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Black into green: A BIG opportunity for North Dakota’s oil and gas producers

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HIGHLIGHTS

• The business inertia of hydrocarbon production can accelerate wind energy production.
• Emissions-to-price ratio makes BIG funding feasible for oil and natural gas in ND.
• BIG’s wind farm is funded from 10% of hydrocarbon revenues and $0.03/kWh of wind power.
• Over 40 years, ND’s oil and gas can fund 89,000 wind turbines, generating 155GW.
• This wind power offsets 100% of the well-to-wheel emissions of ND’s oil and gas.

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ABSTRACT

A new perspective on carbon economics is developed and applied to demonstrate that oil and natural gas producers in North Dakota (ND) have an opportunity to make a profitable transition to wind energy producers. ND’s oil and gas producers can fund this black into green (BIG) transition by: first, investing a fraction of their revenues into wind energy farms; and second, reinvesting a portion of revenues from the wind-generated electricity. Over a period of 40 years, 100% of the greenhouse gas emissions associated with the production and consumption of ND’s oil and gas could be offset with an investment of 10% of both hydrocarbons’ value and a reinvestment of three cents per kilowatt-hour of wind-generated electricity. At the end of the 40-year period, the resultant 155-gigawatt wind farm would have offset 13.4 × 10⁹ tons of carbon dioxide equivalent and cost $9.90/ton of offset carbon dioxide equivalent. This BIG example demonstrates the financial and environmental benefits of ND’s oil and gas producers transforming into renewable energy producers; hence regulators, hydrocarbon producers, and utilities should take note and think BIG. The reconfigurable, Excel-based model used herein is provided to allow readers to extend this example from ND to other regions, hydrocarbons, and green energy sources.

1. Introduction

Climate change and global warming are estimated to put between $2.5 and $24 trillion of global assets at risk [1]. Action to reduce our current greenhouse gas (GHG) emissions is urgently required [2–4]. Delaying our collective climate action will increase the costs of mitigation, increase the costs associated with fossil fuel reserves that will have to be abandoned, and worsen the economic slowdown induced by climate action [2,3].

International consensus has been building that global warming should be limited to well below 2°C warmer than pre-industrial temperatures [5–7]. To meet such targets, some economically recoverable reserves of fossil fuels, especially coal, must remain unused [8–10]. 63% of anthropogenic carbon emissions since 1854 can be traced to 90 corporations [11]. Historically, these corporations have coordinated their resistance to environmental policies and especially to a global carbon tax [12–14]; the stronger a country’s energy-intensive industries are, the more likely it is to have weaker environmental regulations [14]. Workers, unions, regions, and firms who depend on the existing production systems are understandably concerned about how decarbonization will affect their livelihoods [15–17]. Such concerns are unified by narratives like ‘jobs vs. environment’ [15,16] and are most polarizing in regions in which the costs of climate mitigation will be concentrated. But ‘jobs vs. environment’ is a misleading dichotomy.
Taylor et al. [18] introduced the idea that oil producers in Alberta could transition to become wind energy producers if they were required to invest in wind energy in parallel with their oil extraction. In such a case, decarbonization would occur within existing firms in the same region as traditional extraction sites. Accordingly, many of the concerns of the workers, unions, regions, and firms (and their shareholders) would be appeased. The idea of Taylor et al. [18], however, with current weather patterns and hub height technologies, was not viable in Alberta due to low wind speeds. Yet solutions that blend technology, policy, and market forces have the potential to overcome the economic, social, and technical systems that reinforce our current, carbon-intensive economy [12,19–22].

Given the importance of carbon-producers in emitting GHGs and shaping climate policy, we adapt the initial idea of Taylor et al. [18] and consider a Black Into Green (BIG) opportunity for firms to reduce their net GHG emissions. To do so, hydrocarbon producers i) invest a fraction of their hydrocarbon (black) revenues into producing wind (green) energy, and ii) reinvest a portion of the wind-energy revenues into further expanding wind-energy production.

