structures. It is not clear that those price indexes have sufficient weight in solar and wind, which account for a sizable share of electric power investment in the recent data. The EIA documents an average 3.1 percent increase in construction costs for natural gas power plants, which is close to the 2.6 percent increase in the BEA's price index.

The US-REGEN model shows substantial and growing impacts on electricity prices relative to the non-IRA scenario (figure 11 in section III). To a first approximation, the inflation impact of declining retail electricity prices is simply its weight in household prices multiplied by the change in electricity prices (post-IRA). The US-REGEN model finds that retail electricity prices are 1.2 percent higher in 2025 (relative to baseline) but fall 2.2 percent by 2030 and 12.8 percent by 2050. Electricity has a weight of 2.5 percent in the Consumer Price Index (CPI) and 1.3 percent in the price index for personal consumption expenditures. Therefore, electricity prices would add 1.5–3 basis points to inflation in 2025 but subtract 3–6 basis points in 2030 and 15–30 basis points in 2050. Overall, these are small direct effects on inflation. For reference, the impacts on the price of electricity in 2025 and 2030 are an order of magnitude lower than the increase in retail electricity prices experienced over the pandemic.[54]

VI.B. FRB/US Simulation

To quantify the macroeconomic impacts of the climate provisions of the IRA, we rely primarily on the Federal Reserve's US model (FRB/US). This general equilibrium model is regularly estimated and used by Federal Reserve staff in formulating forecasts and assessing the macroeconomic outlook. Ideally, one would be able to model economic and energy market impacts within a single general equilibrium model, where changes in subsidies or a carbon tax would both have a joint impact on industry equilibrium and incorporate feedbacks to the broader economy. The current FRB/US model has only limited modeling of energy market impact on the broader economy (primarily through the price of oil). To simulate the macroeconomic impact of the IRA's climate provisions, we take the principal economic outputs of the US-REGEN model and incorporate those impacts into the current baseline FRB/US model.

Specifically, the tax credits received by households for electric vehicles and for residential improvements (heat pumps, etc.) are modeled as an increase in transfer income to households (akin to cash stimulus), and the increased investment in wind, solar, and other clean power generation is modeled as an increase in the growth rate of business fixed investment.[55] Additionally, we also include a shift in the CPI for energy to reflect the

54. From 2020 to 2022, the CPI for electricity services has risen 22.6 percent.

55. To the extent that household rebates are captured by manufacturers through higher prices, the transfer raises corporate profits and equity valuations. The marginal propensity to consume out of the transfer would likely be lower.

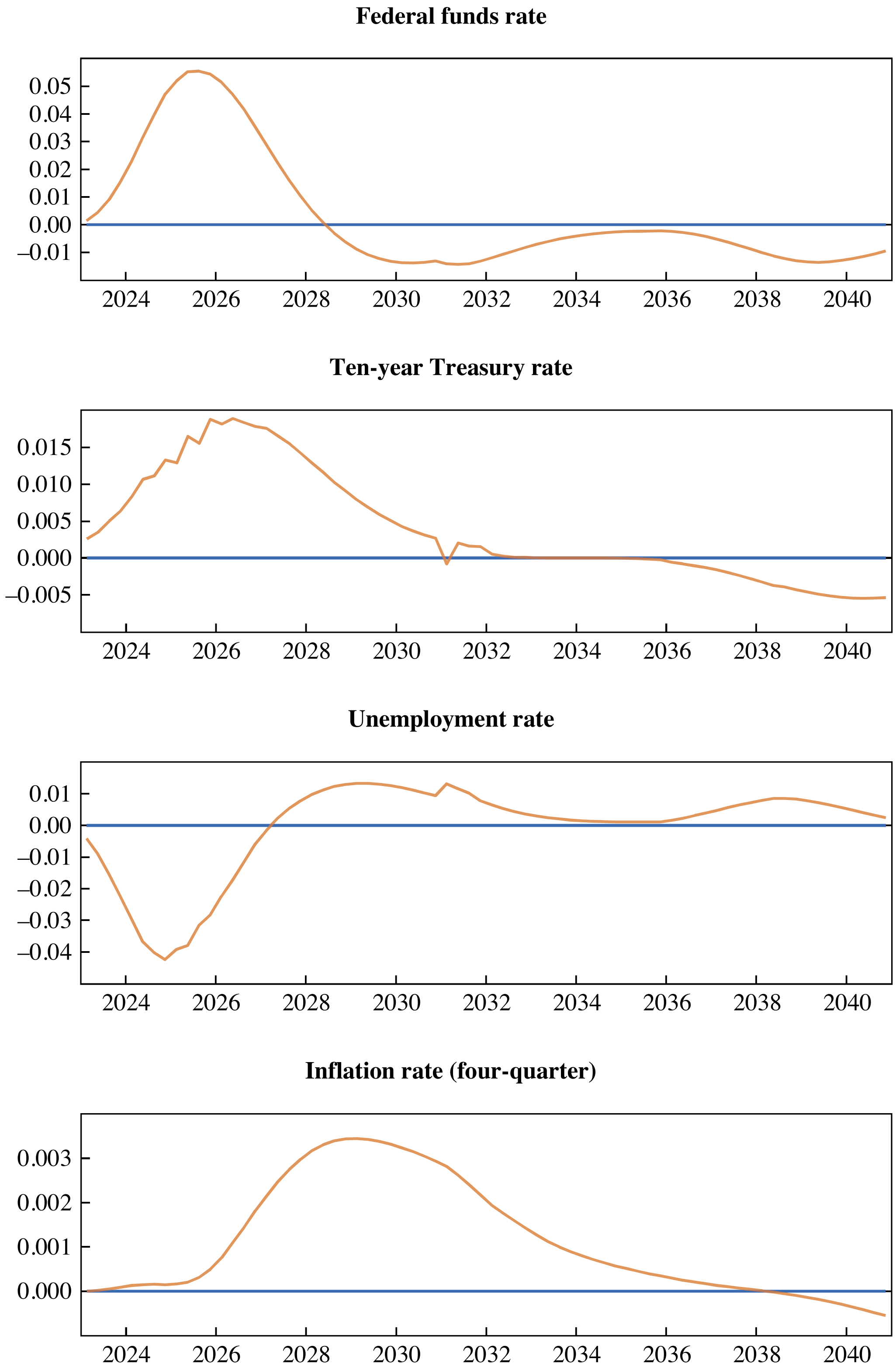
impact of lower retail electricity prices from increased electricity production. The outputs from the US-REGEN model are at five-year time steps, so we convert these values to quarterly shocks for the FRB/US model. The impulse responses below show the relative impact of the IRA on the federal funds rate, the unemployment rate, ten-year Treasury rates, and the inflation rate.

The FRB/US simulation largely confirms what might be expected given the small share of investment accounted for by power generation and the relatively modest size of the household transfers. As figure 17 shows, the federal funds rate rises initially due to stronger nonresidential investment and increased household consumption from clean vehicle and residential improvement tax credits. The federal funds rate and ten-year Treasury rate peak by 2026 and then return to their baseline levels. The funds rate falls slightly below baseline after 2030 as the fiscal impetus from increased nonresidential investment and increasing transfers turns to a drag after 2030. The unemployment rate initially falls before rising above baseline slightly after 2030. Quantitatively, all effects are small. At its peak, the federal funds rate increases about 6 basis points, and the Treasury rate increases about 2 basis points. The maximum fall in the unemployment rate is approximately 4 basis points. Impacts on core inflation are an order of magnitude smaller in the simulation, with core inflation rising relative to baseline over the first decade before falling after 2030. However, headline inflation falls because of the direct effect of lower electricity prices on consumer prices, which the FRB/US model does not include. Including these direct effects on electricity, headline CPI inflation falls about 3–6 basis points by 2030 and up to 30 basis points by 2050.[56]

The FRB/US model may understate the impacts from higher nonresidential investment in power generation in two ways: (1) the model may not fully capture the upstream impacts on manufacturing and materials demand from an increased level of structures and equipment investment; (2) the model is unlikely to capture fluctuations in energy commodity prices (electricity, natural gas, crude oil, and gasoline) that will have material impacts on producer and consumer prices. Using data from BEA input-output tables, we see that the upstream impacts of investment in power structures do not appear significantly larger than demand for any other commodity. The 2012 total requirements table shows that a $1 increase in final demand for investment in power structures implies a $1.64 increase

56. Del Negro, di Giovanni, and Dogra (2023) examine how differential price stickiness and subsidies may lead a green energy transition to be disinflationary.

Figure 17. Interest Rate, Unemployment, and Inflation Rate Response to IRA



Source: Authors' calculations using FRB/US.
Note: Macroeconomic effects of funds rate perturbation (VAR expectations) shown.

in gross output across all commodities.[57] Upstream impacts for electrical transmission and distribution equipment are somewhat higher: $2.46 for each $1 increase in final demand. By comparison, the ratio of gross output to GDP is approximately 1.8.

As we noted earlier, the scale of the increase in fixed investment under the IRA is comparable to the shale oil boom in the early 2010s. The direct contribution of shale oil investment in mining structures and equipment may not have been large (relative to aggregate investment or GDP), but it clearly had significant effects on energy prices that kept overall inflation low and supported a recovery in manufacturing after the financial crisis. Moreover, the sharp drop in global oil prices, slowdown in shale oil investment after 2014, and resulting weakness in US manufacturing stalled the exit from the zero lower bound until 2016.

The macroeconomic impact of the clean energy provisions of the IRA should also be considered in concert with the other major recent legislation that increases demand in domestic manufacturing and construction. Both the Infrastructure Investment and Jobs Act and the CHIPS and Science Act have provisions that are intended to increase structures and equipment investment, with expenditures ramping up on a similar timeline to that of the clean energy investments due to the IRA. The combined impact of this increased investment demand, along with upstream impacts on manufacturing, construction, and raw materials, may carry a more meaningful quantitative impact on the US macroeconomic aggregates. One data point that points to a larger macroeconomic impact is announcements for battery manufacturing since the passage of the IRA; a tabulation finds twenty-nine companies announcing almost $50 billion in domestic battery manufacturing as of March 2023. These investments in battery production that may be eligible for IRA manufacturing tax credits have not been incorporated in our quantitative estimates.

It's important to note that any negative macroeconomic effects on fossil fuel extraction, refining, and utilities are not modeled here, nor are any broader macroeconomic effects for the revenue components of the IRA. Power investment in structures and equipment is small relative to overall economic activity, and so are fossil fuel extraction and refining. Moreover, oil and natural gas are partly global commodities whose outlook

57. Business fixed investment in FRB/US is not modeled at the industry level, so upstream impacts to manufacturing are captured only indirectly, through lagged terms and accelerator effects. Any impact of lower electricity prices on manufacturing is also not captured.

will be strongly influenced by global events (e.g., European demand for liquified natural gas), with demand for natural gas in the United States likely to remain steady in any case. Employment in these industries is small, and investment in fossil fuel power generation (particularly coal) was already waning well before the IRA.

