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A Commodity-specific Border Carbon Adjustment Framework Based on the Costs of Decarbonizing without a Carbon Price

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Abstract

Border carbon adjustments are a class of tariffs under consideration in multiple regions. Their aim is to prevent carbon leakage and the offshoring of manufacturing capacity due to increased costs associated with new domestic requirements to mitigate greenhouse gas emissions. Proposals to date are predominantly based on existing carbon pricing schemes that would extend the same costs to imported goods. However, the United States and most other countries do not have a carbon price, and any border carbon adjustment they implement would either have to introduce one or rely on other metrics. This paper explores the latter situation, providing a capital-based method of calculating border carbon adjustments that would complement non-pricing policy prescriptions. Fertilizers, as an emissions intensive industry, are used to show the magnitude of hypothetical duties under the framework. The requirements and constraints are also discussed in terms of implementation, different logistical trade-offs, and broader political economy considerations.

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Introduction

A border carbon adjustment (BCA) is a trade policy meant to support a broader transition away from fossil fuels within the country that implements it.[1] In general terms, a BCA levies a duty on imported goods that is proportional to the greenhouse gas (i.e., carbon) emissions required to bring that product to market. They are generally structured to be complementary to other domestic policies aimed at mitigating climate change, such as adding an explicit price on emissions or an implicit price for an industry. An explicit price would take the form of a direct levy on greenhouse gas emissions, while an implicit price is indirectly created when industry is required to implement emissions-abating process changes.

The desire to implement BCAs is driven by concerns that climate change-mitigating policies within a country will push certain industries to relocate to other less regulated countries, resulting in *carbon leakage* (i.e., an increase in emissions in a less regulated country resulting from the emission reducing policies of another country).[2] Decarbonizing any manufacturing sector will naturally incur costs for firms as they change operations or install capital to comply with new standards.[3] If moving production to a different country and shipping goods from that country to the home market is less expensive than the costs associated with reducing emissions, firms would have a financial incentive to do so.[4] If the goal of the underlying policy is to reduce emissions, that carbon leakage would work against its overall success. Similarly, domestic producers could lose market share to foreign competitors if the increased costs on domestic producers are passed on in the price of their domestically produced goods, while imports are unaffected. The BCA would increase the price of imports from countries that do not engage in decarbonization, essentially maintaining domestic competitiveness. BCAs may also incentivize decarbonization in other nations, which is required to fully mitigate climate change.[5] In general, the potential objectives of a BCA can be summarized as follows:

1. mitigate the risk of carbon leakage;
2. preserve domestic competitiveness; and
3. incentivize action in other countries.

Constructing a BCA depends on the objectives of the policymakers creating it and the existence of other emissions-mitigating policies. This paper explores a new approach for constructing a BCA in the absence of an explicit carbon price. It is based on the comparative costs of decarbonization engendered by a regulatory or other requirement that requires an industry to abate their emissions. The framework uses differences in capital and operational costs between decarbonized and status quo scenarios to arrive at

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[1] Other discussions use the terms like carbon border adjustment (CBA), but the meaning is equivalent. Campbell, McDarris, and Pizer, "Border Carbon Adjustments 101," November 10, 2021. The literature cited throughout the introduction serve as good resources for additional information on the basics of BCAs for the interested reader.

[2] Abnett, "EU Sees," January 18, 2021; Keen, Parry, and Roaf, "Border Carbon Adjustments," September 27, 2021; Cosbey et al, "Developing Guidance," 2019.

[3] These costs can either be direct costs, such as switching from burning fossil fuels for energy to using renewable electricity, or indirect costs that are passed up the value chain from other stages in the value chain.

[4] Campbell and Pizer, "Border Carbon Adjustments," July 29, 2021.

[5] For example, the United States accounts for approximately 15 percent of global emissions, meaning complete decarbonization domestically would not solve the problem. USEPA, "Global Greenhouse Gas Emissions Data," accessed June 4, 2021.

an ad valorem duty rate applied to each country, which is modulated by comparative emissions between U.S. and foreign industries.[6] It is scoped to be best applied to a subset of emission-intensive products. The overall assessment of the approach is based on objective (1), to mitigate the risk of carbon leakage. Additional information on BCAs and the choices undergirding their construction is provided in the following subsections.

Scope

One consideration when constructing a BCA is the overall scope of the policy.[7] All goods presently manufactured require fossil fuel inputs at some point in their production.[8] For example, while aluminum can be refined using renewable electricity, the machines used to extract the ore and transport materials between production nodes still rely on fossil fuels for energy. The *embedded emissions* (i.e., the amount of greenhouse gas emissions required to bring a product to market) of any import could thus be calculated and made subject to the policy. Choosing the scope of the desired BCA is dependent on the data, resource, and other constraints that are required to implement it.[9]

In a universal BCA, duties would be levied on all imports from a given country based on some macro-parameter. For example, economy-wide energy consumption and greenhouse gas emissions could be the point of comparison for setting a relative universal BCA rate. Aggregate energy consumption reflects the electricity, heat, and transportation required to bring products to market in each country. This method has the advantage of being simpler from an implementation standpoint, as a flat rate would be applied to all imports from a given country instead of having to define rates for each product from each country.[10] A universal rate would also engender broader decarbonization, as any decrease in emissions will lower the resulting BCA for every product emanating from that country.[11]

The primary disadvantage of universal rates is that they would not accurately address leakage for each individual product. As a result, duties applied could be higher than necessary for some products, and lower than necessary for others. The emissions profile of a commodity will vary substantially based on the existence of technology that allows decarbonization or the energy intensity required to manufacture it. Steel, for example, typically requires more energy and generates more emissions than all other products, meaning a universal rate would undercount its true embedded emissions. Process-specific emissions would also not be captured in universal calculations that rely on aggregate energy consumption. For example, manufacturing cement releases carbon dioxide from chemical reactions in addition to the energy used to drive production.

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[6] A variant creating a per unit duty rate is outlined in footnotes 28 and 45.

[7] Keen, Parry, and Roaf, "Border Carbon Adjustments," September 27, 2021.

[8] While it is possible that some production nodes are fully decarbonized, no complete value chain—ranging from raw material extraction, transportation, and processing—is fully decarbonized at present.

[9] Keen, Parry, and Roaf, "Border Carbon Adjustments," September 27, 2021.

[10] It is also easier to calculate universal rates using more aggregated data that is more likely to be available. Those implementing the tariff would not need to collect global data from every industry, sub-region, or point of emission to obtain a usable value.

[11] This shift would likely be driven by a country-wide political incentive to change decarbonization policy rather than firm-level behavior, as each entity would only see a fraction of the return on their individual investment.

More targeted duties may be desirable to minimize the disruption caused by new policies. The primary question is which products to include within the policy framework. The general consensus in the literature is to focus on emissions-intensive trade-exposed (EITE) industries.[12] This assessment follows the reality that a minority of products—such as fertilizers, metals, and cement—result in the majority of emissions, so applying a BCA to these items specifically could have a substantial impact without disproportionate disruption. These products are also traded in vast quantities as global commodities, meaning they are also highly susceptible to carbon leakage risks.