The success of either a carbon tax or a cap-and-trade system depends more on the details of its implementation than the choice between systems [23–25]. In this paper, we assume that either a carbon tax or a cap-and-trade system has been imposed and that it is based on a firm’s net GHG emissions. Under such a system, firms have an incentive to reduce their net GHG emissions, provided that such reductions are cheaper than the costs associated with the carbon tax or cap-and-trade system. Thus, a BIG approach would allow firms to keep what they would have paid under either system as an asset on their balance sheets, increasing their long-term business prospects. This paper develops a method for quantifying the minimum GHG-emissions penalty (associated with either a carbon tax or a cap-and-trade system) required to incentivize hydrocarbon producers to participate in the proposed BIG approach. By participating, firms avoid paying a carbon penalty, and instead build greater long-term value for their companies.

To evaluate the initial feasibility of BIG, we apply BIG in North Dakota (ND) as an example, since ND has substantial wind, oil, natural gas, and coal resources [26]. The shale oil in ND’s Bakken formation is the largest known source of oil in the United States (U.S.) [27]. Leveraging this resource to stimulate green energy production will be critical in shaping the U.S.’ energy mix and environmental footprint. Over 20% of U.S.’s total emissions come from fossil fuels extracted on federal land [28], providing the government with a unique opportunity to influence the trajectory of this emissions source [28,29]. Yet concerning, fossil fuel extraction on federal lands is increasing, not decreasing [30].

This paper first considers the potential for BIG to offset the GHG emissions associated with the production and consumption of ND’s hydrocarbons. Second, this paper quantifies what investment and reinvestment rates are required to achieve these GHG offsets. Finally, the financial efficiency of BIG’s GHG-mitigation is compared to California’s cap-and-trade price (2014–17 average of $13/ton of carbon dioxide equivalent (t CO$_2$e) [31]) and the price of voluntary emissions offsets in North America (average $2.9/t CO$_2$e in 2016 [32]).

Due to the sometimes-contentious nature of combing hydrocarbon and green energy production, this paper uses a transparent and reconfigurable Excel-based model. Readers wishing to investigate results with different inputs or assumptions are encouraged to download the model from the Supplemental Materials (SM), SM-Model 1. With a view of short- and long-term success for all, this paper’s BIG proposal suggests a potential mechanism to transform ND’s energy production landscape, benefit climate and environmental outcomes, and maintain the livelihoods of workers, unions, regions, and firms dependent on hydrocarbon production.

### 2. Methods

The viability of this BIG proposal depends on: (i) the GHG-intensity of hydrocarbon production and consumption, (ii) the availability of wind power, (iii) the ability for wind-generated electricity to offset GHG emissions, and (iv) the feasibility of the funding scheme. This section explains each of these model components and the metrics used to quantify BIG’s efficacy and financial efficiency. BIG’s performance was assessed over a 40-year time horizon and across the state of ND.

While a multitude of methods exist for detailed evaluations of clean energy policies [33], we present a deterministic (and positivist), techno-economic model [34,35] of how our proposed investment structure could influence the cumulative emissions associated with ND’s oil and gas production. This first-order analysis aims to demonstrate that energy producers should consider simultaneous investments into clean energy production as a liability reduction strategy in the presence of carbon-penalizing regulations. Given the polarized nature of current policy debates, we submit that a simpler, more transparent model provides decision makers better insights amidst modeling uncertainties [36].

Before a BIG proposal is actually implemented, our first-order analysis should be supplemented with more detailed studies that include social and political dynamics, implementation details, and market responses to the BIG proposal [34]; the results of said studies should be used accordingly to evolve the first-order model of the BIG idea presented in this paper.