VII. Impacts of the Macroeconomic Environment on the IRA

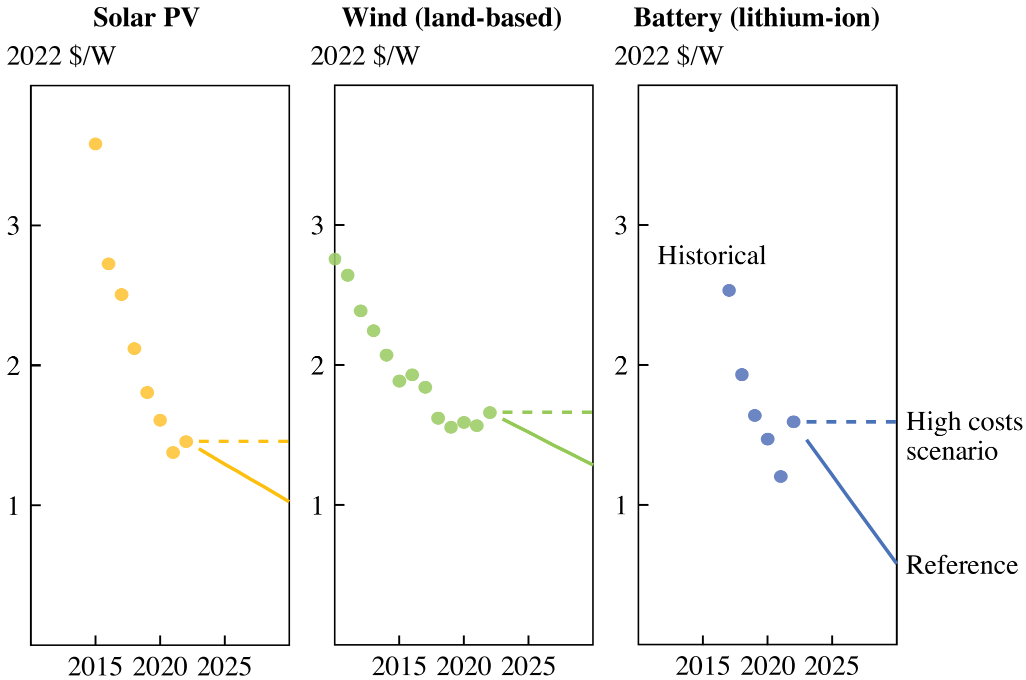
To test the sensitivity of IRA impacts to the assumed macroeconomic environment, we compare the US-REGEN electric sector outputs from earlier sections to a scenario with higher supply-side costs and interest rates. In this illustrative scenario, the discount rate for power sector investments is increased from 7 percent in the reference run to 11 percent (Dunkle Werner and Jarvis 2022; EPA 2018). In addition, this higher cost scenario assumes that upward pressure on labor and materials costs leads to increases in the capital costs of generation and energy storage technologies. Elevated costs in 2022 are assumed to persist through 2030 instead of following the declining cost trajectories used in earlier sections (figure 18), as discussed in Bistline, Roney and others (2023).

This stylized scenario with a more pessimistic macroeconomic outlook and higher costs leads to higher emissions and lower clean electricity generation relative to the scenario with reference costs presented earlier (figure 19). Higher interest rates increase the costs of new investments, especially for capital-intensive technologies such as many IRA-subsidized, zero-emitting resources (as the LCOE examples in section III illustrate). This dynamic lowers the deployment of wind, solar, and CCS-equipped capacity and increases generation from existing assets, especially coal- and gas-fired capacity.[58] These changes lead to increases in CO_2 emissions in the higher cost scenario, which are 1,190 MtCO_2/year in 2030 (compared with 870 MtCO_2/year with reference costs).

Table 2 in section II compares emissions and fiscal costs associated with this scenario with those of the central IRA case. Economy-wide emissions reductions are similar to reference levels with higher costs, and cumulative tax credit expenditures through 2031 are $244 billion (i.e., similar to the CBO/JCT score) instead of $781 billion in the central case.

58. The ratio of wind to solar generation increases with higher costs in 2030, given the relative magnitudes of their capital cost increases (figure 18).

Figure 18. Capital Cost Assumptions for Utility-Scale Solar PV, Land-Based Wind, and Lithium-Ion Battery Storage with Four-Hour Duration



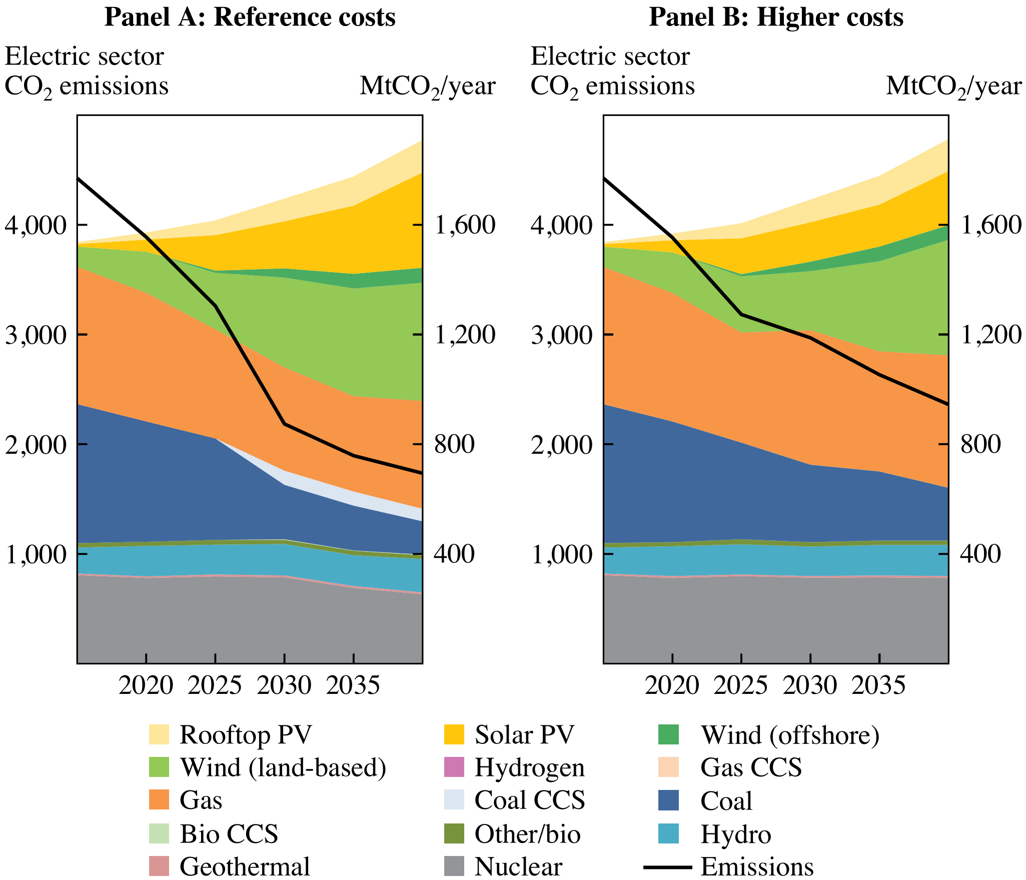
Sources: Lawrence Berkeley National Laboratory; Electric Power Research Institute; and authors' calculations.

Note: Costs are expressed in 2022 dollar terms before accounting for IRA subsidies. Historical costs (dots) for wind come from Wiser and others (2022); for solar, Bolinger and others (2022); and for batteries, Hostert and others (2022). Values for 2022 are based on EPRI (2022) cost estimates.

These comparisons illustrate how macroeconomic conditions may have larger impacts on IRA investments than IRA investments have on macroeconomic conditions, at least for the magnitudes investigated here. There is considerable uncertainty about the persistence of these shocks and their magnitudes, which depend not only on domestic conditions but also on global factors. For instance, prices of materials—including specialty metals and bulk commodities—depend on global material production and demand, which are driven by the pace of decarbonization-related deployment and non-energy demand (International Energy Agency 2023; Wang and others 2023).[59]

59. Another global driver is increasing liquified natural gas exports from the United States, which connect domestic gas markets with global ones. This fuel market integration could lead to a prolonged period of higher US natural gas prices. The scenarios above do not include higher natural gas price sensitivities, which could increase short-run coal generation (and associated emissions) but decrease fossil fuel consumption (and emissions) in the long run (Stock and Stuart 2021; Bistline and Young 2022).

Figure 19. Generation by Technology over Time for a Scenario with Reference Cost Assumptions and with Higher Costs from the US-REGEN Model



Source: Authors' calculations.

VIII. Conclusions

IRA incentives are expected to significantly alter the economics of decarbonization, encouraging deployment of clean energy technologies and lowering emissions. Economic tools will play important roles in the years to come in understanding potential macroeconomic and microeconomic implications of IRA incentives. This paper offers several initial perspectives on what the IRA's climate-related provisions could imply for energy transitions and key macroeconomic indicators, using stylized examples, data analysis, detailed energy systems modeling, and general equilibrium modeling of the economy.

This analysis using EPRI's US-REGEN model suggests that the IRA, along with other policies and market trends, shifts baseline expectations of firms, households, and policymakers for the pace and extent of future decarbonization.

Clean electricity investments span 34–116 gigawatts of nameplate capacity added annually under the IRA through 2035, compared with 18 GW/year on average in the previous decade and 36 GW/year in 2021 (figure 4 in section II). Average annual additions of low-emitting capacity in US-REGEN are 51 GW/year with the IRA through 2035, which nearly doubles the 27 GW/year in the counterfactual without the IRA.

Electric vehicle sales increase from over 6 percent of new light-duty vehicle sales in 2022 to nearly half of new sales by 2030 (figure 3 in section II). The IRA increases the electric vehicle share of new vehicle sales by 12 percentage points in 2030 from 32 percent in the reference without the IRA to 44 percent with IRA credits.

The projected pace and extent of these changes depend on assumptions about future policies, technologies, and markets. The uncertainty associated with these projections reflects IRA implementation details and unknown responses to siting and permitting challenges, workforce changes, global supply chain shifts, and non-cost barriers to deployment. The IRA continues to drive emissions reductions in this modeling beyond 2030, as key power sector tax credits may last until electricity CO_2 emissions reach 25 percent of their 2022 levels, potentially providing support throughout the 2030s.

The acceleration in the deployment of clean supply- and demand-side technologies in this modeling leads to greater uptake of IRA incentives than initial estimates indicated. These projections indicate that fiscal costs of IRA tax credits for clean electricity, carbon capture, and electric vehicles may be $781 billion by 2031 in our central case—nearly three times the CBO/JCT score for comparable credits. This finding that budgetary effects of the IRA may be larger than initial CBO estimates is reflected in other studies that indicate that US-REGEN estimates in this paper could be conservative for several uncapped tax credits. Notably, the CBO/JCT fiscal score does not reference the implied carbon reductions. Models that indicate emissions reductions in the range of 40 percent imply larger fiscal costs than CBO/JCT. US-REGEN estimates also suggest that the increasing economic competitiveness of transport electrification and renewables in the power sector means that nontrivial shares of these tax credits would be inframarginal transfers.

This analysis points to limited macroeconomic effects of the IRA, though the macroeconomic environment is shown to influence IRA-incentivized investments. The conceptual framework in section IV provides intuition for fiscal and macroeconomic impacts of the IRA, including the dependence on supply elasticities for labor and key materials, price elasticity of demand for fuels, market and nonmarket bottlenecks, stock dynamics for emissions-intensive assets, and potential for endogenous technical change for low-carbon energy technologies (e.g., learning-by-doing effects). Although changes in investment from the IRA are large in absolute terms (i.e., tens of billions of dollars per year), even substantial investment increases for power generation, transmission, and distribution carry relatively modest macroeconomic impacts given their low shares relative to overall investment. Magnitudes of change in fixed investment under the IRA are comparable to the shale oil and gas revolution in the 2010s.[60] Likewise, household transfers through tax credits for electric vehicles, heat pumps, and so on are relatively modest in size.

Numerical simulations in section VI using the Federal Reserve's FRB/US model with inputs from US-REGEN show the relative impact of the IRA on the federal funds rate, ten-year Treasury rates, and inflation, which rise initially from increases in nonresidential investment and household consumption before returning to their baseline levels. Quantitative effects are small in all cases. Comparisons in section VII using US-REGEN illustrate how increases in the cost of capital and supply-side costs for electricity generation and storage technologies lead to lower IRA-induced investments in low-emitting capacity and higher emissions over time.