The primary concern for product-specific duties is the availability of the necessary data. One would need to estimate the embedded emission in a given product manufactured in each country, and the information required for that calculation may be difficult to accurately ascertain. Embedded emissions will vary depending on the energy mix and the sources of raw materials, including upstream goods or components that are sourced from third countries. Accounting for these factors could extend almost infinitely throughout the supply chain, requiring a large, dedicated monitoring system.

Political Economy Considerations

Products covered by a BCA do not exist in a vacuum, and changes in their price could have substantial downstream effects. Nitrogen fertilizer, as an example, is a base input for the entire agricultural supply chain whose price is ultimately reflected in food costs. The existence of a policy necessitating a BCA to mitigate carbon leakage implies a rise in prices that needs to be dealt with. While an added import duty may level the playing field for one industry, some increase in consumer and downstream industry costs will likely still occur. For critical commodities like foodstuffs, this may create a negative response from those who have to pay the higher price. Alternatively, higher domestic food prices may encourage greater imports of agricultural products, negatively affecting U.S. producers.

Mitigating the downstream effects of decarbonization and BCAs could take the form of complementary policies introduced alongside them. For example, to alleviate price increases in food caused by fertilizer regulations, some form of relief could be provided to manufacturers to alleviate the costs of upgrading their capital. Alternatively, direct help to farmers who buy fertilizer could be added to existing farm assistance regimes. In the former case, a BCA may not be required or be required to a much-diminished extent if substantial costs associated with decarbonization are mitigated. This highlights the complexity of factors that one would consider throughout the construction of this type of policy.

It is also important to acknowledge how the two types of BCAs described above intersect with other climate change policy goals. Because natural gas only releases 54 percent of the emissions as coal per unit energy released, a universal BCA rate could create an incentive for switching to that fuel instead of complete decarbonization. This situation would not be a complete solution to the overall climate change issue, as fossil fuels are still consumed, and emissions continue beyond neutrality. A product-specific basis, on the other hand, would avoid that dilemma if the initiating domestic policy is focused on complete decarbonization.

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[12] Some researchers suggest identifying these industries with a set cut-off based on the embedded emissions per unit of product, for example, the 2020 report from Resources for the Future defines EITE goods as possessing more than 0.5 tons of emissions per ton of product or 0.25 tons of emissions per megawatt-hour of electricity. Flannery et al, "Framework proposal," October 23, 2020.

BCAs are inherently complex policy instruments that have wide ranging impacts. Placing constraints on imports to offset pressure on domestic industry in pursuit of climate goals will intersect with all other diplomatic and domestic priorities. In the case of something like fertilizer, there will be downstream impacts on domestic agriculture. For a product like steel or cement, construction and manufacturing industries will be impacted. Retaliation or other adverse effects on other unrelated foreign affairs activities are also possible.[13] The choice of the final form of any BCA thus has to be weighed against those possible consequences.

Current Policy Proposals

Recent activity in Europe points towards a future where BCAs become a real component of international trade policy.[14] The policy framework proposed by European Union (EU) is tied into its pre-existing emissions trading system (ETS) that assigns a cost for greenhouse gasses and sets the total amount of allowable emissions economy-wide.[15] The EU BCA would have importers buy allowances tied to the price on domestic greenhouse gas emissions.[16] The allowances would also be traded on a market similar to the ETS.[17]

Importers would surrender the appropriate amount of allowances at the end of the year based on the embedded emissions of the products brought into the EU. The EU framework relies on estimating the embedded emissions of products based on their specific source where data is available, but defaults to the average performance of the least decarbonized European producers if that information isn't available. Presently, the EU proposed BCA would only impact a handful of emissions-intensive products at the outset, including certain types of metals, cement, and fertilizers.

Implementing a U.S. BCA has become an item of discussion and the subject of several legislative proposals.[18] Some U.S. frameworks include a domestic carbon price along with the BCA, while others do not.[19] As of publication, none of the proposals have been signed into law, and no domestic carbon price currently exists in the United States at the federal level. How any form of U.S. BCA would be constructed

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[13] Keen, Parry, and Roaf, "Border Carbon Adjustments," September 27, 2021. Campbell, McDarris, and Pizer, "Border Carbon Adjustments 101," November 10, 2021. The creation of *carbon clubs*, nations that band together to implement consistent BCA systems, is also possible, but beyond the scope of this work.

[14] EURACTIV, "European Parliament," March 11, 2021.

[15] In short, this system is a variant of cap-and-trade. An overview of the EU emissions trading system may be found here: European Commission, "EU Emissions Trading System," accessed June 4, 2021.

[16] The current proposal details six different policy variations, with this scheme being the most supported. European Commission, "Proposal for a Regulation," July 14, 2021.

[17] There is ongoing debate around this policy due to the emissions allowances included in the ETS system. EU producers are currently allowed some emissions per year that are not subject to the pricing scheme. How this would be applied to imports and the number of allowances one must surrender is not entirely clear. It is also unclear how this situation affects compatibility with WTO rules and requirements.

[18] Lawder, "Biden Administration," March 1, 2021; Jordans, "Kerry Says," May 18, 2021; Save our Future Act, Senate Resolution 2085, 117th Congress; Hayashi and Schlesinger, "Tariffs to Tackle," November 2, 2021.

[19] For example, the proposed FAIR Transition and Competition Act uses the costs of complying with federal, state, and local regulations that mitigate greenhouse gas emissions as the basis for a BCA instead of a direct carbon price. FAIR Act, H.R. 4534, 117th Congress.

largely depends on the existence of a carbon price, as that would serve as either the primary basis of the new duties or become an intrinsic parameter one would have to estimate by other means.

A Comparative Capital-based Approach for BCAs

The framework of a country's BCA will depend on whether or not it possesses a domestic carbon price. Basing a BCA on a domestic carbon price is, generally, more straightforward. It becomes an accounting exercise to estimate the quantity of embedded emissions. This is the approach of the proposed EU system, where there is harmonization between the EU's internal ETS and the duties importers would pay on goods entering the Union. The benefit of this approach is that the larger climate change-mitigating policy framework is naturally complementary to the BCA and the duty levied on embedded carbon is unambiguous; it is simply what domestic producers are charged for their own product. However, there are several issues that need to be addressed for such a framework to be fully implemented.

Basing a BCA on carbon pricing needs to address emissions accounting and reciprocity with other systems.[20] It may be difficult to reliably obtain the data required to accurately determine the embedded emissions of foreign products. Without a dedicated auditing system and full access, there will always be uncertainty for the BCA-implementing country, which is why the EU proposal includes a default option. Other countries may also have their own carbon pricing scheme, and a BCA may in effect double-charge foreign producers for the same amount of embedded emissions. One could include a rebate as part of the policy framework to avoid this duplication. Another related complication may be, however, whether exporting countries subsidize the nominal carbon price in some way, such as the free allowances allowed under the current EU ETS system, making precise evaluation somewhat ambiguous.[21]

Setting the necessary BCA rate without a domestic carbon price requires accounting of its own. Without a direct price, the motivating event would be some policy that causes industry to incur costs as they comply.[22] To ensure that the BCA rate is properly tuned to minimize any impacts beyond responding to that policy, one must convert the relevant cost of domestic policies and regulations into an effective price of carbon. This is somewhat more difficult to implement than in an EU-like scenario, as there is not an objective cost that imports would be weighed against. Instead, one needs to use industrial cost estimates, which may also be prone to data limitations that compound any emissions accounting required to evaluate imports. Some have also offered that such a framework is less likely to comport with existing laws and WTO rules necessitating objective, non-discriminatory, and non-protectionist trade barriers.[23] However, it could be more able to accurately estimate the true cost of carbon emissions, since it is tied to the physical reality of abatement for a given industry rather than a more arbitrarily set economy-wide price on carbon.