#### 2.1. GHG emissions of hydrocarbon production in North Dakota

To account for the GHG emissions associated with oil, gas, and coal extraction, the metric of carbon dioxide equivalent (CO$_2$e) per gigajoule (GJ) of thermal energy was used. For energetic conversions, the lower heating value was used throughout this paper. The GHG emissions of each hydrocarbon are summarized in Table 1 and were accounted for using two categories:

1. production emissions: the total GHG emissions caused by producing, upgrading, refining, and transporting the hydrocarbon (i.e., well-to-tank); and
2. total emissions: the total GHG emissions caused by all steps from production through end consumption of the hydrocarbon (i.e., well-to-wheel/combustion).

The production and total emissions of shale oil were estimated to be 21.4 and 94.6 kg CO$_2$e/GJ, respectively [37] (Table 1). Production and total emissions of ND’s natural gas (shale gas) were estimated to be 14.6 and 70.9 kg CO$_2$e/GJ, respectively [38] (Table 1). Finally, the total emissions of ND’s lignite coal was estimated to be 116 kg CO$_2$e/GJ [39], 4% of which (4.64 kg CO$_2$e/GJ) is due to production [40] (Table 1). The rationale for selecting these specific emissions references is detailed in Section SM-1. Table 1 also includes the 2017 prices for oil, natural gas, and coal that were used in this study.

|                | Production emissions (kg CO$_2$e/GJ) | Total emissions (kg CO$_2$e/GJ) | Price in 2017 ($/GJ) | Production in ND (10$^9$ GJ/year) |
|----------------|-------------------------------------|---------------------------------|---------------------|----------------------------------|
| Shale oil      | 21.4 [37]                           | 94.6 [37]                       | 8.87 [44]           | 2.28 [41]                       |
| Shale gas      | 14.6 [38]                           | 70.9 [38]                       | 3.98 [45]           | 0.72 [42]                       |
| Lignite coal   | 4.64 [39,40]                        | 116 [39]                        | 1.52 [46]           | 0.41 [43]                       |
The annual production in ND was estimated in 2017 to be 2.28 billion GJ of oil (388.3 million barrels) [41] and 725 million GJ of natural gas (687.1 billion cubic feet) [42]. Production of coal was estimated using the 2016 gross production value of 414 million GJ (392 trillion Btu) [43]. A constant growth rate of 1% for oil, natural gas, and coal production was assumed in the BIG model to ensure its conclusions do not rely on artificially-high projected growth rates.

2.2. Wind power generation

Two options were considered for the allowable size of the BIG-funded wind farm: first, wind turbines were allowed throughout ND (area of 178,111 km$^2$ [47]); second, wind turbines were limited to ND’s oil-producing counties (39% of ND; 68,600 km$^2$ [48]). As in Taylor et al. [18], the maximum wind turbine density was set as one turbine per km$^2$. Moreover, for a given land area, only half of it was assumed to be feasible for turbine siting (net density of 0.5 turbines per km$^2$).

Wind speed distributions at 80 m above ground [49] were spatially averaged using ImageJ [50]. RETScreen was used to convert these average wind speeds into capacity factors using turbine power-curve data [51] and a wind-shear exponent of 0.2 [52]. The Vestas V126 3.45 MW turbine was selected as a reference turbine, however, because more detailed power-curve data was available for the V126 3.3 MW version, the latter’s data was used to calculate the capacity factor.

The state of ND and its oil-producing counties were found to have average capacity factors of 50.5% and 51.5%, respectively (details in Section SM-2). The calculated capacity factors are higher than more general estimates of the wind capacity factor in the U.S. interior (e.g., Wiser et al.’s estimate of 42.7% [53]), because of the slower wind speeds in the U.S. interior and older turbine models used in such studies. Capacity factors of 50.5% and 42.7% are considered in the results below. Turbine sizes and hub heights have increased over time and such new technology developments continue to increase capacity factors and the potential of BIG.

Installed wind turbines were conservatively estimated to have a life expectancy of 20 years [54]. Turbine capital and maintenance costs were approximated as $1.71 per watt (W) [55] and $0.031/W/year [56], respectively. GHG emissions associated with wind-generated electricity were estimated to be 10.4 g of CO$_2$e per kilowatt hour of wind-generated electricity (kWh$_{wind}$) [57].