Our survey of potential IRA impacts points to several areas for additional research. Ex ante and ex post analysis of individual IRA provisions will be important for updating baselines for future policies and for understanding the effectiveness of IRA incentives. Assessing interactions between IRA incentives and changes in federal regulations, state policies, and company targets will also be important. Future work should also quantify aggregate macroeconomic impacts of the IRA, the Infrastructure Investment and Jobs Act, and the CHIPS and Science Act, as all three are expected to increase investments across a similar timeframe and have impacts on manufacturing, construction, and raw materials. Finally, understanding the economic incidence of subsidies and distributional implications of the IRA

60. Although the direct contribution of shale oil and gas investment may not have been large (relative to aggregate investment or GDP), it clearly had significant effects on energy prices that kept overall inflation low and supported a recovery in manufacturing after the financial crisis.

will be valuable to policymakers and other stakeholders, especially since many IRA provisions target energy equity, environmental justice, and disadvantaged communities.

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Comments and Discussion

COMMENT BY

JASON FURMAN I do not remember ever seeing a more sophisticated after-action report on a piece of legislation that combines public finance, macroeconomics, and statistics on the environment, together with lots of institutional details. Which makes me even more guilty that my main reaction is to list everything I wanted to know that did not fit into the paper—and Bistline, Mehrotra, and Wolfram would probably agree with most of my wish list. So my comments are mostly about using their paper as a springboard for some broader observations about the Inflation Reduction Act (IRA) and also different approaches to climate change. My comment makes four points.

1. WILL THE INFLATION REDUCTION ACT REDUCE THE DEFICIT? Bistline, Mehrotra, and Wolfram provide updated estimates of the cost of the climate provisions of the IRA that are considerably higher than the initial Congressional Budget Office (CBO) score of the legislation. These higher numbers are generally in line with a number of other ex post estimates made by the climate analytics community. But the authors do not provide any bottom line estimates of the cost of the full legislation because they do not reestimate the other pieces outside the climate domain.

To provide greater context, the first CBO score projected that the initial version of the IRA would reduce or have minor effects on the deficit every single year. The legislation was changed in the process of the negotiation, resulting in a CBO score that showed it raising the deficit slightly in the first five years but cutting it over the full ten-year window, as shown in table 1.

After the law passed, the administration scored it for the PAYGO (pay as you go) scorecard. The administration's estimate, including its estimate

Table 1. Scores for the Inflation Reduction Act

	2022–2026	*2027–2031*	*2022–2031*
Nominal ($ billions)			
CBO	26	–264	–238
Administration	151	–341	–190
CBO plus authors' scores	248	24	272
CBO plus authors' scores and higher raisers	202	–225	–23
Percentage of GDP (%)			
CBO	0.0	–0.2	–0.1
Administration	0.1	–0.2	–0.1
CBO plus authors' scores	0.2	0.0	0.1
CBO plus authors' scores and higher raisers	0.1	–0.1	0.0

Source: Author's calculations based on Congressional Budget Office, Office of Management and Budget, and data provided by Bistline, Mehrotra, and Wolfram.

of the unscored revenue from tax reform, was that the legislation would raise the deficit slightly less over the ten-year window—with larger deficit increases in the first five years and larger deficit reduction in the second five years. The administration did not provide any detail about the components of its score or why it differed from the CBO, but it is reasonable to guess that the difference at least partly reflects the administration's higher score for the energy provisions partly offset by a larger score for the tax offsets.

If you combine the CBO score of the non-climate provisions with the authors' score of the climate provisions, the result is that the legislation raises the deficit over ten years by $272 billion, with a larger deficit increase in the first five years than in the last five years.

The CBO, however, likely underestimated how much revenue the tax increases included in the legislation would raise. First, its score of the tax enforcement provisions explicitly did not include any effect of the legislation on deterrence because of their scorekeeping practices, not because they argued this would be zero. The administration's estimate of the enforcement savings was higher. Second, the nominal corporate income baseline has been much higher than the assumption underlying the CBO score, which was set a year and a half before the legislation passed. Just shifting corporate revenues up proportionally to the higher baseline results in additional savings. Finally, initial indications are that behavior is less sensitive to the buyback tax than expected, leading that measure to raise more revenue. Combining the authors' climate provisions, plausibly rescored tax provisions, and the CBO estimates for everything else, the result is that the legislation costs $202 billion in the first five years and raises $225 billion in the second five years—for a ten-year budgetary savings of $23 billion.

Overall, especially if you look at the numbers as a fraction of GDP, the deficit impact of the legislation basically rounds to zero—and then we can argue about the second, third, and fourth decimal places but we will never truly know.

2. WILL THE INFLATION REDUCTION ACT AFFECT THE MACROECONOMY? Much of the authors' paper is a sophisticated macroeconomic analysis of the IRA. This analysis convinces me that the macroeconomics of the IRA are not especially important. Figure 17 in the paper shows their major macroeconomic results. These magnitudes can be put into perspective by looking at both the baseline and the changes, as shown in figure 1, using numbers provided by the authors in March 2023. Here you can see that the impact of the IRA is essentially imperceptible.

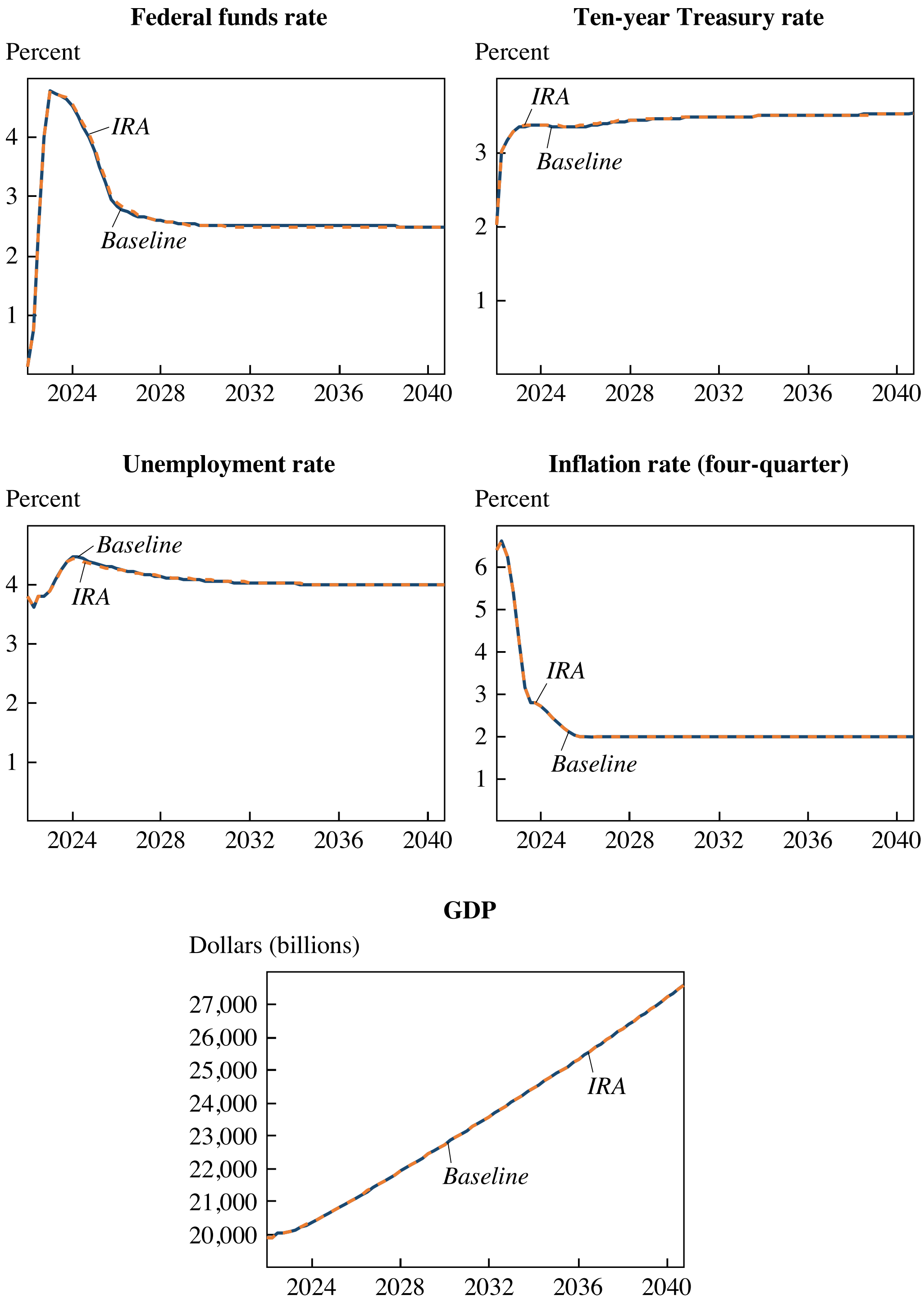
Note these estimates include only the climate parts of the legislation. To close their model, the authors assume lump sum financing for the rest. As a result, they are analyzing a situation in which the user cost of capital is reduced.

Of course, the rest of the legislation did not involve lump sum financing. In fact, the corporate tax increases included in the legislation have the opposite effect, raising the user cost of capital. Thus the legislation, as a whole, might not actually subsidize capital; instead it might subsidize capital in the climate sector but raise the bar for it outside the climate sector.

The authors' estimates also do not consider the Keynesian impact of the legislation. Using a set of multipliers consistent with what the CBO has proposed in the past, figure 2 shows the macroeconomic impact of the legislation on nominal GDP—with the breakout between prices and quantities ambiguous and dependent on the cyclical state of the economy. Moreover, this assumes no Federal Reserve reaction, so the estimates become increasingly less relevant over the ten-year window. Regardless, the most important result is that this effect, too, is relatively small.

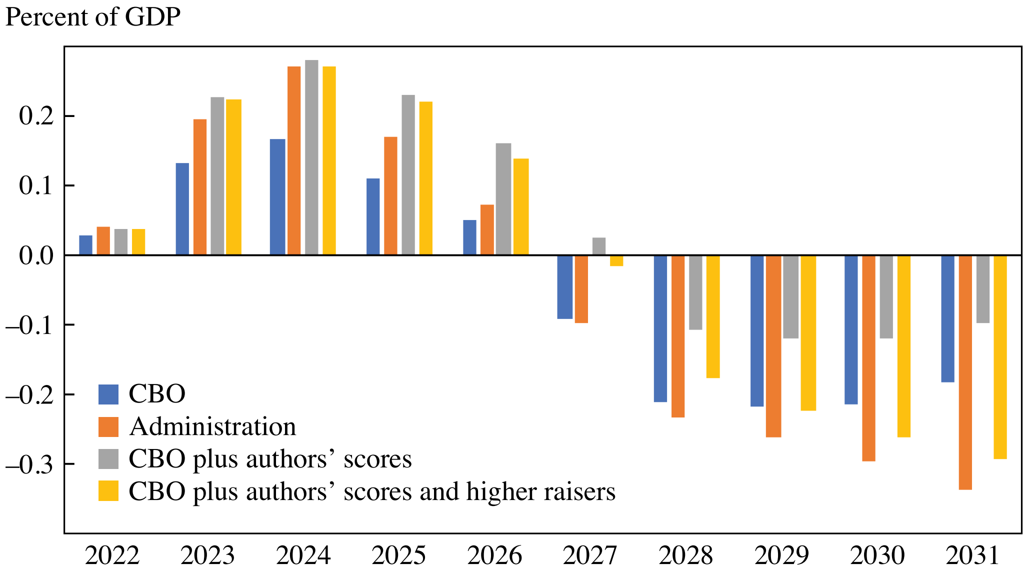
There are other macroeconomic effects that also do not show up in the authors' analysis, which could be just as big as the ones that do. The legislation will have large distributional effects (discussed in the next section) that could feed back into consumption, interest rates, and growth. The sectoral shifts that it causes could be first order, potentially raising unemployment over time by worsening job matching. Induced changes in other countries through technological spillovers and change could be important. Finally, the authors do not attempt to analyze any macroeconomic impact of the changes in climate that result from this legislation—although those are likely to be small.