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[20] There is also a potential question of scope concerning which emission throughout the value chain are factored into the calculation of total embedded emissions. Campbell, McDarris, and Pizer, "Border Carbon Adjustments 101," November 10, 2021.

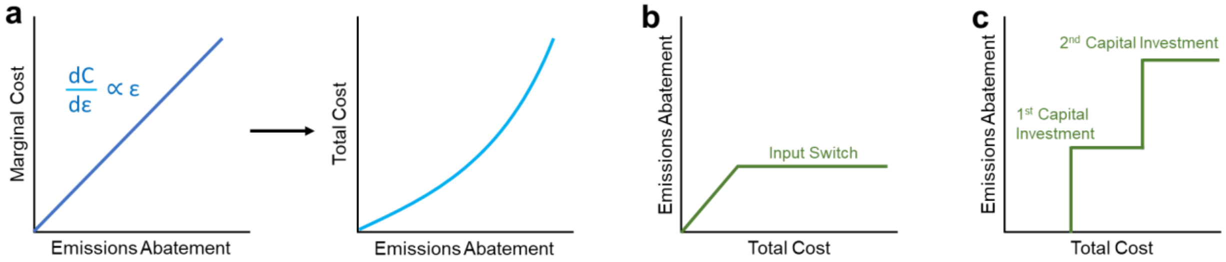
[21] Keen, Parry, and Roaf, "Border Carbon Adjustments," September 27, 2021.

[22] Keen, Parry, and Roaf, "Border Carbon Adjustments," September 27, 2021.

[23] Keen, Parry, and Roaf, "Border Carbon Adjustments," September 27, 2021; Campbell, McDarris, and Pizer, "Border Carbon Adjustments 101," November 10, 2021.

Several recent papers describe the conceptual approach to accomplishing this calculation.[24] Its framework sets a marginal cost of emission abatement that serves as a boundary condition to allow the calculation of an implicit carbon price implied by a new policy. In this model, the marginal cost ($dC/d\varepsilon$) linearly and continuously depends on the level of emissions abatement (ε) expressed as greenhouse gas emissions per unit output (figure 1a). Integrating that function yields the overall cost of the policy on producers, which would be equal to the implicit carbon price, so long as the remaining embedded emissions are not otherwise taxed.

Figure 1 BCA model concepts in the absence of a carbon price



Source: Author.
Note: (a) marginal cost model presented in cited work and its transformation to total cost; (b) impact on emissions abatement as a result of switching fungible inputs as a function of cost; (c) impact on emissions abatement as a result of installing new capital as a function of cost.

While conceptually useful, this type of model requires further refinement to accurately reflect industrial constraints. First, the assumption of a continuous marginal abatement cost only applies when substituting a fungible input. For example, hydrogen can be produced either with emissions (using natural gas as a feedstock) or without any emissions (using water electrolysis). A downstream industry that buys hydrogen on the market could buy it from either source without changing any other aspect of their process, and the resulting cost of decarbonization would depend on the weighted average of each source's price. Figure 1b shows this linear relationship between overall emissions abatement and total cost in this scenario (note that the axes are flipped compared to figure 1a).[25]

Substituting inputs will not fully decarbonize a process in many instances. On-site boilers or other heating systems reliant on fossil fuels are not fungible with renewable electricity brought in from the grid. The manufacturer would need to install new capital that allows for that electrification. The cost of new capital does not have any marginal dependence on the level of emissions abatement. It is either installed and abates a certain amount of emissions or it is not. The price model in such a case is discontinuous (figure 1c). Until the investment is made, no emissions abatement occurs, and no additional abatement is possible beyond that point unless alternative or additional capital is purchased.

The framework presented below accounts for this physical reality of decarbonization. It assumes that some policy is engendering a move from one form of production to a less carbon-intensive one,

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[24] Pizer and Campbell, "Border Carbon Adjustments," July 2021; Keen, Parry, and Roaf, "Border Carbon Adjustments," September 27, 2021.

[25] The only continuous shape allowed on the cost curve is linear and only for this scenario. Other cost differences involving bulk orders or discounts would introduce discontinuities. For example, buying a certain volume of hydrogen from a given source may entail a discount that no longer applies if the amount purchased is below a certain threshold, making the cost for that source discontinuous.

involving either a change in capital or operating costs, and that those costs can be accurately determined to calculate an implicit carbon price.

Mathematical Framework

There are infinite variables and functional forms that could be used to calculate the duty rate applied to a specific product and country of origin. A set of guidelines is helpful for narrowing down the set of options. A first pass could include prioritizing a model that is conceptually and mathematically simple and minimizes the amount of data required to implement. Doing so would make the results more transparent and easily understood. Simplicity may also aid implementation, as fewer decisions would have to be made by policymakers about setting individual rates for products and countries. As the BCA would likely have to change over time to reflect changes in emissions within a given sector, ensuring the model is adaptable may also be helpful.

A high-level version of the model may take the form of equation 1. The overall ad valorem BCA rate on commodity x from country y ($R_{x,y}$) is dependent on two functions: the added costs of decarbonizing a given commodity (C_x) and the relative embedded emissions of foreign goods ($P_{x,y}$).

$$\boldsymbol{R_{x,y} = C_x \cdot P_{x,y} \times 100\%} \tag{1}$$

The added cost factor is wholly dependent on conditions within the United States and serves as a baseline for determining what the effects of the required decarbonization will be on domestic industry. Its construction will depend on the requirement that is driving the change that needs to be adapted to and how much of a force the BCA needs to provide. As the scenario considered in this paper is defined as some policy affecting domestic manufacturing operations, this cost factor would depend on the type of change required and the magnitude of its financial impact. As the cost goes to zero, so does the duty rate for all trading partners.

The relative emissions component of the framework varies on a country-by-country basis and modulates the tariff rate based on the relative performance of each trading partner with the United States. Not all trading partners will have the same levels of emissions intensity. Existing policies in other nations may yield the same rates of decarbonization in a specific industry, reducing the risk of carbon leakage by switching to imports from those sources.[26] This factor allows countries that have taken greater action to mitigate greenhouse gas emissions to be subject to lower duties than those that have not. As the resulting likelihood of carbon leakage goes to zero, so does the BCA for that trading partner.