2.3. GHG-emission offsets from wind-powered electricity generation

Electricity production from wind power only reduces net GHG emissions when a generation technology that emits more GHG than wind is turned off. In the case of this first-order model, the generation technology that would be turned off was assumed to have the average GHG intensity of the region to which the wind power was transmitted. Additional transmission lines for the wind power were estimated to cost $372/MW/km [58] (the mid-point estimate of Delucchi and Jacobson [58], whose low and high estimates were $299-$429/MW/km). The transmission system was assumed to have a 40-year life expectancy (an average life expectation for transmission line components) [58]. Transmission losses were approximated as 1.5% + 1%/1000 km of average power, following Delucchi and Jacobson [58].

The GHG intensity of the electricity grid is segmented by the Environmental Protection Agency (EPA) into 26 “eGRID subregions” [59]. The BIG model considers sending wind-generated electricity to the closest 20 subregions, including North Dakota’s (“MRO West”; Fig. 1). Subregional capacities, generation mixes, and GHG intensities are accounted for in the BIG model and summarized in Section SM-3.

The BIG model dispatches electricity to the different eGRID subregions according to a user-definable transmission priority. When one subregion reaches its maximum capacity for wind power, assumed to be 20% of produced power (not generation capacity) [61], the model builds transmission lines to the next prioritized subregion. The default transmission priority (SM-Table 2) was set by GHG intensity.

2.4. Funding mechanism

Different investment and reinvestment combinations were examined to show their influence on GHG emissions and financial efficiency. Typical electricity-utility profit margins in the U.S. range from 6 to 15% [62], but these include capital and maintenance costs, which are accounted for in our BIG model. Accordingly, as a first approximation, the maximum reinvestment rate was considered to be 25% of the average electricity price in the U.S. ($0.12/kWh [63]), equivalent to a maximum reinvestment rate of $0.03/kWh$_{wind}$. Conservatively setting this maximum reinvestment rate ensures that hydrocarbon producers would have an incentive to keep their wind turbines operating at their full potential.

2.5. BIG’s performance metrics

Predicted peak global warming values are strongly correlated with cumulative emissions of carbon [64]. Focusing on cumulative emissions, instead of annual emissions, simplifies policy discussions and makes policies more robust to the uncertainties in climate models [64]. Financial investments in infrastructure, resource extraction, and resource exploration implicitly commit to the use of those investments far into the future [65–67]. By considering the cumulative emissions of those investments, the total climate impacts of current investments can be quantified [65–67].

Cumulative, offset GHG emissions were used to assess the efficacy of BIG. These offsets were compared to the cumulative emissions associated with the extracted hydrocarbon(s) used to fund BIG. The goal of BIG could be to offset 100% of the cumulative total emissions or the cumulative production emissions of the associated hydrocarbon(s). For example, if BIG were funded by oil and gas production in ND for 40 years, it would be reported to have offset 100% of the total emissions of oil and gas if the sum of all GHG offsets from the wind farm earned over 40 years equaled the sum of all GHG emissions from the production and consumption of ND’s oil and gas over that same time horizon. No discounting factor was used to distinguish between future and present GHG emissions.

The financial efficiency of BIG was considered as the equivalent cost per ton of offset GHG emissions, calculated as the net present cost of all expenditures divided by the total offset GHG emissions. Two discount rates were compared in the model: the mean industry-specific discount rate (7% [68]), and, to be conservative, 3% (a higher discount rate improves the favorability of BIG).

3. Results

3.1. Emissions-to-price ratio is key to BIG’s viability

BIG is initially funded by a fixed percentage of revenues from the sale of hydrocarbons. BIG’s ability to offset GHG emissions, therefore, depends on the ratio of total GHG emissions to price for each hydrocarbon (Table 2). In an extreme example, if offsetting GHG emissions costs more than the price of a hydrocarbon, it becomes cheaper to forgo burning the hydrocarbon (this occurs at $13.1/ton of CO$_2$e for coal; Table 2). Coal emits seven times more GHGs than oil on an equal-price basis (Table 2). Natural gas emits four times less than coal, but 67% more than oil, again on an equal-price basis (Table 2).