Figure 1. Macroeconomic Effects of the Inflation Reduction Act



Source: Data provided by Bistline, Mehrotra, and Wolfram.

Figure 2. Effect of Inflation Reduction Act on Nominal GDP



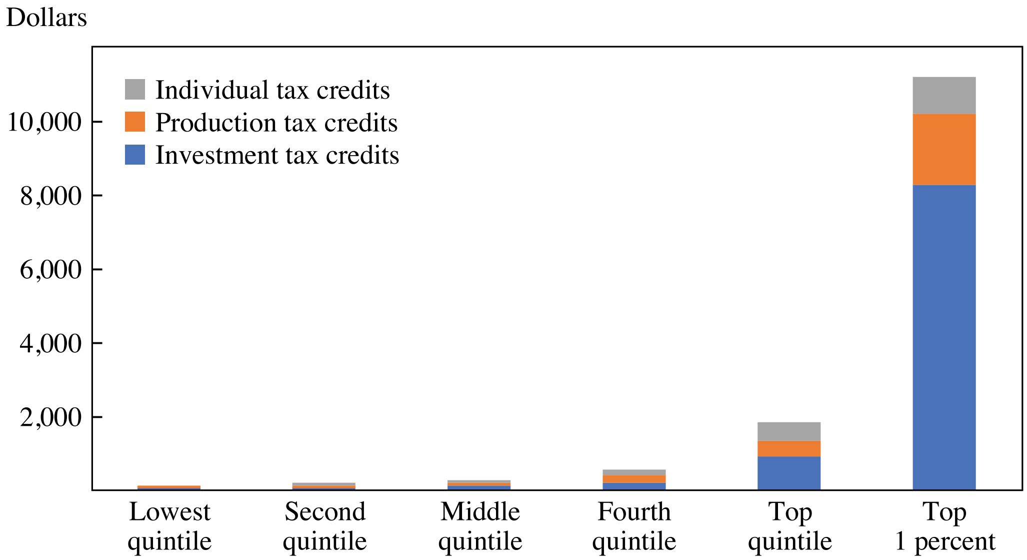
Source: Author's calculations based on Congressional Budget Office, Office of Management and Budget, and data provided by Bistline, Mehrotra, and Wolfram.

3. WILL THE INFLATION REDUCTION ACT AFFECT THE DISTRIBUTION OF AFTER-TAX INCOME? The distributional impact of the IRA is considerably more important than the macroeconomic impact. The authors' Federal Reserve Board US model (FRB/US) simulation finds that the legislation raises GDP by $79 billion through 2031. In contrast, the US Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model's central scenario has $781 billion in total tax credits through 2031. How the latter are distributed could be considerably more important than the GDP effect.

In fact, these tax subsidies are roughly the same size as the earned income tax credit (EITC), the Supplemental Nutrition Assistance Program (SNAP), Supplemental Security Income (SSI), or the health insurance premium tax credit. Nevertheless, the distribution of the tax credits has received almost no discussion—in contrast to the endless discussions about the distribution of a carbon tax.

So what is the incidence of the subsidies? The authors say, I think plausibly, that most of them are passed on to consumers. But about 60 percent of those consumers are commercial and industrial users of electricity so it also matters what those consumers do with the savings. In some ways the subsidies are more like a corporate tax cut. In addition, the incidence also depends on regulatory rules as well as the comparative elasticity of supply

Figure 3. Reduction in Average Taxes from Climate Tax Provisions of the Inflation Reduction Act, 2027



Source: Author's calculations based on data from the Tax Policy Center.

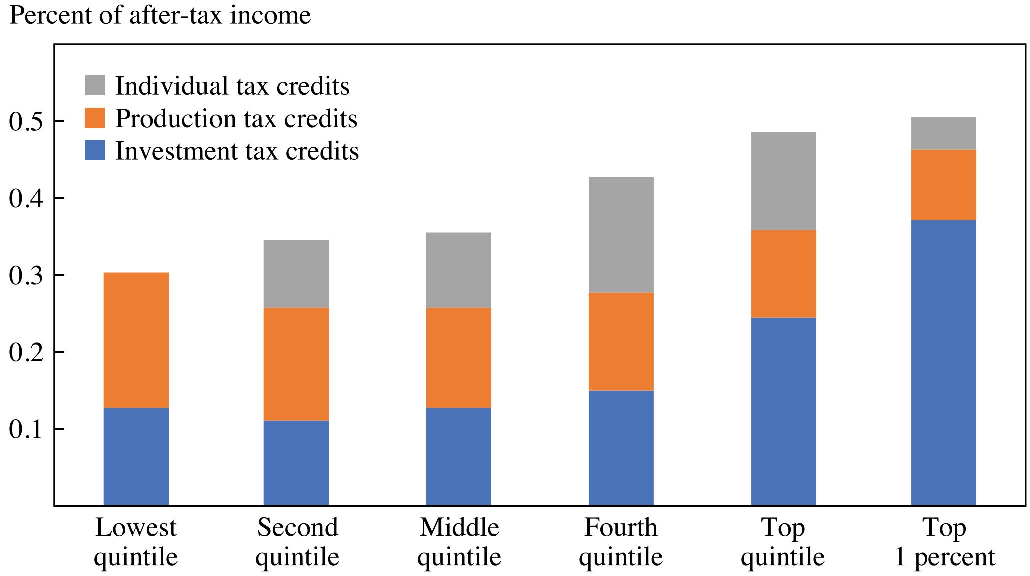
and demand. And at least for some users, like industrial, the demand is not perfectly inelastic. Moreover, demand is more elastic over longer periods of time—suggesting that more of the incidence of the tax cuts may fall on producers over time.

To get a rough indication of the distributional impact of the legislation I took some unpublished tables that the Tax Policy Center provided to me and readjusted them to match the authors' estimates of the total cost in dollars. The breakdown of the resulting tax cuts are shown in figure 3, with the large majority going to the top 1 percent.

The best way to assess the progressivity is to show those tax changes as a share of after-tax income, as is done in figure 4. This shows that overall the climate provisions in the legislation may have been slightly regressive—providing larger gains to higher-income households than to middle-income households. Note also that the average increase in after-tax income from the incidence of the tax changes is about 0.4 percent, which is about twenty times larger than the approximately 0.02 percent increase in GDP in 2027.

As an aside, a carbon tax raises taxes on people. As a result they have gotten much more scrutiny than these sorts of industrial policies that give money to companies. If you are doing industrial policy, you are compensating

Figure 4. Change in After-Tax Income from Climate Tax Provisions of the Inflation Reduction Act, 2027



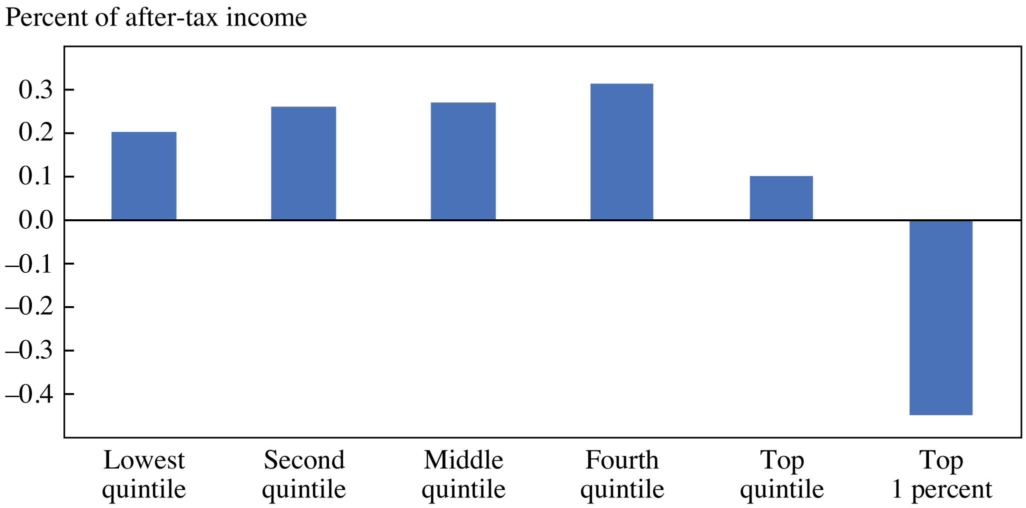
Source: Author's calculations based on data from the Tax Policy Center.

people through businesses, you are giving money to businesses and hoping that money eventually gets to people. The idea that you can count on that in any sort of way is much less certain and deserves more attention. These exact numbers for the distribution may be wrong; my point is more that these issues require much more attention—even relative to the macroeconomic impact.

Note that this point is about the climate provisions only. The legislation as a whole was almost certainly progressive when the highly progressive tax raisers are taken into account. This is shown in figure 5.

4. CARBON TAXES VERSUS CLEAN ENERGY SUBSIDIES The authors do not break out the consequences of the different subsidies in the IRA or which have high bang for the buck, which have low, and what the consequences of the unevenness are. Reading between the lines in the paper, it appears as if the authors think the investment tax credit and production tax credit are very valuable, possibly almost as good as a carbon tax. But the electric vehicle subsidies have a substantial inframarginal cost. Some provisions have close to zero or even a negative impact on carbon emissions, like domestic content bonuses and manufacturing subsidies. In addition, other aspects of the legislation, like bonuses for paying prevailing wages, have an ambiguous and possibly negative impact on carbon emissions.

Figure 5. Change in After-Tax Income from the Inflation Reduction Act, 2027



Source: Author's calculations based on data from the Tax Policy Center.

Table 2. Change in Generation Share from 2021 to 2035

	Percentage points	
	IRA	*Carbon tax*
Coal	–14	–18
Natural gas	–21	–5
Coal CCS	3	0
Wind and solar	28	19
Other	4	4
CO_2 (% drop from 2005)	68%	68%
Abatement cost ($/*t* – CO_2)	$45–61	$10

Source: Author's calculations based on table 3 in the paper.

Taking the legislation as a whole, it is possible to compare it to a carbon tax. According to the authors, the IRA gets the same amount of carbon reductions as a $10 carbon tax, both resulting in a 68 percent drop in carbon usage in 2035 relative to 2005. The way in which they get these reductions, however, is very different, as shown in table 2.

To the degree that the carbon tax is the gold standard—with those changes reflecting an optimal Pigouvian tax that internalizes the externalities—then the differences in the IRA reflect ways in which it results in an unnecessarily high social cost of emissions reductions. In particular, a carbon tax gets the same emissions reductions more cheaply by relying more on shifting from coal to natural gas. By comparison, the IRA actually results in more coal use (because coal is not especially penalized as compared to natural gas) but makes up for this with even larger wind and solar. It is possible, however, that the IRA approach will be better than a carbon tax in leading to more induced innovation.

Clean energy subsidies and carbon taxes can be equivalent if demand is inelastic on every timescale and innovation is unresponsive to price. In reality these are both unlikely to be true, and in particular, the fact that the US-REGEN model predicts the legislation will lower electricity prices by about 13 percent in 2050 makes me concerned that it will reduce innovations for greater energy efficiency.