The Cost of Decarbonizing

Policies aimed at mitigating emissions will typically entail U.S. entities installing new capital to achieve compliance. The added cost of recapitalizing would thus be the primary economic force that needs to be mitigated by the BCA. Decarbonizing a sector or specific form of manufacturing incurs up-front costs from two sources: one needs to invest in both new capital that is less carbon-intensive and write-off the

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[26] This situation may maintain an incentive to offshore industry to decarbonized nations if the costs of doing so are otherwise mitigated for some other reason. However, as the primary goal of the BCA is to prevent carbon leakage, that is not an overriding concern within the scope of this paper.

book value of the capital that is being replaced.[27] For computing our cost function, we can normalize this decarbonization cost (C_D) by the maintenance of the status quo absent that policy (C_F) to serve as our basis.[28]

A definition of the decarbonized cost would require considering the value of new capital (V_D) and the book value of existing capital (V_B, equation 2). V_D represents the upfront costs to industry to comply with the new policy, while V_B represents the assets, they would lose by entering into compliance with the decarbonization policy.[29] For example, if a steel manufacturer is required to use a new type of furnace, the firm would have to invest in the new capital (V_D) and lose the value of the asset being replaced (V_B). The newly compliant process will also have some operational costs (A_D) that impact the overall costs of the switch. If those operational costs are different than for the status quo scenario, for example, by switching to decarbonized inputs or renewable electricity, that force would have to be accounted for as well. All of these factors are normalized by the expected lifetime of the new capital (l_D), effectively amortizing the cost of the transition.[30]

$$\boldsymbol{C_D = \frac{V_D + V_B + l_D A_D}{l_D}} \tag{2}$$

The costs of decarbonization are compared to the situation where the previous status quo is maintained. In this scheme, it is assumed that the existing capital (V_B) will continue to be used until its natural retirement date and be replaced with equivalent capital. The cost of that replacement capital (V_F) is amortized in the same manner as the transition scenario by the remaining lifespan of the baseline capital (l_B) and anticipated lifespan of the replacement capital (l_F). The annual operating costs for each are added as well (A_B and A_F) to yield the amortized cost of the status quo scenario (C_F) in equation 3.

$$\boldsymbol{C_F = \frac{V_F + V_B + l_B A_B + l_F A_F}{l_B + l_F}} \tag{3}$$

The values of C_D and C_S will vary depending on the specific manufacturer being considered. Some may already be operating with lower carbon intensity and require less expenditure to comply with a new policy, while others may have to rebuild from the ground up. Similarly, a newly constructed facility will have a substantially different book value than one built twenty years ago. Instead of assuming either extreme, one could calculate average values for all domestic producers and use the aggregate costs C_D and C_F when calculating the final BCA rate.

The final form of the cost function is shown in equation 4.[31] What the ratio of C_D to C_S shows is how much more expensive, in relative terms, it is to produce a given product after decarbonization on a per unit basis. One would expect this to be the relative cost that needs to be mitigated in order to prevent

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[27] For additional information on the resulting stranded assets, the following citations provide some introduction: Lehr and O'Boyle, "Depreciation," December 2018; Lehr, "Utility Financial Transition Impacts," December 2018.

[28] It would also be possible to calculate C_x as the difference between C_S and C_D instead of the ratio. This would yield a per unit duty instead of an ad valorem rate. Once that difference is zero or negative, the transition has become self-sustaining, and the BCA is no longer required.

[29] For ease of comparison, these values would be recorded in dollars per unit of nameplate capacity, such as dollars per kilowatt-hour for power generators or dollars per ton per year of finished product.

[30] Lifetime here refers to the working life of the physical capital before it degrades and must be replaced, not unexpected retirements due to market or other regulatory events.

[31] In this equation, the variable *n* represents the number of manufacturers within a given sector.

carbon leakage. One is subtracted from this ratio to provide a boundary condition. When the cost of decarbonizing is equal to or less than the replacement cost of the previous status quo, the BCA rate becomes zero. This would imply the new normal has become self-sustaining from a cost perspective, and that the BCA is no longer required to mitigate the decarbonization policy.

$$\boldsymbol{C_x = \frac{\overline{C_D}}{\overline{C_F}} - 1 = \frac{1}{n}\sum_{n}\left[\frac{(l_B + l_F)(V_D + V_B + l_D A_D)}{l_D(V_F + V_B + l_B A_B + l_F A_F)}\right] - 1} \tag{4}$$

The costs estimated in this section would need to be regularly updated to remain accurate. The costs of decarbonization technology will likely vary as more development occurs and economies of scale aid further deployment. Improvements in technology for the decarbonized option—that is, making it become cheaper or longer lasting—will naturally reduce the tariff rate. As the amount of baseline capital that needs to be replaced decreases, the equation reduces down to the relative costs of the decarbonized versus fossil fuel option.

Adjustment for Embedded Emissions of Imports

Not every trading partner has an equal risk of carbon leakage. Some may be in the process of, or are already, taking action that would decarbonize their economies such that switching to more carbon-intensive imports is unlikely. That is, if the climate impact is similar for domestic and imported manufacturing, less of a duty is required to achieve the BCA’s goals. The purpose of the relative emissions factor ($P_{x,y}$) is to represent these differences and minimize the imposed rates where possible. It also creates a force to encourage foreign decarbonization, as the U.S. market would be more open to goods with fewer embedded emissions.

Calculating the embedded emissions factor could be based on a comparison of the emissions intensity of some good produced by the United States and its trading partners (equation 5). Greenhouse gas emission can be a good basis for this factor because it stands as a proxy for comparing the overall likelihood of leakage. In this equation, G_y represents the embedded emissions of a product on a per unit basis from country y. A ratio is justified as, without a carbon price, the comparison must be to the emissions allowed by the policy necessitating the BCA. The ratio is constructed such that as U.S. emissions decrease relative to imports, the overall tariff rate is increased. Conversely, as imported products approach parity with the United States, the rate decreases. If imports have lower intensity than domestic goods, the rate becomes zero. The impact of all decarbonization investments made to date are captured so long as average values are used, as in the cost factor above.

$$\boldsymbol{P_{x,y} = 1 - \frac{G_{US}}{G_y}} \tag{5}$$

Example Application: Nitrogen Fertilizers

A test of the above framework would involve estimating what the final BCA rates might look like if they were applied to a given product. As even a conceptually reasonable model can provide unreasonable results that conflict with other policy priorities and existing constraints, having an idea of the likely impact is useful. The example chosen is fertilizer production. This process is one of the largest greenhouse gas emitting industries in the economy, and it comes with high capital costs.