BIG models of each hydrocarbon individually showed that BIG was only viable for ND’s oil and gas industries (coal required an investment rate of 43% to offset its total emissions, Section SM-4). Accordingly, the results that follow model a combined BIG scenario that offsets ND’s oil and gas (but not coal) emissions.
3.2. Cumulative efficacy and financial feasibility

If wind turbine installations are limited to oil-producing counties (39% of ND’s area), area is a limiting constraint and only 69% of the total emissions from ND’s oil and gas can be offset (Section SM-5 and SM-Fig. 1). However, if the area allowed for the wind farm is increased to the whole state of ND (still assuming only half is viable for siting a wind turbine), offsetting 100% of the total emissions from oil and gas is feasible with different combinations of investment and reinvestment rates. Minimum combinations of investment and reinvestment rates form the curves plotted in Fig. 2, which depend on the capacity factor and if BIG’s goal is to offset 100% of oil and gas production emissions or 100% of their total emissions.

With a capacity factor of 50.5% (results assuming a 42.7% capacity factor are shown in parentheses) and without reinvestment, offsetting 100% of total emissions would require an investment rate of at least 44% (51%) (Fig. 3). With a reinvestment rate of $0.03/kWh wind, investment rates could be as low as 9.7% (15%) (Fig. 3). An intermediate reinvestment rate of $0.015/kWh wind would require an investment of at least 23% (30%). Promisingly, therefore, with an investment of less than 10% of the revenues from ND’s oil and natural gas production, the total GHG

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Table 2

|                | 2017 Price ($/GJ) | Total emissions (kg of CO2e/GJ) | Total emissions to price (kg CO2e/$) | Price to emissions ($/t CO2e) |
|----------------|-------------------|---------------------------------|--------------------------------------|-------------------------------|
| Crude oil      | 8.87 [44]         | 94.6 [37]                       | 10.7                                 | 93.5                          |
| Natural gas    | 3.98 [45]         | 70.9 [45]                       | 17.8                                 | 56.2                          |
| Coal           | 1.52 [46]         | 116 [39]                        | 76.3                                 | 13.1                          |

Fig. 1. The GHG intensity of eGRID subregions across the contiguous U.S. Data from [29] and figure modified from [60].

Fig. 2. Combinations of investment (y-axis) and reinvestment (x-axis) rates required to offset 100% of production emissions (solid lines) and 100% of total emissions (dashed lines), with capacity factors (CF) of 50.5% (grey lines) and 42.7% (black lines). The wind farm was allowed to span ND.

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Fig. 3. The annual expenditures [left axis] and the number of active wind turbines [right axis] for the suggested BIG scenario (50.5% capacity factor, 9.7% investment, and $0.03/kWh wind reinvestment).
emissions (production and end use) of ND’s oil and gas can be offset.

Reinvestment plays a critical role in BIG’s viability because it induces an exponential growth mechanism, creating a reinforcing feedback loop between the number of installed wind turbines and funds to build new turbines. For example, under a fixed investment rate of 9.7% and capacity factor of 50.5%, the number of turbines after 40 years of the project increases eight times when the reinvestment is raised from $0 (10,806 turbines) to $0.03/kWhwind (89,056 turbines) (SM-Fig. 2).

The minimum possible investment rate that can offset 100% of the total emissions of ND’s oil and gas is 9.7% with $0.03/kWhwind reinvestment (assuming $0.03/kWhwind is the maximum reasonable reinvestment rate, assuming a 50.5% capacity factor, and allowing the wind farm to span ND). This scenario will be denoted as the suggested BIG scenario.