As discussed above, clean energy subsidies raise issues regarding the distribution of their benefits. To the degree that they are mildly regressive this creates a headwind for the progressivity of the overall legislation. In contrast, carbon taxes raise revenues that can be explicitly allocated to achieve almost any distributional goal.

Finally, carbon taxes operate on multiple margins. For example, in the vehicle sector they do not just affect the choice of vehicle but also the amount of driving. In addition, they operate across sectors—not just in the energy sector.

Of course policymakers considering the IRA could not compare it to the almighty (a carbon tax) but had to compare it to the alternative (do nothing). And the authors make a convincing case that it is considerably better than that with a $45–61 per ton abatement cost that is considerably below a plausible social cost of carbon.

SUMMARY AND BIG QUESTIONS GOING FORWARD The net economic impact of the IRA, especially when the offsets (which are beyond the scope of this paper) are included, was approximately zero and very uncertain. The macroeconomic impact was very small. The distributional impact was an order of magnitude larger and possibly mildly regressive. Relative to a carbon price, the actual subsidy policy may be far from optimal, leading to sustained electricity price declines and distributional impacts—but it is still better than nothing.

Going forward, the most important questions concern what the next steps are. The IRA is equivalent to a $10 per ton carbon tax, so much more will need to be done to meet the US net zero commitments or the Paris commitment, or even just to have the optimal Pigouvian tax. The IRA, however, may not be easily scalable—and certainly could not be scaled ten times, which is what would be needed to approximate the social cost of carbon. Are there other approaches, other than carbon pricing, that could work at scale? And if so, what are they—and what are the most efficient ways to scale them up?

COMMENT BY

KENNETH GILLINGHAM The global mean surface temperature has increased by nearly 2 degrees Fahrenheit since 1880, and the rate of warming has doubled since 1981 to 0.32 degrees Fahrenheit per decade (Lindsey and Dahlman 2023). Clearly the climate is changing, and the science is settled that greenhouse gas emissions from human activities are far and away the dominant cause (IPCC 2023). The Inflation Reduction Act (IRA) of 2022 made the largest outlay toward greenhouse gas emission reductions in the history of the United States as part of a larger package that included lowering prescription drug prices. One of the major goals of the IRA was the reduce the US government fiscal deficit, for the expectation was that the savings from the non-climate spending measures would easily offset the spending from climate measures.

Bistline, Mehrotra, and Wolfram make a convincing argument that the uptake of the climate incentives may be several times greater than expected, implying that the fiscal costs of the climate provisions in the IRA may be much larger than projected. In fact, the numbers in the paper suggest that the entire bill might possibly be in the red when it comes to the fiscal impact. This finding aligns with a few other recent studies and suggests that the official scoring of the IRA could be quite far off (Jenkins and others 2022; O'Boyle, Esposito, and Solomon 2022; Roy and others 2022). From a climate perspective, this could be seen as a reason to rejoice, as it implies greater emission reductions. From a fiscal perspective, this could be seen as quite problematic. It also raises questions about the political durability of the IRA if the costs substantially exceed expectations.

Bistline, Mehrotra, and Wolfram's contributions go far beyond making the point that the fiscal cost of the IRA may exceed expectations. In this comment, I delve into what I consider the major contributions of the paper to be. I then discuss five key points that I believe emerge from the work that indicate how the IRA will be shaping emissions and the fiscal budget in the next decade.

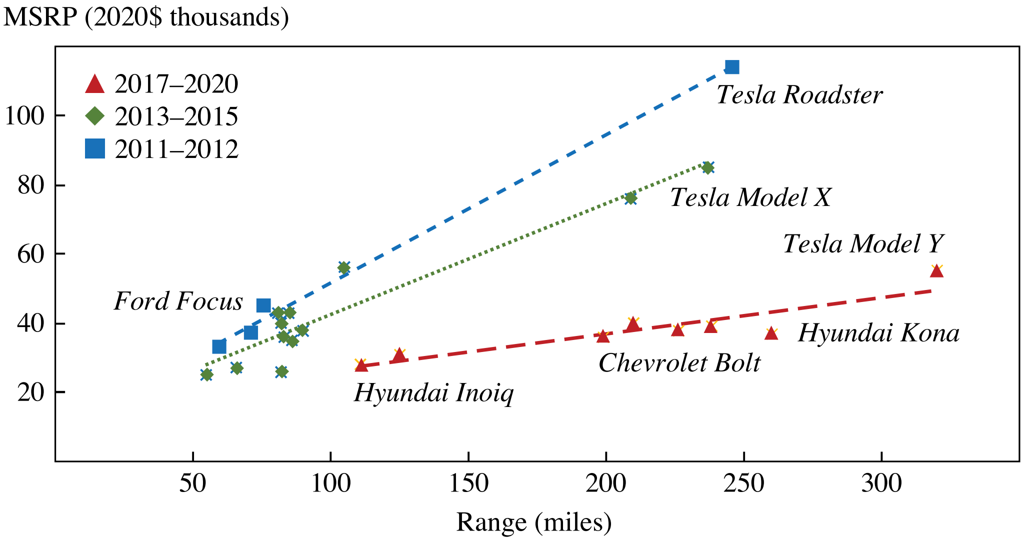
CONTRIBUTIONS Bistline, Mehrotra, and Wolfram perform a set of runs with a large-scale energy model of the United States, US Regional Economy, Greenhouse Gas, and Energy (US-REGEN). This is an extensively developed model created and run by the Electric Power Research Institute. My view of the model is that it is exceptionally careful in the modeling of the electricity system, right in the middle of the pack in its assumptions for electric vehicle market share, and perhaps somewhat optimistic in the modeling of electrifying building end uses. No model is perfect, but US-REGEN provides a useful set of results that can provide real insights into the nature of the energy system. The results of the US-REGEN model suggest that the IRA can lead to economy-wide reductions of carbon dioxide emissions from 2005 levels of 35 percent by 2030, an estimated emission reduction in line with other studies and only modestly lower than the announced reductions of 40 percent by 2030 (Senate Democrats 2022).

Total fiscal cost and electric vehicles. The central case US-REGEN results suggest is that the total undiscounted fiscal cost of the IRA by 2031 could be approximately $780 billion. This is roughly double the $392 billion scoring from the Congressional Budget Office (CBO 2022), which used inputs from the Joint Committee on Taxation (JCT). Of course, the IRA is a bundle of different tax credits. The biggest difference between the two estimates stems from the treatment of electric vehicle tax credits. The CBO/JCT estimate for the cumulative cost of the electric vehicle tax credit through 2031 is $14 billion, which followed based on an assumption that the take-up of these tax credits would be low due to certain provisions. Specifically, the electric vehicle tax credits in the IRA can be as high as $7,500, but to obtain the full tax credit the batteries and critical minerals are required to be at least partly domestically sourced. Moreover, there are income thresholds that make high-income households (often the households that buy new cars) ineligible for taking the tax credits and price caps so that the most expensive electric vehicles are not eligible. There are also used vehicle tax credits with income thresholds and a price cap of $25,000 for the used vehicles. US-REGEN makes very different assumptions regarding these provisions.

Rather than the $14 billion CBO/JCT score, the US-REGEN score for the total fiscal costs of clean vehicle credits is $390 billion. This is a massive difference! Indeed, it accounts for a large fraction of the differences between the two scores. The US-REGEN central case results suggest an electric vehicle market share in 2030 of 44 percent (increased by the IRA from 32 percent). Recent work by Cole and others (2023), as well as a report by Goldman Sachs (2023), also suggests substantially higher cumulative spending on electric vehicles. Cole and others (2023) estimate cumulative federal tax expenditures for electric vehicles of approximately $450 billion by 2030.

Are these much larger cumulative expenditures on electric vehicles possible? They definitely are. Recent work in the literature, including Gillingham and others (2023) and Forsythe and others (2023), suggests that there is substantial unmet demand for electric vehicles. The National Academies of Sciences, Engineering, and Medicine (2021) highlight the remarkable innovations that have occurred over the past decade in electric

Figure 1. Electric Vehicles: Price versus Range



Source: Gillingham and Stock (2018), updated to reflect newer data.
Note: Scatterplot of manufacturer suggested retail price (MSRP) when introduced versus vehicle range (in miles), grouped by vehicle release year. Trend lines show linear regression fit.

vehicle technology, while also projecting continued improvements in the technology going forward. This substantial innovation can also be seen in figure 1, which plots vehicle price against vehicle range, showing a steady march downward in the cost of vehicles along with an increase in range over time.

With the continued innovation projected by the National Academies, a 44 percent market share of electric vehicles in the new vehicle fleet by 2031 appears completely reasonable. It is substantially less than would be needed if the US Environmental Protection Agency (EPA) light-duty vehicle greenhouse gas standards are finalized at the currently proposed levels—which EPA modeling suggests could be met at 67 percent electric vehicles by 2032.[1]

However, just because it is very possible that the electric vehicle market share will be at 44 percent by 2031 does not necessarily mean that all of the new vehicles will receive the full tax incentives. The US Treasury has thus far read the language of the IRA in a way that permits more vehicles to be eligible. For example, there is a "commercial vehicle" provision that

1. Environmental Protection Agency, "Proposed Rule: Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles," https://www.epa.gov/regulations-emissions-vehicles-and-engines/proposed-rule-multi-pollutant-emissions-standards-model.

permits fleets to purchase electric vehicles without the domestic content provision. This clause is being used by some automakers (most notably Kia and Hyundai) to offer much lower lease rates by having the leasing company take the tax credit (Schaffner 2023). It is not clear how the domestic content provisions will be interpreted going forward, and it will depend in part on future administrations. Moreover, there is substantial uncertainty in the evolution of the vehicle market, let alone the evolution of electric vehicle technology. The CBO/JCT score takes a notably more pessimistic view of growth in electric vehicle market share and eligibility of vehicles and vehicle buyers for tax credits.

There are other differences between the assumptions of US-REGEN and the CBO/JCT scoring, such as the likelihood that the tax credits for carbon capture and sequestration (45Q credits) will be used, but these are swamped by the difference in the electric vehicle tax credits. There is substantial uncertainty in whether carbon capture and sequestration will ever be economically viable, with the cost currently remaining quite high. But the new EPA-proposed rule for power plant greenhouse gas emissions would put immense pressure on fossil fuel–powered electricity generating units to add carbon capture and sequestration technology should it be finalized. Thus, there is reason to believe that the US-REGEN estimates of the growth of carbon capture and sequestration could really come to pass.

Cost-effectiveness of the IRA. Bistline, Mehrotra, and Wolfram make the ambitious effort to estimate the cost-effectiveness of the IRA power sector climate provisions. They take an administrative cost perspective, which divides the total IRA expenditure by the total emission reductions from the legislation. Note that this perspective is not the same as a social welfare perspective. Indeed, much of the expenditure can be thought of as transfers from taxpayers to recipients of the tax credits. For a social welfare perspective, the social cost of public funds would have to be applied to the expenditures to calculate the deadweight loss from raising the tax revenue. If the tax revenue was raised by correcting externalities, there could even be no social cost of public funds. Yet, the administrative cost perspective is the standard perspective taken in the literature, and it is useful to consider this perspective for comparison purposes.