Fertilizer emissions largely derive from the energy and materials required to form ammonia from nitrogen and hydrogen through the Haber-Bosch process. Between 30–40 million BTU of energy is required per ton of ammonia produced in the United States.[32] As this energy almost exclusively derives from burning natural gas, about 2.4 tons of carbon dioxide-equivalent emissions are currently produced per ton of ammonia.[33] Emissions are also generated during hydrogen production as an intermediate step to synthesizing ammonia. A supply of hydrogen gas (H_2) is necessary to take atmospheric nitrogen (N_2) and manufacture ammonia (NH_3, equation 6). Natural gas (CH_4) is the primary source of this hydrogen, which is produced using the water gas shift and steam reforming reactions (summarized in equation 7). As carbon dioxide (CO_2) is a byproduct of this reaction, additional greenhouse gas emissions on the order of 1.3 tons of CO_2-equivalents per ton of ammonia are produced.[34] Thus, producing one ton of ammonia leads to about 3.6 tons of CO_2-equivalent greenhouse gas emissions. As the United States produces on the order of 15 million tons of ammonia per year, this sector represents a substantial overall source of emissions.[35]

$$\mathbf{N_2 + 3H_2 \rightarrow 2NH_3} \tag{6}$$

$$\mathbf{CH_4 + 2H_2O \rightarrow CO_2 + 4H_2} \tag{7}$$

It is possible to largely eliminate emissions from both energy and material use when manufacturing ammonia. The heat energy required to drive the reaction could be sourced from electric power that, if produced by renewable sources, which would completely eliminate those 2.4 tons of emissions.[36] Hydrogen could also be sourced using renewable power instead of natural gas. Electrolysis can be used to split water into hydrogen gas and oxygen gas (O_2) using electricity that could also be fully decarbonized (equation 8), necessitating decarbonized energy and new capital to replace the water-gas shift infrastructure based on natural gas.[37]

$$\mathbf{2H_2O \rightarrow O_2 + 2H_2} \tag{8}$$

The scenario behind this calculation assumes that some domestic policy is driving the full decarbonization of ammonia production. All energy and hydrogen would have no embedded emissions when fully implemented. The following subsections describe how the BCA rate would be calculated using both product-specific information and economy-wide data. Note that these are back-of-the-

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[32] Suresh et al, "Ammonia," July 15, 2020, 28; Nutrien, "Fact Book 2020," September 2020 45.

[33] This represents 1.8 tons of direct CO_2 emissions from combustion and 15.7 kg of methane (CH_4) lost throughout the extraction and transportation of that volume of gas. Alvarez et al, "Assessment of Methane Emissions," 2018.

[34] These emissions are circa 990 kg CO_2 from hydrogen production and 8.3 kg methane leakage during extraction and transport.

[35] Suresh et al, "Ammonia," July 15, 2020, 38.

[36] This is represented by the linear region on figure 1b.

[37] Hydrogen produced this way is often called "green hydrogen" to draw a distinction between hydrogen production from natural gas coupled with carbon capture and sequestration that is termed "blue hydrogen."

envelope calculations based on readily available public data and the results should be treated as instructive of the likely order of magnitude.[38]

Product-specific Basis

Transitioning away from fossil fuels in the fertilizer sector would require substantial investments in new capital. A new facility under construction in Saudi Arabia entirely based on renewable energy will cost on the order of $5 billion and is slated produce 1.2 million tons of ammonia per year.[39] However, more modest investments can retrofit an existing facility to achieve decarbonization. One proposal in the United States would invest $100 million to produce 20,000 tons of ammonia per year using renewable electricity.[40] Combining those routes leads to an average capital cost (V_D) of approximately $4,600 per ton of nameplate capacity. In comparison, a new fossil-fuel based ammonia plant might be expected to have capital costs (V_F) on the order of $1,300 per ton of nameplate capacity.[41]

For a first approximation, we can assume that the initial work will all be retrofits to preserve as much existing capital as possible. This allows us to drop the baseline terms from our calculation (l_B, V_B, and A_B) as a first approximation. As the anticipated lifespan of the fossil fuel and renewable options are likely to be similar and on the order of 20–30 years (l), we can further reduce the calculation down to equation 9 if we normalize operating costs on a per ton basis.

$$\boldsymbol{C_{NH_3} \approx \frac{V_D + l \cdot A_D}{V_F + l \cdot A_F} - 1} \tag{9}$$

Estimates for the operating costs of renewable options are currently higher than the status quo.[42] For hydrogen production, the fossil fuel configuration will cost about $310 per ton of ammonia, compared to $790 per ton generated with renewables.[43] The renewable and fossil fuels options will cost an additional $350 and $470 per ton of ammonia, respectively, for energy.[44] Taken together, the overall operating costs for renewables are on the order of $1,100 per ton of ammonia, while fossil fuels cost $780 per ton. Completing the calculation thus yields an estimated cost factor of 0.55.[45]

The relative emissions factors for ammonia would all be the same. Since the hypothetical policy would require complete decarbonization, G_{US} goes to zero and the emissions factor goes to one. No process using electrolysis is currently operating on a large scale, meaning all imports would involve carbon

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[38] This calculation is also based on data reported before the 2021–22 spike in fertilizer prices.

[39] Scott, "Tension Arises," July 9, 2020.

[40] Tullo, "Is Ammonia," March 8, 2021.

[41] Cited value includes estimated increase due to inflation since reference was created. Incitec Pivot Limited, "Louisiana Ammonia Plant," April 17, 2013, 3. This estimate aligns with known capital expenditure in U.S. nitrogen plants. CropLife Staff, "CF Industries Plans," November 5, 2012.

[42] Tullo, "Is Ammonia," March 8, 2021.

[43] The exact cost will depend on the local electricity market and available renewable infrastructure, and the relative costs can range from 1.5–4 times greater for renewables compared to fossil fuels. An average is used here for simplicity. Scott, "Tension Arises," July 9, 2020.

[44] Assuming 30 of the 36 MMBTU of energy is consumed at this stage. Ghavam et al, "Sustainable Ammonia," March 29, 2021. Dollar values calculated from estimated average levelized costs of energy for wind, solar, and gas reported in: Marcacci, "Renewable Energy Prices," January 21, 2020.

[45] Performing the calculation using the form described in footnote 28 would yield a C_{NH_3} value of $490 per ton.

leakage relative to the domestic end-state.[46] Only the EU currently has lower emissions in this sector than the United States, which would still exceed the zero emissions targeted by a total decarbonization policy.[47]

Based on the estimated cost factor, the BCA rate for ammonia will be about 55 percent, compared to the current MFN rate of free. This rate would be binary, with those that don't decarbonize paying the full tariff and those that do paying nothing. A less aggressive decarbonization requirement in the U.S. would allow for further delineation among trading partners, and other commodities would not necessarily produce such stark contrasts. Cement, for example, will always have some embedded emissions due to the nature of the product, meaning G_{US} will always be nonzero. Steel production is similar and has more options for recapitalization, making the resulting duty rates occupy more of a spectrum.[48]

An interesting situation arises for downstream fertilizers like urea. Synthesizing this chemical requires carbon dioxide inputs to the tune of 730 kg per ton of final product (equation 10). If the rest of the production process were decarbonized, urea manufacturing would then have negative carbon emissions. That situation could provide a competitive advantage for U.S. exporters in foreign markets with a carbon tariff that allows duty reductions based on net negative emissions within their framework.

$$\mathbf{2NH_3 + CO_2 \rightarrow CO(NH_2)_2 + H_2O} \tag{10}$$

Economy-wide Basis

Accurate and up-to-date information on trading partners or domestic producers for commodities like ammonia may not always be available, complicating the determination of the BCA rate. In such a scenario, it may be desirable to use higher-level data for the calculation as a proxy. One option would be to use power generating infrastructure as the baseline for an entire economy. Electricity is used to some extent by all manufacturers and basing the calculation on the power grid will also capture the added costs of electrifying processes that had previously relied on fossil fuels for energy. The cost factor would be based on the capital and operating costs of renewable and fossil fuel power sources within the United States.