To contextualize the scale of the suggested BIG scenario, the number of active turbines and the required expenditures over time are plotted in Fig. 3. In this scenario, investment and reinvestment revenues are allocated towards four substantial costs: newly built turbines, transmission line construction, maintenance, and replaced turbines (Fig. 3). The majority of revenues go to building new turbines, despite the replacement costs that appear after 20 years (the assumed lifespan of the turbines; Fig. 3). Spending decreases (and unused income is generated) when the wind farm reaches its maximum allowable size going into year 38 (Fig. 3). In year 40, the suggested BIG scenario generates 155 GW (GW) of average power (i.e., not nameplate capacity); this power is dispatched to 14 of the 26 eGRID regions in the contiguous U.S. (Fig. 4).

### 3.3. Financial efficiency of BIG

The financial efficiency of the suggested BIG scenario is assessed in contrast to the scenario whereby investment is held constant (at 9.7%), but reinvestment is halved (to $0.015/kWhwind). If the reinvestment rate is halved, the total offset emissions are reduced from 100% to 47% (Table 3). If reinvestment is not included in the total costs (i.e., only the investment costs are considered), doubling the reinvestment rate (from $0.015 to $0.03/kWhwind) more than doubles BIG’s financial efficiency.

#### Table 3

| Investment rate  | 9.7% | 9.7% |
|------------------|------|------|
| Reinvestment rate| $0.015/kWhwind | $0.03/kWhwind |
| Offset GHG emissions | % of total emissions ($10^9$ t CO2e) | 47% (6.4) | 100% (13.4) |
| Financial discount rate | 3% | 7% | 3% | 7% |
| Net present cost, excluding reinvestment | Billions $ | 63 | 36 | 63 | 36 |
| Net present cost, including reinvestment1 | Billions $ | 125 | 62 | 309 | 132 |
| Efficiency, excluding reinvestment | $/t CO2e | 10 | 5.7 | 4.7 | 2.7 |
| Efficiency, including reinvestment | $/t CO2e | 20 | 9.8 | 23 | 9.9 |

1 Unused income is generated by reinvestment and is accounted for in the net cost only when reinvestment is included.

(Table 3). When reinvestment costs are included, the reinvestment rate had a slightly negative effect on BIG’s financial efficiency because turbines installed at the end of the project are not used for their whole lifespan.

Most costs associated with BIG are negative cash flows in the future. Accordingly, a higher discount rate makes the suggested BIG scenario more favorable. The suggested BIG scenario, produces 89 thousand wind turbines and offsets 100% of ND’s total oil and gas emissions for a cost of only $36 billion without reinvestment ($132 billion with reinvestment; using the industry-average cost of capital, 7% [68], as the discount factor; Table 3). The efficiency of this suggested scenario is, therefore, $2.7 and $9.9/t of CO2e without and with reinvestment costs,
respectively (Table 3).

If reinvestment costs are not included, BIG’s efficiency ($2.7/t of CO2e) is better than the average price of voluntary carbon offsets in North America ($2.9/t of CO2e [32]; Fig. 5). Even when reinvestment is included in the cost, BIG’s efficiency ($9.9/t of CO2e) is still better than California’s average cap-and-trade prices ($13/t of CO2e [31]; Fig. 5). Capital costs of the wind turbines account for 68% of BIG’s equivalent cost (Fig. 5).

3.4. Sensitivity of the BIG model

The sensitivity of the developed model was assessed by increasing and decreasing each of the input assumptions by 10% and recording the resultant required investment rate. Only three of the 23 factors considered affected the investment rate by more than 10% (Fig. 6). Capacity factor and turbine capital costs were the most influential parameters, as they changed how much revenue could be generated by the wind farm and how much it cost to expand the wind farm; both factors slowed the exponential growth of the wind farm. Oil emissions had a disproportionate effect because they increased the total emissions required to be offset. Given the land-area constraint, the maximum size of the wind farm must be reached sooner to offset the higher emissions and therefore a disproportionate investment increase is required to achieve this growth.