The primary cost-effectiveness result in the paper may be surprising to some. The authors calculate several different estimates and restrict the analysis to looking only at impacts in the US economy. The central case range provided is that average abatement cost in the power sector alone is \$45–61 per metric ton of CO_2. Even at the high abatement cost scenario in the US-REGEN results, the average abatement cost is still only \$36–87 per metric ton of CO_2. These numbers are a big result, as the common standard is to compare them to the social cost of carbon dioxide. Based on the results of the best evidence available today, in Rennert and others (2022), the central estimate of the social cost of carbon dioxide is \$185 per metric ton of CO_2 in 2020 (and would be slightly greater in 2030). The range in Rennert and others (2022) is from \$120 to \$400 per metric ton of CO_2 in 2030, with the variation here based on the discount rate.

Thus, these results indicate that the cost of abatement from the power sector provisions in the IRA is much less than the social cost of carbon dioxide emissions. In short, these abatement opportunities appear to be a great deal! There are numerous caveats laid out in the paper, but this basic finding speaks very well for the IRA. It also makes sense because renewable energy is becoming increasingly inexpensive and is already at a lower cost (on a levelized cost basis) than new fossil fuel power plants in most situations.

The authors notably do not calculate the cost-effectiveness of the many other tax credits in the IRA. There is a mention that the electric vehicle tax credits are likely to be less cost-effective due to a high degree of inframarginal customers who would have purchased electric vehicles anyway. But otherwise, the paper provides very little guidance on the cost-effectiveness of the rest of the bundle of tax credits. This is a glaring omission but understanding the abatement cost of the entire set of tax credits (or at least the largest ones) is of utmost importance for policy. One might speculate that some extremely cost-effective tax credits may be bundled with some much less cost-effective credits. As is discussed by Gillingham and Stock (2018), there is substantial heterogeneity in the abatement cost from different measures to reduce greenhouse gas emissions. The IRA has a smattering of different measures, including some that may not reduce greenhouse gas emissions at all, such as some of the hydrogen tax credits. Thus, very important work remains to assess the cost-effectiveness of all of the bundle of tax credits included in the IRA.

The impact of the IRA's clean power provisions. One striking finding by Bistline, Mehrotra, and Wolfram is displayed in figure 10 in the paper. This figure shows that under the IRA somewhere in the range of 22 to 45 percent of all hours over the year in the Southwest Power Pool region (primarily composed of South Dakota, Nebraska, Kansas, and Oklahoma) will have zero or negative wholesale prices of electricity. This comes about because so much renewable generation comes online and such renewable generation can operate at zero or negative prices due to the production tax credit. This is an incredibly striking result that occurs even with deployment of more battery storage to store electricity from the worthless hours to use in the more valuable hours.

Having up to 44 percent of hours with zero or negative prices would make it difficult for baseline power plants, such as natural gas combined cycle plants, to stay online. Peaking plants could continue to be profitable due to the occasional times with high prices and low standby maintenance costs. But if so many hours become zero or negative priced, one would expect a dramatic reshuffling in electricity markets, possibly accompanied by the retirement of a large capacity of efficient baseload power. This issue is often known as the "missing money" problem (Hogan 2019) because the wholesale prices are so low so often that there just isn't enough revenue to keep baseload power plants online. Capacity markets in many regions pay power plants to remain active and may at least help prevent retirements—but potentially at a high cost.

What the authors do not do is tell us whether the issue observed in figure 10 is an extreme case or if it is prevalent throughout the electricity system. Even if it is an extreme case, it is a very important point. But if it is prevalent throughout the electricity system, this is a crucial insight for electricity system planners and policymakers. What it might mean is that capacity markets would have to provide substantial payments to certain key dispatchable or baseload power plants to keep them online (most likely fossil fuel plants). Alternatively, massive investments in energy storage would need to be made. This would substantially raise the overall total system cost of the electricity system. Presumably, US-REGEN already accounts for this in its detailed electricity system modeling. But a key insight from this consideration of grid integration and reliability costs is that retail electricity rates—which must pay for reliability—may not necessarily drop, even with the generous tax credits for renewables, which are effectively subsidizing electricity generation (and thus would be expected to reduce electricity rates).

Macroeconomic implications. Bistline, Mehrotra, and Wolfram provide a further contribution by exploring the macroeconomic implications of the IRA in two ways. First, they examine the macroeconomic impact of the IRA itself. In 2021, the US GDP was $23.32 trillion.[2] The total cumulative clean energy expenditure—while the largest outlay for clean energy in history—is going to be on the order of hundreds of billions of dollars over nearly a decade. Total spending per year will likely be less than $50 billion

2. FRED, Federal Reserve Bank of St. Louis, "Gross Domestic Product," https://fred.stlouisfed.org/graph/?g=15TKS.

at most. This is not pocket change, but relative to the size of the economy, it is quite small.

Thus, it may not be much of a surprise that the authors find minimal macroeconomic impacts. Of course, they perform their analysis in a much more rigorous fashion, using the Federal Reserve Board's US model (FRB/US), with inputs from US-REGEN. The model shows that the IRA is likely to increase demand initially and then later raise the capital stock and output. This result is sensible, but the magnitudes are so small that they are nearly a rounding error in macroeconomic aggregates.

The more important point that the authors make is that macroeconomic aggregates can substantially affect the implications of the IRA for clean energy investment. With a higher interest rate environment—something we are currently seeing as of the date of this writing—it will be more difficult to arrange financing for the clean energy investments of the IRA. This will dampen investment and reduce the emission reductions and fiscal cost of the IRA. Similarly, higher costs of labor and materials can dampen investment.

The authors perform a series of useful explorations of the sensitivity of the clean energy investments of the IRA to macroeconomic conditions. Figure 19 in the paper best shows the effects. I take away two findings from this figure. First, and perhaps most important, is that regardless of the costs of labor and materials (the sensitivity being explored in this figure), the power sector is projected to be substantially decarbonizing. However, higher costs of labor and materials could slow the growth of clean energy in the power sector. The authors do not perform similar calculations for the IRA tax credits outside of the power sector, and it would be useful to know if these two findings hold more broadly for the IRA investments.

Stepping back, it appears that while macroeconomic aggregates could be very slightly affected by the IRA and macroeconomic conditions could in turn affect the IRA, the bigger story is that the power sector is clearly on a path to decarbonize. Coal plants are quickly being retired (although some remain in the US-REGEN simulations as late as 2040, a result that I find to be unlikely) and the capacity to generate hundreds of gigawatts of renewable energy is being built (Fasching and Ray 2023).

Conceptual framework for understanding social welfare. Bistline, Mehrotra, and Wolfram develop a simple macroeconomic-style model to provide a conceptual framework for the welfare analysis of the IRA. This framework is applied to highlight the differences between the subsidies in the IRA and carbon taxes. This is well-trodden ground, and I'm not sure that a theory model was entirely necessary. The main point is that an optimal carbon tax is going to be preferable from a welfare standpoint unless there are substantial deployment externalities. This is intuitive because the economy-wide carbon tax provides incentives to internalize the carbon dioxide externality and assures that the prices in the economy are the prices that maximize social welfare. By increasing prices based on the carbon content of goods, the carbon tax provides incentives for reducing carbon intensity through energy efficiency, fuel switching, and energy conservation. Now, in the electric power sector it may not be so obvious that electricity prices are too low because retail electricity rates are often far from the socially optimal level (Borenstein and Bushnell 2022). Indeed, sometimes retail electricity rates are already too high, in which case, some of the advantage of carbon pricing is eroded.

The authors' model is clear, and the treatment of deployment externalities is new to the literature to the best of my understanding. The deployment externalities in the authors' model are learning-by-doing spillovers, whereby the cost of the technology declines for everyone when a single decision-maker deploys more of the technology. The intuition for how learning-by-doing spillovers can lead to an under-deployment of new technologies relative to the social optimum follows from previous work (Gillingham and Sweeney 2010). Specifically, if a technology exhibits a substantial amount of learning spillovers, then the technology will be deployed too little by the private market, and policy that increases deployment (including tax credits like those in the IRA) can increase social welfare.

If such deployment externalities are sufficiently large, it is possible that the social welfare gains from a subsidy approach like the IRA can exceed the social welfare gains from a carbon pricing approach. The authors do not emphasize this, but really, the socially optimal strategy would be a carbon price to internalize the carbon externality along with a deployment subsidy to internalize the deployment externality. In this sense, the IRA might be thought of as only half of what is needed to really address climate change in an economically efficient manner.

A final nice insight in the model is the inclusion of bottlenecks. Bottlenecks are real-world frictions that can reduce investment in clean energy. The novelty of the approach is a new distinction between market bottlenecks (those that manifest as a higher price of investment when investment goes beyond a certain threshold) and nonmarket bottlenecks (a constraint on investment that does not have an impact on price). This distinction turns out not to be important for the total amount of investment, as long as the threshold is the same. However, the distinction can be very relevant for the fiscal costs of the investment tax credit, for the higher price of investment could lead to larger federal expenditures from the tax credit, which is given as a percentage of the total investment. Indeed, at very high prices of capital due to bottlenecks, very little investment may be happening at high fiscal costs. This is a classic Laffer curve result from public finance that is intriguing to consider. It does not seem likely to be empirically relevant. However, some mix of market and nonmarket bottlenecks probably will occur with the substantial increase in clean energy investment spurred by the IRA. The large interconnection queues for renewable energy currently underway in many regions of the United States are just one example of a nonmarket queue that could slow the growth of clean energy, hampering the effects of the IRA (Penrod 2023).

FIVE KEY POINTS TO TAKE AWAY I conclude my remarks by summarizing five key takeaways from this insightful paper by Bistline, Mehrotra, and Wolfram, each of which lends itself to areas of future work to help us more deeply understand the IRA.

The first takeaway is that there is quite massive uncertainty in both the emission reductions from the IRA and the fiscal costs of the IRA. There is a tremendous upside in the IRA for emission reductions if the cost of renewables, electric vehicles, heat pumps, and other technologies continues to decline. But there are many reasons why the uncertainty bounds on future projections are extremely wide. The authors mention all of the reasons: technology uncertainty, market acceptance uncertainty, regulatory uncertainty, and macroeconomic conditions. One way to take the main result of the paper is that it points out just how far off of the CBO/JCT projections we could be in a decade.

The second takeaway is that the power sector tax credits in the IRA are remarkably cost-effective. Based on the estimated ranges in the paper, the abatement cost for the IRA power sector tax credits is well below the best estimates of the social cost of carbon dioxide that are available. This is not necessarily an obvious result, but it is a major result worth emphasizing. It also raises further questions, such as how long we can expect abatement costs to remain this low and what uncertainties they are most sensitive to.

The third takeaway is that the power sector tax credits can lead to some striking effects on the electricity system. Wholesale electricity prices could be zero or negative for up to 40 percent of hours of the year in some regions. The authors would have benefited from providing details on how many regions this is likely to be an issue for. Zero or negative wholesale prices would pose a huge problem to many legacy fossil fuel plants and would likely lead to a major impetus for stationary energy storage and to substantial increased retirements in the absence of additional payments (either side payments or payments through capacity markets). What it also means is that the costs of reliability and grid integration may be sufficiently high such that it is quite possible that the IRA tax credits for clean electricity actually raise electricity rates, counter to what might be expected for a subsidy.

A fourth takeaway is that the overall welfare effects of the IRA really hinge on the success of the tax credits spurring innovation through increased deployment of clean energy. If the IRA really can lead to large learning-by-doing spillovers, it can substantially improve social welfare. But to be a market failure, one must have both substantial learning by doing with further deployment and spillovers across firms that lead firms outside the innovating firm to benefit from the innovation. Given the remarkable industrywide technological leaps that have been occurring over the past decade in both renewable energy and electric vehicles as the technologies have been deployed, I find it eminently plausible that such induced innovation is possible. But understanding this more deeply is certainly a topic for future research.