Putting numbers to these variables starts with defining the decarbonized case. Projects for 2021 anticipate that about 56 percent of new renewable power will be solar and 44 percent wind.[49] Using that ratio, we can create a weighted average of the anticipated lifespan for our new renewable capacity. With an expected useable life of 33 and 25 years, respectively, our l_D can be defined as 29.5 years.[50] The average capital costs (V_D) can be defined in a similar manner to yield a value of \$1,640,000 per

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[46] Suresh et al, "Ammonia," Chemical Economics Handbook, July 15, 2020, 14, 29.

[47] Hoxha and Christensen, "The Carbon Footprint," 2019. Over 90 percent of embedded emission of ammonium nitrate come from ammonia production, making this a reasonable comparison.

[48] Fan and Friedmann, "Low-Carbon Production," April 21, 2021.

[49] USEIA, "Renewables Account," January 11, 2021.

[50] Hering, "US Solar Farm Lifespans," June 2, 2020; Renewables First, "How Long," accessed June 10, 2021.

megawatt (MW) of nameplate capacity.[51] The final piece is the annual operations and maintenance costs for wind and solar, which yield a combined annual A_D of approximately $17,200 per MW.[52]

The fossil fuel alternative is more straightforward. Only natural gas power plants are being constructed in the United States in 2021, yielding a V_F of $837,000 per MW.[53] Overall estimates for l_F and A_F can similarly be estimated as 27.5 years and $20,000 per MW per year, respectively.[54]

The baseline situation requires more analysis to extract the necessary information. Presently, about 77 percent of the fossil fuel capacity is composed of natural gas and the remainder coal.[55] Coal power plants have a design life of about 46 years and present average age of 40 years, while natural gas has a typical lifespan of 27.5 years and an average age of 22.[56] A weighted average thus yields an l_B of 5.6 years. Adding in the capital and operational costs of coal to a weighted average of the natural gas values above similarly yields values for V_B and A_B of $287,000 per MW and $25,200 per MW per year, respectively.[57] With these values in hand, we can estimate the cost factor as about 0.51, which is within the same order of magnitude of the product-specific calculation above. There is uncertainty in the available data, however, which could push that number either as high as 0.8 or as low as 0.3.

Calculating the relative emissions factor is complicated because fossil fuel power sources release different quantities of greenhouses gasses per unit energy produced. The variable G_y from equation 5 can be calculated based on the energy mix in each country with different weights assigned to each type of power plant (equation 11). The factor a_i represents the emissions of a particular form of energy (E_i). For example, burning natural gas releases approximately 53.1 million metric tons per quadrillion BTUs (Mt/Q) versus coal's 98.0 Mt/Q.[58] The overall number for the United States is approximately 54.6 Mt/Q, and the values for the largest ammonia trading partners are summarized in table 1. While the binary endpoint is the same for ammonia for complete decarbonization, there is room for greater variability in schemes that allow for some residual emissions from energy production.

$$\boldsymbol{G_y = \frac{{}_i\, a_i E_i}{{}_i\, E_i}} \tag{11}$$

Table 1 2020 U.S. Ammonia imports, economy-wide calculations

Trading Partner	**Import Value ($)**	**Import Quantity (t)**	**G_y (Mt/Q)**
United States	-	-	54.6
Canada	361,683,898	1,052,308	44.0
Trinidad & Tobago	276,789,285	1,353,613	54.4
Other	3,556,017	9,762	65.1

Source: IHS Markit, Global Trade Atlas Database for HTS heading 2814.10, accessed November 17, 2019; USEIA, "International," accessed November 17, 2021.

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[51] USEIA, "Average," September 16, 2020; Hyder, "What is a Solar Farm," updated December 8, 2020.
[52] Walker et al, "Model," June 2020, 3; Blewett, "Wind Turbine Costs," March 24, 2020.
[53] USEIA, "Average," September 16, 2020.
[54] Cavalcante, "Combined-Cycle Plant," accessed June 10, 2021; Lo, "Power Plant O&M," updated June 9, 2020.
[55] Cui et al, "Quantifying Operational Lifetimes," 2019; Barnard, "EIA Releases," February 18, 2020; Cavalcante, "Combined-Cycle Plant," accessed June 10, 2021; USEIA, "U.S. Energy Facts Explained," updated May 14, 2021.
[56] USEIA, "Natural Gas Generators," April 20, 2017.
[57] USEIA, "Capital Cost and Performance," February 2020, 45–47.
[58] USEIA, "How Much Carbon Dioxide," June 17, 2020.

Universal Product-specific Basis

Calculating BCA rates for every trading partner may encounter several limitations in actual application. While it is assumed the rates would be updated regularly, that does not factor in new producers entering the market during the interim for which duties would not be collected. For example, if a new producer comes online in a country that had not previously participated in that sector, that country would either not be assigned a duty rate until the next overall refresh or be subject to one based on some global average. The data quality will also likely vary from country to country, meaning some duties would be more accurate (i.e., fair) than others. Finally, a trading partner may allege some form of unfair discrimination if the duty rates for each country are different, despite an objective accounting of each situation.

A way around these difficulties would be to apply a universal rate to all imports of a given product type. Continuing with fertilizer, all ammonia imported by the United States would be assessed the same BCA rate based on a global evaluation of the emissions intensity of the industry. Doing so ensures all possible imports are covered and each trading partner is treated exactly the same. The downside is that countries with low risk of carbon leakage will be assessed duties that are in excess of what is strictly necessary, while those with higher risks are not assessed duties that are high enough. It also removes some of the decarbonization incentive for each partner, as any investments that would otherwise directly lower their specific rates are diluted across the entire world. Some high emitters would thus be able to ride the coattails of those taking action and be in a better relative position.

The first step of creating a universal rate entails choosing a basis. One could use either current import sources for a commodity or global production statistics. In the former, the most recent trade data would gate which countries are included in the calculation basket, which represents a more accurate picture of the current state of trade. The latter would be more adaptable for shifting trade to other global producers that might hypothetically happen. In either case, a weighted average would yield the modified relative emissions factor, shown in equation 12, where $t_{x,y}$ is the fraction of either imports or production of a given product from each country included in the calculation.

$$\boldsymbol{P}'_x = {}_y\, \boldsymbol{t}_{x,y} \boldsymbol{P}_{x,y} \tag{12}$$

This form of the calculation introduces new issues that work against the overall goals of the BCA. It formalizes a free rider problem, where countries that take action to decarbonize are disproportionally penalized while those that don’t are able to access benefits they shouldn’t otherwise be able to. However, applying universal rates on a given product may be required to put the policy in a favorable position vis-à-vis the requirements of existing trade regimes. While there is no guarantee that any BCA will pass the requirements of WTO rules, the requirement not to discriminate on the basis of national origin may favor more universally applied duties.[59] While this paper makes no claim to assuring any such compatibility with any of the presented forms, that is a definite consideration for policy makers as BCAs are created.

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[59] Flannery et al, “Framework proposal,” October 23, 2020.