A final takeaway is that there is likely to be substantial heterogeneity in the abatement costs from the IRA, which is a bundle of many different tax credits. The authors allude to the possibility that the abatement costs would be higher for electric vehicles than renewable energy because so many electric vehicle buyers would be inframarginal (this of course may be countered by the large innovation potential in electric vehicle technology). But what about the energy efficiency and heat pump tax credits? What about the hydrogen tax credits? Carbon capture and sequestration tax credits? All of these unanswered questions underscore the vast uncertainty about the cost-effectiveness of the IRA. It is quite likely that many of these provisions will be extremely different in their cost-effectiveness. A full understanding of the economics of the IRA is not possible without estimates of the abatement cost of these measures. I see very high value in future work to begin peeling back the layers of the IRA to reveal which parts of the bundle are most likely to be cost-effective at reducing emissions.

Bistline, Mehrotra, and Wolfram break new ground in the depth and breadth of analysis on the IRA, which provides a historic expenditure to reduce greenhouse gas emissions. They uncover several striking findings but also leave open an important set of questions that are necessary to answer for a complete understanding of the IRA, which is crucial as the United States and the world consider the next steps in reducing greenhouse gas emissions.

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GENERAL DISCUSSION James Stock began the discussion by noting that there is additional support for the authors' findings in the US Energy Information Administration's annual energy outlook for 2023, which estimated that the Inflation Reduction Act (IRA) would have a 7 percentage point marginal effect on emissions by 2030.[1]

1. US Energy Information Administration, *Annual Energy Outlook 2023: Issues in Focus—Inflation Reduction Act Cases in the AEO2023* (Washington: Department of Energy, 2023), https://www.eia.gov/outlooks/aeo/IIF_IRA/pdf/IRA_IIF.pdf.

Kenneth Rogoff discussed estimates showing that even with the IRA, the United States is not making sufficiently significant emission reductions to have a significant global impact and that the overwhelming growth in future emissions is coming from elsewhere.[2] He acknowledged the importance of leading by example but questioned the term "cost-effective" given that the relative impact on global emissions was not discussed in greater depth. Rogoff stated that he found the learning-by-doing aspects of the IRA powerful and important in a global context. Maurice Obstfeld agreed that while US efforts are small relative to the challenge, doing what is politically possible is still important. Obstfeld also noted that one potentially positive impact of this legislation is that the European Union could make green subsidies more accessible to remain competitive with green investment in the United States.[3]

Steven Davis asked whether the authors' carbon abatement cost estimate was for within the United States or an estimate of how it would affect global emissions abatement. He expressed concerns over the export, and potentially lower prices, of fossil fuels abroad if the United States reduces its reliance on carbon energy sources. Davis agreed with Rogoff's questioning the use of national measures of impact when many of the outcomes of interest are global. Davis also supported the benefits brought up by Rogoff and Obstfeld, stating that induced innovation and international policy bandwagon effects were potentially important positive aspects of the legislation. Catherine Wolfram responded to Davis's concerns about exporting emissions abroad, stating that estimates of leakage are low, particularly at a price of $12 per ton of carbon.[4]

Glenn Rudebusch recognized that while the macroeconomic benefits of less carbon pollution may appear to be small, there are important co-benefits of less carbon pollution for health and labor force participation in addition to distributional effects, based on where carbon pollution is occurring. Rudebusch also mentioned the importance of directed technical change, suggesting that the authors might include greater discussion of innovation externalities. Pinelopi Goldberg highlighted the importance of the IRA and noted that until recently the United States was one of the only countries

2. Climate Action Tracker, "USA," https://climateactiontracker.org/countries/usa/.

3. Jacob Funk Kirkegaard, "The US-EU Race for Green Subsidies Can Help Fight Climate Change," Realtime Economics, Peterson Institute for International Economics, February 14, 2023, https://www.piie.com/blogs/realtime-economics/us-eu-race-green-subsidies-can-help-fight-climate-change.

4. Florian Misch and Philippe Wingender, "Revisiting Carbon Leakage," working paper 21/207 (Washington: International Monetary Fund, 2021).

that had not made significant progress toward addressing climate change—despite being the second-largest carbon emitter and one of the richest countries in the world.[5]

Stock responded to the comments made by Rogoff and Davis, stating that he doubted they would have asked, "Why should we adopt a cost beneficial policy in the United States to reduce emissions when most of the emissions are abroad?" if instead the question was, "Why should we adopt a cost-beneficial policy to help the uneducated poor children of the United States when most uneducated poor children are abroad?" Stock continued, explaining that four reasons to adopt such a policy are: (1) it is cost beneficial, (2) the political economy is such that those experiencing the impacts abroad do not vote in the United States, (3) there will be positive spillover effects from involvement in international negotiations such as the Paris agreement, and (4) it will help advance technological innovations through learning by doing.

Wolfram responded to comments regarding spillover effects, noting the importance of learning by doing as well as spillovers with pricing, such as the carbon border adjustment mechanism implemented in the European Union, which has encouraged other countries to adopt carbon pricing. John Bistline noted that prior literature examining the impacts of induced technical change in wind and solar will likely be important for thinking about the impacts—via mechanisms such as learning by doing, economies of scale, and research and development subsidies—of the IRA going forward.

John Haltiwanger mentioned the importance and need to further examine the distributional consequences and sectoral shifts mentioned by Jason Furman in his comment, particularly the between-sector effects and within-sector effects. Haltiwanger wondered if subsidies will mostly go to large incumbent businesses, which could have adverse effects for innovation and productivity growth that are worth recognizing and discussing. Adele Morris emphasized the importance of Furman's discussion of distributional effects and the potential for subsidies, such as those for electric vehicles (EVs), to be potentially regressive, complicating some of the benefits of learning by doing.

Wolfram stated that the distributional effects highlighted by Furman and Kenneth Gillingham are very important and pointed out that this work is a first analysis of the IRA and that there will likely be many papers written

5. Monica Crippa, D. Guizzardi, M. Banja, E. Solazzo, M. Muntean, E. Schaaf, and others, *CO2 Emissions of All World Countries* (European Commission, 2022), https://edgar.jrc.ec.europa.eu/report_2022.

on the IRA discussing aspects of the legislation going forward. Bistline responded to these remarks as well, highlighting previous work that had examined how electrification incentives could have distributional impacts for local air quality.[6]

Phillip Swagel pointed out that legislation that generates changes in the Internal Revenue code are estimated by the Joint Committee on Taxation (JCT), not the Congressional Budget Office (CBO).[7] Swagel stated that creating preliminary estimates takes time and is challenging, particularly in the case of the IRA, which was a prolonged legislative effort. Swagel also responded to Gillingham's discussion of implementation regarding rules of origin and tax credits only applying to certain limits, noting that this may not be a fair critique of the JCT. He speculated that the JCT may have evaluated the rules as the statute stipulated but that the Treasury instead determined that income limits do not apply under specific circumstances.

Morris expressed the need to distinguish between fiscal cost and real resource cost, particularly when discussing the cost per ton abated. She remarked that in some instances abatement cost is the combined private and fiscal cost on average whereas a carbon tax sets the marginal abatement cost of an incremental environmental improvement. Morris also affirmed examining the legislation in the broader regulatory framework, noting that if EV makers can sell credits into the corporate average fuel economy credit market, this could have a significant impact on the net environmental benefits of an EV subsidy, relative to a counterfactual where EV makers cannot sell these credits.

Joe Beaulieu explained that he was surprised by the expected wholesale prices becoming negative and was reminded of the 2000–2001 California electricity crisis in which abrupt changes in the energy market structure had unexpected results.[8] Beaulieu wondered if changes to the market structure of the energy system from the IRA might be relevant to discuss or consider in this work. Wolfram responded to Beaulieu by clarifying that while the authors predict negative wholesale prices, the figure shown was for one region with a lot of wind capacity and that this does not reflect

6. John E. T. Bistline and others, "Economy-Wide Evaluation of CO2 and Air Quality Impacts of Electrification in the United States," *Nature Communications* 13 (2022): 6693, https://www.nature.com/articles/s41467-022-33902-9.

7. Joint Committee on Taxation, "Statutory Basis," https://www.jct.gov/about-us/statutory-basis/.

8. James L. Sweeney, "The California Electricity Crisis: Lessons for the Future," *The Bridge* 32, no. 2 (2002): 23–31, https://www.nae.edu/Publications/Bridge/OurEnergyFuture/TheCaliforniaElectricityCrisisLessonsfortheFuture.aspx.

prices nationwide. Tristan Reed pointed out that large increases in capital investment imply an increase in demand for construction which, in an environment with low unemployment, could lead to a bottleneck in implementation. Reed contemplated whether this was something the authors could explore or discuss in their model.

Goldberg noted that while it is very useful to compare policies to a carbon tax, carbon taxes have not been implemented in the past. Goldberg encouraged a greater discussion of alternative policies to a carbon tax that might be more politically feasible. Wolfram responded to Goldberg by pointing out that a number of countries, including the European Union, United Kingdom, and Canada have implemented carbon prices, in addition to states in the United States such as California and others in the Northeast.[9] Stan Veuger commented that he believed that the motivation for the IRA was not to increase innovation externalities but instead a result of political constraints, such as a lack of support for carbon taxes as well as protectionist goals of the government. Veuger explained that he believed this was worth highlighting because of the international response to the legislation.

Wolfram responded to Furman's comment by adding some caution to the work of Bornstein and Kellogg, stating that their finding that the retail price of electricity had been higher than the social marginal cost was based on old social cost of carbon numbers.[10] Wolfram also noted that it may not be an equal comparison to scale the CBO/JCT estimates to the authors' estimates due to the difference in the EV tax credits.

9. World Bank, "Carbon Pricing Dashboard," https://carbonpricingdashboard.worldbank.org/map_data.

10. Severin Borenstein and Ryan Kellogg, "Carbon Pricing, Clean Electricity Standards, and Clean Electricity Subsidies on the Path to Zero Emissions," *Environmental and Energy Policy and the Economy* 4 (2023): 125–76.

A Macroeconomic Framework

In this section, we lay out the macroeconomic framework used in Section 5 to analyze the qualitative macroeconomic impacts of the clean energy tax credits. A neoclassical growth model is augmented with electricity generation and clean energy capital.

A.1 Households

A representative household chooses a path for consumption and investment in clean energy power generation. The capital stock is owned by the household and used to generate electricity that is sold at price p_t^e in each period. Electricity is consumed by both households and firms. Electricity generation is captured by a generation function $G(\cdot)$ that is increasing in the clean power capital stock. The representative household inelastically supplies a fixed level of labor $\bar{N}$ that is paid wage W_t by the representative firm. The household can purchase new clean energy capital at relative price p_t^c in each period, and invests in one-period government debt that pays interest rate r_{t-1}. There is no aggregate or idiosyncratic risk.