Assessment

There will be difficulties in properly structuring a BCA in the absence of a carbon price in achieving all of its objectives. The need to comply with existing systems may favor a more universal application, while minimizing the economic impacts would likely necessitate more granular applications. The accuracy of any price estimate will also be subject to unavoidable uncertainty. It seems unlikely that any implementation would have access to the complete data required for a fully rigorous calculation, even for domestic industries. One might have to sacrifice a preference for absolute economic efficiency in favor of taking action that accomplishes the underlying goals.

An issue with the calculations presented here is the scope of the potential duties, regardless of accuracy and potential for mitigating carbon leakage. At the extreme where the United States is fully decarbonized, the above frameworks would institute double-digit rates on applicable products. That leads to unavoidable political economy considerations, as any trade exposed sector would likely see substantial increases in prices filtered down to consumers. Philosophically, the magnitude of the duties is also well outside the norm of the past fifty years of trade liberalization. However, it is not outside of the historical norm. Universal tariffs on that order of magnitude were common throughout the 19th and early 20th centuries, where they served to help incubate domestic industry until it could compete on more even footing with other industrialized nations.[60] The debate around "the tariff" was one of the defining political differences throughout the first 150 years of U.S. history, and a return to such a regime would likely require a substantial re-evaluation of policy beyond this one issue.

Conclusions

Removing a domestic carbon price as a factor for determining a BCA adds to the complexity of creating the policy framework. There are an infinite number of mathematical forms they could take, or it could be set entirely arbitrarily with no grounding in tangible assets. This paper has explored a set of options for computing BCAs based on the likely costs of complying with some decarbonization requirement. It has shown that it is possible to construct a BCA non-arbitrarily in the absence of a carbon price. The choice of form largely depends on the granularity of scope weighted against the accuracy of the final result. The ability to achieve both depends on further trade-offs surrounding data gathering and implementation. Whether the resulting values of the duties are acceptable is a separate non-technical policy question that is shaped by their intersection with other priorities.

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[60] For a discussion on how past tariffs contributed to industrial development in this way, see chapter 2 of: Chang, "Kicking Away the Ladder: Development Strategy in Historical Perspective," 2003.

Bibliography

Abnett, Kate. “EU Sees Carbon Border Levy as ‘Matter of Survival’ for Industry.” *Reuters*, January 18, 2021. https://www.reuters.com/business/sustainable-business/eu-sees-carbon-border-levy-matter-survival-industry-2021-01-18/.

Alvarez, Ramón A., Daniel Zavala-Araiza, David R. Lyon, David T. Allen, Zachary R. Barkley, Adam R. Brandt, Kenneth J. Davis, Scott C. Herndon, Daniel J. Jacon, Anna Karion, Eric A Kort, Brian K. Lamb, Thomas Lauvaux, Joannes D. Maasakkers, Anthony J. Marchese, Mark Omara, Stephen W. Pacala, Jeff Peischl, Allen L. Robinson, Paul B. Shepson, Colm Sweeney, Amy Townsend-Small, Steven C. Hofsy, and Steven P. Hamburg. “Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain.” *Science* 361 (6398), 2018. https://dx.doi.org/10.1126/science.aar7204.

Barnard, Michael. “EIA Releases 2050 Projections for Energy & Makes it Clear that it Hasn’t Been Paying Attention.” *Clean Technica*, February 18, 2020. https://cleantechnica.com/2020/02/18/eia-releases-2050-projections-for-energy-makes-it-clear-that-they-havent-been-paying-attention/.

Blewett, Dan. “Wind Turbine Costs: How Much? Are they Worth it in 2020?” *Weather Guard*, March 24, 2020. https://weatherguardwind.com/how-much-does-wind-turbine-cost-worth-it/.

Campbell, Erin and William Pizer. “Border Carbon Adjustments: How to Implement in Countries that Don’t have a Carbon Price.” *Resources for the Future*, July 29, 2021. https://www.resources.org/common-resources/carbon-border-adjustments-how-to-implement-in-countries-that-dont-have-a-carbon-price/.

Campbell, Erin, Anne McDarris, and William Pizer. “Border Carbon Adjustments 101.” *Resources for the Future*, November 10, 2021. https://www.rff.org/publications/explainers/border-carbon-adjustments-101/.

Cavalcante, Thomas. “Combined-Cycle Plant Life Assessments.” *Sargent & Lundy*, accessed June 10, 2021. https://sargentlundy.com/wp-content/uploads/2017/05/Combined-Cycle-PowerPlant-LifeAssessment.pdf.

Chang, Ha-Joon. “Kicking Away the Ladder: Development Strategy in Historical Perspective.” Anthem Press: London, 2003.

Cosbey, Aaron, Susanne Droege, Carolyn Fischer, and Clayton Munnings. “Developing Guidance for Implementing Border Carbon Adjustments: Lessons, Cautions, and Research Needs from the Literature.” *Rev. Environ. Econ. Policy*, 13 (1), 2019, 3–22. https://doi.org/10.1093/reep/rey020.

CropLife Staff. “CF Industries Plans $3.8 Billion Nitrogen Fertilizer Expansion.” November 5, 2012. https://www.croplife.com/crop-inputs/fertilizer/cf-industries-plans-3-8-billion-nitrogen-fertilizer-expansion/.

Cui, Ryna Yiyun, Nathan Hultman, Morgan R. Edwards, Linlang He, Arijit Sen, Kavita Surana, Haewon McJeon, Gokul Iyer, Pralit Patel, Sha Yu, Ted Nace, and Christine Shearer. “Quantifying Operational Lifetimes for Coal Power Plants under the Paris Goals.” *Nature Communications*, 10 (2019), 4759. https://www.nature.com/articles/s41467-019-12618-3.

EURACTIV. “European Parliament Backs Plan to Price Carbon at EU’s Border.” EURACTIV, March 11, 2021. https://www.euractiv.com/section/energy-environment/news/european-parliament-backs-plan-to-price-carbon-at-eus-border/.

European Commission. “EU Emissions Trading System (EU ETS).” Accessed June 4, 2021. https://ec.europa.eu/clima/policies/ets_en.

European Commission. “Proposal for a Regulation of the European Parliament and of the Council Establishing a Carbon Border Adjustment Mechanism.” July 14, 2021. https://ec.europa.eu/info/sites/default/files/carbon_border_adjustment_mechanism_0.pdf.

Fair, Affordable, Innovative, and Resilient Transition and Competition Act, House Resolution 4534, 117th Congress. https://www.govinfo.gov/app/details/BILLS-117hr4534ih.

Fan, Zhiyuan and S. Julio Friedmann. “Low-Carbon Production of Iron and Steel: Technology Options, Economic Assessment, and Policy.” *Joule* 5, April 21, 2021. https://doi.org/10.1016/j.joule.2021.02.018.

Flannery, Brian, Jennifer A. Hillman, Jan Mares, and Matthew C. Porterfield. “Framework proposal for a US Upstream GHG Tax with WTO-Compliant Border Adjustments: 2020 Update.” *Resources for the Future*, October 23, 2020. https://www.rff.org/publications/reports/framework-proposal-us-upstream-ghg-tax-wto-compliant-border-adjustments-2020-update/.

Ghavam, Seyedehhoma, Maria Vahdati, I. A. Grant Wilson, and Peter Styring. “Sustainable Ammonia Production Processes.” *Front. Energy Res.* 29, March 29, 2021. https://doi.org/10.3389/fenrg.2021.580808.

Hayashi, Yuka and Jacob M. Schlesinger. “Tariffs to Tackle Climate Change Gain Momentum. The Idea Could Reshape Industries.” *The Wall Street Journal*, November 2, 2021. https://www.wsj.com/articles/tariffs-climate-change-greenhouse-gases-manufacturing-steel-11635862305.

Hering, Garrett. “US Solar Farm Lifespans Lengthen, Driving Energy Prices Down.” *S&P Global*, June 2, 2020. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/us-solar-farm-lifespans-lengthen-driving-energy-prices-down-58892859.

Hoxha, Antoine and Bjarne Christensen. “The Carbon Footprint of Fertiliser Production: Regional Reference Values.” *International Fertiliser Society*, 2019. https://www.fertilizerseurope.com/wp-content/uploads/2020/01/The-carbon-footprint-of-fertilizer-production_Regional-reference-values.pdf.

Hyder, Zeeshan. “What is a Solar Farm? Costs, Land Needs & More.” *Solar Reviews*, updated December 8, 2020. https://www.solarreviews.com/blog/what-is-a-solar-farm-do-i-need-one.

Incitec Pivot Limited. “Louisiana Ammonia Plant.” April 17, 2013. https://investors.incitecpivot.com.au/static-files/5a7e21ea-8105-4749-9cdf-0beb49234908.

Jordans, Frank. "Kerry Says US Examining Carbon Border Tax, Sees Risks." *AP News*, May 18, 2021. https://apnews.com/article/europe-environment-and-nature-business-government-and-politics-6a020cd7bb93a639e7445cf4999276a2.

Keen, Michael, Ian Parry, and James Roaf. "Border Carbon Adjustments: Rationale, Design and Impact." *International Monetary Fund*, WP/21/239, September 27, 2021. https://www.imf.org/en/Publications/WP/Issues/2021/09/24/Border-Carbon-Adjustments-Rationale-Design-and-Impact-466176.

Lawder, David. "Biden Administration to Consider Carbon Border Tax as Part of Trade Agenda: USTR." *Reuters*, March 1, 2021. https://www.reuters.com/article/us-usa-trade-biden/biden-administration-to-consider-carbon-border-tax-as-part-of-trade-agenda-ustr-idUSKCN2AT3EX.

Lehr, Ron, and Mike O'Boyle. "Depreciation and Early Plant Retirements." *Energy Innovation*, December 2018. https://energyinnovation.org/wp-content/uploads/2018/12/Depreciation-and-Early-Plant-Retirements-Brief_12.3.2018.pdf.

Lehr, Ron. "Utility Financial Transition Impacts: from Fossil to Clean." *Energy Innovation*, December 2018. https://energyinnovation.org/wp-content/uploads/2018/12/From-Fossil-to-Clean-Brief_12.3.18.pdf.

Lo, Chris. "Power Plant O&M: How Does the Industry Stack up on Cost?" *Power Technology*, updated June 9, 2020. https://www.power-technology.com/features/featurepower-plant-om-how-does-the-industry-stack-up-on-cost-4417756/.

Marcacci, Silvio. "Renewable Energy Prices Hit Record Lows: How Can Utilities Benefit from Unstoppable Solar and Wind?" *Forbes*, January 21, 2020. https://www.forbes.com/sites/energyinnovation/2020/01/21/renewable-energy-prices-hit-record-lows-how-can-utilities-benefit-from-unstoppable-solar-and-wind/?sh=f34183e2c84e.

Nutrien. "Fact Book 2020." September 2020. https://www.nutrien.com/sites/default/files/uploads/2020-10/Nutrien%20Fact%20Book%202020.pdf.

Pizer, William A., and Erin J. Campbell. "Border Carbon Adjustments without Full (or Any) Carbon Pricing)." *Resources for the Future*, working paper 21-21, July 2021. https://media.rff.org/documents/WP_21-21_v4.pdf.

Renewables First. "How Long Does a Wind Turbine Last?" *Renewables First*, accessed June 10, 2021. https://www.renewablesfirst.co.uk/windpower/windpower-learning-centre/how-long-do-wind-turbines-installations-last/.

Save our Future Act, Senate Resolution 2085, 117th Congress. https://www.congress.gov/bill/117th-congress/senate-bill/2085/text?r=2&s=4.

Scott, Alex. "Tension Arises as Clean Hydrogen Projects Spread." *Chemical and Engineering News*, July 9, 2020. https://cen.acs.org/energy/Tension-arises-clean-hydrogen-projects/98/i27.

Suresh, Bala, Henry He, Ralf Gubler, and Yuko Yamaguchi. "Ammonia." *Chemical Economics Handbook*, July 15, 2020. https://ihsmarkit.com/products/ammonia-chemical-economics-handbook.html (fee required).

Tullo, Alexander H. "Is Ammonia the Fuel of the Future?" *Chemical and Engineering News*, March 8, 2021. https://cen.acs.org/business/petrochemicals/ammonia-fuel-future/99/i8.

U.S. Energy Information Administration (USEIA). "Average U.S. Construction Costs for Solar and Wind Generation Continue to Fall." September 16, 2020. https://www.eia.gov/todayinenergy/detail.php?id=45136.

U.S. Energy Information Administration (USEIA). "Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies." February 2020. https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capital_cost_AEO2020.pdf.

U.S. Energy Information Administration (USEIA). "How Much Carbon Dioxide is Produced when Different Fuels are Burned?" Updated June 1, 2021. https://www.eia.gov/tools/faqs/faq.php?id=73&t=11.

U.S. Energy Information Administration (USEIA). "International." Accessed various dates. https://www.eia.gov/international/overview/world.

U.S. Energy Information Administration (USEIA). "Natural Gas Generators Make up the Largest Share of Overall U.S. Generation Capacity." April 20, 2017. https://www.eia.gov/todayinenergy/detail.php?id=30872.

U.S. Energy Information Administration (USEIA). "Renewables Account for Most New U.S. Electricity Generating Capacity in 2021." January 11, 2021. https://www.eia.gov/todayinenergy/detail.php?id=46416.

U.S. Energy Information Administration (USEIA). "U.S. Energy Facts Explained." Updated May 14, 2021. https://www.eia.gov/energyexplained/us-energy-facts/.

U.S. Environmental Protection Agency (USEPA). "Global Greenhouse Gas Emissions Data." Accessed June 4, 2021. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.

Walker, Andy, Eric Lockhart, Jal Desai, Kristen Ardani, Geoff Klise, Olga Lavrova, Tom Tansy, Jessie Deot, Bob Fox, and Anil Pochiraju. "Model of Operation-and-Maintenance Costs for Photovoltaic Systems." *NREL Technical Report NREL/TP-5C00-74840*, June 2020. https://www.nrel.gov/docs/fy20osti/74840.pdf.