The household pays lump sum taxes T_t to the government in each period and receives both a production and investment tax credit. The production tax credit is proportional to electricity generated while the investment tax credit reduces the effective price of clean energy investment. The household's dynamic optimization problem is given below:

$$V(K_0) = \max_{C_t, E_t^h, B_{t+1}^g, K_{t+1}^c} \sum_{t=0}^{\infty} \beta^t u\left(C_t, E_t^h\right)$$

$$\text{subject to} \quad C_t + \left(1 - \tau_t^{inv}\right) p_t^c I_t^c + p_t^e E_t^h + B_{t+1}^g = \left(p_t^e + \tau_t^p\right) E_t + \left(1 + r_{t-1}\right) B_t^g - T_t + W_t \bar{N} \quad \text{(A1)}$$

$$K_{t+1}^c = I_t^c + (1 - \delta_c) K_t^c \quad \text{(A2)}$$

$$E_t = G\left(K_t^c\right) \quad \text{(A3)}$$

The optimal path for investment satisfies a dynamic condition where the marginal cost of investing an additional unit of clean power equals the marginal benefit from additional power generation. Household electricity demand is given by a static condition equating marginal utility for electricity consumption and marginal cost.[70]

$$p_t^c \left(1 - \tau_t^{inv}\right) u_c\left(C_t, E_t^h\right) = \beta u_c\left(C_{t+1}, E_{t+1}^h\right) \left[G_c\left(K_{t+1}^c\right)\left(p_{t+1}^e + \tau_{t+1}^p\right) + p_{t+1}^c\left(1 - \tau_{t+1}^{inv}\right)(1 - \delta_c)\right] \quad \text{(A4)}$$

$$u_c\left(C_t, E_t^h\right) = \beta u_c\left(C_{t+1}, E_{t+1}^h\right)(1 + r_t) \quad \text{(A5)}$$

$$u_e\left(C_t, E_t^h\right) = p_t^e \quad \text{(A6)}$$

[70]Retail electricity prices for households typically also include charges for funds that pay for energy efficiency, clean energy, and transmission/distribution. The modeling here ignores those considerations, and is probably closer to price-setting in the wholesale market.

A.2 Firms

Firms hire labor and purchase electricity to produce a consumption good and can transform consumption goods to investment goods at $1/p_t^c$ in each period. The production function is increasing in both factors of production, features decreasing returns to each individual factor but has constant returns to scale:

$$\begin{aligned} \max \quad \Pi_t &= Y_t - W_t N_t - p_t^e E_t^f \\ Y_t &= F\left(E_t^f, N_t\right) \end{aligned} \tag{A7}$$

The firm's optimal choice of electricity and labor imply standard factor demands:

$$F_e\left(E_t^f, N_t\right) = p_t^e \tag{A8}$$

$$F_n\left(E_t^f, N_t\right) = W_t \tag{A9}$$

A.3 Government and Market Clearing

The government collects taxes from households to finance the investment and production tax credit for power generation. For simplicity, we assume no government spending. The government can also finance expenditures via debt issuance. The government's flow budget constraint is given by:

$$\tau_t^p E_t + \tau_t^{inv} p_t^c I_t^c + (1 + r_{t-1}) B_t^g = T_t + B_{t+1}^g \tag{A10}$$

Market clearing requires the price of electricity and the wage to clear each factor market:

$$E_t^f + E_t^h = E_t \tag{A11}$$

$$N_t = \bar{N} \tag{A12}$$

An equilibrium is given by quantities $\{N_t, Y_t, C_t, E_t, E_t^f, E_t^h, K_{t+1}^c, I_t^c, T_t\}_{t=0}^{\infty}$ and prices $\{r_t, p_t^e, W_t\}_{t=0}^{\infty}$ that jointly satisfy equations A1-A12 given exogenous processes for clean energy tax credits $\tau_t^p, \tau_t^{inv}, B_{t+1}^g$ and the relative price of clean energy investment p_t^c.

A.4 Extension with Fossil Fuel Electricity

To consider the impact of carbon taxes, we modify the household's problem by adding fossil fuel capital as an additional source of electricity production. Fossil fuel capital K_t^f generates electricity via an increasing generation function $G^f(\cdot)$ and electricity generated from fossil fuels is a perfect substitute for electricity generated by clean energy. A carbon tax τ_t^f is levied on electricity produced by fossil fuels with κ representing a technological constant for carbon emissions generated from a given stock of fossil fuel capital.

With fossil fuel capital, the representative household's budget constraint, laws of motion for capital, and electricity production are given below:

$$C_t + \left(1 - \tau_t^{inv}\right) p_t^c I_t^c + p_t^f I_t^f + B_{t+1}^g = p_t^e E_t + \tau_t^p E_t^c - \tau_t^f \kappa E_t^f + \left(1 + r_{t-1}\right) B_t^g - T_t + W_t \bar{N} \quad \text{(A13)}$$

$$K_{t+1}^c = I_t^c + \left(1 - \delta_c\right) K_t^c \quad \text{(A14)}$$

$$K_{t+1}^f = I_t^f + \left(1 - \delta_f\right) K_t^f \quad \text{(A15)}$$

$$E_t^f = G^f\left(K_t^f\right) \quad \text{(A16)}$$

$$E_t^c = G^c\left(K_t^c\right) \quad \text{(A17)}$$

where δ_f is the depreciation rate for fossil fuel capital which may differ from the depreciation for clean energy capital δ_c.

The optimal choice of fossil fuel capital by the representative household is given the following Euler equation:

$$p_t^f \lambda_t = \beta \lambda_{t+1} \left[G_1^f\left(K_{t+1}^f\right)\left(p_{t+1}^e - \tau_{t+1}^f \kappa\right) + p_{t+1}^f \left(1 - \delta_f\right)\right] \quad \text{(A18)}$$

$$\text{(A19)}$$

where $\lambda_t = u_c\left(C_t, E_t^h\right)$ is the marginal utility of consumption.

In this extension of the model, an equilibrium consists of the quantities and prices in the baseline model along with allocations for K_{t+1}^f, I_t^f, E_t^f and exogenous sequences for the carbon tax τ_t^f and the relative price of fossil fuel capital p_t^f.

A.5 Externalities and the Planner's Problem

To consider optimal fiscal policy, we make two changes to the baseline model extended with carbon taxes and fossil fuel capital. We modify the representative household's utility function to include both damages from cumulative carbon emissions and a law of motion for cumulative emissions. The planner's problem is given below:

$$V\left(K_0, Q_0\right) = \max_{C_t, K_{t+1}^c, K_{t+1}^f} \sum_{t=0}^{\infty} \beta^t u\left(C_t\right) - D\left(Q_t\right)$$

$$C_t + p_t^c I_t^c + p_t^f I_t^f = F\left(E_t, \bar{N}\right) \quad \text{(A20)}$$

$$K_{t+1}^c = I_t^c + \left(1 - \delta_c\right) K_t^c \quad \text{(A21)}$$

$$K_{t+1}^f = I_t^f + \left(1 - \delta_f\right) K_t^f \quad \text{(A22)}$$

$$E_t = E_t^f + E_t^c = G^c\left(K_t^c\right) + G^f\left(K_t^f\right) \quad \text{(A23)}$$

$$Q_{t+1} = Q_t + \kappa E_t^f \quad \text{(A24)}$$

where Q_t is the cumulative level of emissions and $D\left(\cdot\right)$ is a damages function that is increasing in cumulative emissions and enters the planner's utility function. The planner chooses clean energy and fossil fuel investment subject to laws of motion for emissions and the respective capital stocks.

The planner's Euler equations under optimal policy are given below:

$$p_t^c = \frac{1}{1+r_t}\left[p_{t+1}^e G_c'\left(K_{t+1}^c\right) + p_{t+1}^c\left(1-\delta_c\right)\right]$$
$$p_t^f = \frac{1}{1+r_t}\left[p_{t+1}^e G_f'\left(K_{t+1}^f\right) + p_{t+1}^f\left(1-\delta_f\right)\right] - \underbrace{\mu_{t+1}\kappa G_f'\left(K_{t+1}^f\right)}_{\text{time-varying carbon tax}}$$

where μ_{t+1} is the multiplier that implicitly prices, in real dollar terms, the damages from cumulative carbon emissions Q_t. Relative to the competitive equilibrium, the planner's choice for clean energy capital is undistorted (i.e. no subsidy is required) but the optimal choice of fossil fuel capital requires a time-varying carbon tax. Thus, optimal policy only requires a carbon tax.

A learning-by-doing externality is present if the relative price of clean energy capital is now a decreasing function of the stock of installed capital: $p_t^c = p\left(K_t^c\right)$. The planner's resource constraint becomes:

$$C_t + p\left(K_t^c\right) I_t^c + p_t^f I_t^f = F\left(E_t, \bar{N}\right) \tag{A25}$$

The Euler equation for investment from the planner now differs from the private optimality condition with an extra term that reflect the additional future benefit from lower cost of future investment:

$$p\left(K_t^c\right) u_c\left(C_t\right) = \beta u_c\left(C_{t+1}\right)\left[p_{t+1}^e G_c\left(K_{t+1}^c\right) + p\left(K_{t+1}^c\right)\left(1-\delta_c\right) - p_c\left(K_{t+1}\right) I_{t+1}^c\right] \tag{A26}$$

This higher level of investment can be achieved by an appropriately chosen time-varying subsidy.

B Event Study

To assess the impact on firm profits of the Inflation Reduction Act, we look at the response of equity prices around key announcement dates. Table 5 shows the daily excess return for selected clean energy equities. Specifically, we take the daily return (from open to close) relative to the S&P 500.[71] The clean energy ETF return is an equal-weighted average of the following ETFs: ICLN, TAN, PBW, FAN, and LIT. The fossil fuel ETF is an equal weighted average of PXE and IEO. Selected clean energy stocks are an equal-weighted basket of TSLA, RIVN, FSLR, ALB, and NEE. Selected fossil fuel stocks are CVX, DVN, BTU, and ARCH. In related work, Bauer, Offner and Rudebusch (2023) examine the response of returns in fossil fuel and clean energy equities around the Manchin/Schumer announcement dates in July of 2022 and investigate the implications for pricing climate risk in financial markets.

The event study shows results that are broadly consistent with increased profits and higher valuations as a result of the Inflation Reduction Act. Clean energy ETFs and stocks fell sharply

[71] For announcement days that fall on the weekend, the daily return is difference between the opening price and previous close.

Event date	Event	Excess daily return (relative to S&P 500) Clean energy ETFs	Fossil fuel ETFs	Selected clean energy stocks	Selected fossil fuel stocks	S&P 500 return	10-year Treasury (bp change)
19-Nov-21	House passage of Build Back Better	2.1	-1.7	2.2	-0.7	-0.2	-5
19-Dec-21	Manchin announces decision to vote against Build Back Better	-3.1	-3.0	-2.6	-2.6	-0.7	2
14-Jul-22	Annoucement of end of Manchin-Schumer negotiation	0.5	1.0	1.3	0.3	0.7	5
27-Jul-22	Annoucement of agreement on Inflation Reduction Act	0.6	0.9	-0.1	1.2	1.8	-3
03-Aug-22	CBO/JCT score of Inflation Reduction Act	-1.9	-4.9	-1.5	-4.5	1.1	-2
07-Aug-22	Senate passage of Inflation Reduction Act	1.6	-0.1	2.7	-0.2	0.3	-6
12-Aug-22	House passage of Inflation Reduction Act	0.6	0.2	0.7	1.8	1.3	-3

Table 5: Equity price response around key announcement dates.

after Senator Manchin's announcement that he would not support the Build Back Better Act passed by the House in November of 2011. Fossil fuel stocks also fell on his announcement, but this may reflect that Manchin's announcement occurred over the weekend and Omicron cases were impacting oil markets. Clean energy stocks did not respond strongly to the announcement of an agreement between Manchin and Schumer on July 27, 2022, perhaps reflecting continued uncertainty about the likelihood of Senate passage. However, on Senate passage of IRA, clean energy ETFs rose 1.6% while fossil fuel ETFs and stocks fell slightly. On Senate passage, First Solar (FSLR) had a 6.9% excess return relative to the overall market. The muted response of fossil fuel stocks suggests that IRA had little in the way of negative impacts for oil and gas producers.

Overall, the event study suggests that the major stock responses were around Manchin's BBB announcement and Senate passage of IRA. These responses suggest that some increase in stock valuation may reflect the prospect of increased profits from as a result of IRA.