Reducing the life expectancy of the transmission components by 10% (to 36 years) had no effect because during the 37th year of the project, the unused income (in the baseline case) was sufficient to cover the replacement transmission costs without changing the investment rate. The effects of increased transmission lifespan were not observable during the 40-year time horizon of this study.

4. Discussion

Major carbon producers are likely to use their resources to resist typical proposals for emissions pricing [12–14]. Our BIG proposal suggests a way to leverage the resources of such corporations to accelerate decarbonization rather than resist it, all while increasing the short- and long-term health of corporations, their surrounding communities, and our climate.

Because of BIG’s scale, BIG has potential to transform ND’s oil and natural gas industries and mitigate their GHG emissions. The suggested BIG scenario would result in wind farms that would span ND and generate 155 GW in the project’s final year, which is equivalent to 11.5% of the electricity generation capacity within the contiguous U.S. [60]. A wind farm of this scale would increase the world’s existing wind power production by 30% [70], yet is comparable to other proposals to substantially decarbonize the U.S.’ energy mix (e.g., [71]).

The electricity from this wind farm would saturate 13 of 26
subregions in the grid with 20% wind-generated power (i.e., increase their current fraction of wind-generated power to 20%) and thereby limit the ability of other projects to produce useful wind-generated power. Accordingly, BIG cannot simply be simultaneously applied to other locations at the same scale until the transmission grid evolves to be able to handle a larger fraction of wind power. A complementary BIG option might thus include investing in electricity grids (e.g., underground high-voltage DC lines and energy storage systems) that will be able to handle larger fractions of intermittent, renewable energy supplies. BIG could then be replicated at scale in other areas.

Only 13% of capital costs in the suggested BIG scenario were due to transmission, despite power being transmitted to 14 of 26 eGRID subregions across the contiguous U.S. (Fig. 4). Similarly, only 3.2% of the total generated electricity was lost to transmission and conversion. These relatively small transmission costs emphasize that wind availability (not electricity demand) should drive wind farm siting decisions. This paper focused on applying BIG in ND, but BIG could instead (or additionally, if grid issues are addressed) be implemented in other windy states such as Nebraska or Wyoming (with capacity factors of 54.8% and 45.4%, respectively; Section SM-3). BIG lessons learned might then be applied to other regions and industries.

While this BIG solution provides a meaningful way to reduce oil and gas emissions, a different solution for ND’s coal emissions is urgently required. More than two-thirds of the world’s committed power generation emissions are from coal [67]. Fortunately, there are efforts underway to seek more valuable uses for coal than simply burning it (e.g., coal as a source for carbon nanomaterials [72,73]).

BIG has been framed as a transitional pathway for hydrocarbon producers. However, the BIG opportunity could apply equally well to electricity utilities in the U.S., whose autonomy makes their firm-level choices about GHG intensity critical to reducing country-wide GHG emissions [74]. The BIG proposal could be of particular interest to utilities with regulated maximum margins in years when margins exceed the maximum, thereby requiring utilities to return profits to shareholders or to find new opportunities to invest. Similarly, BIG thinking could also transform other carbon-intensive industries (e.g., cement producers who invested in green energy would reduce their net GHG emissions and thereby reduce or avoid carbon-induced liabilities).

The recent leases of U.S. federal lands for hydrocarbon extraction [30] present another BIG opportunity. Hydrocarbon extraction on federal lands requires the payment of a royalty of 12.5% [30]. This example from ND demonstrates that, if used correctly, this royalty would be sufficient to offset 100% of the total emissions associated with this extraction in ND, providing quantitative support for the hypothesis of [28]. Extending the BIG model to such leases, perhaps hydrocarbon companies should be offered a reduced royalty rate if they offset their GHG emissions.

The BIG idea presented in this paper has several limitations. First, fundamental limitations must be placed on the total amount of hydrocarbons that can be produced and consumed if climate change is to be mitigated [8–10]; BIG does not change this fact. Second, the presented analysis assumes that hydrocarbons are burned. Yet hydrocarbons can provide sources for non combusted high-value products (e.g., [72,73]). Third, while our BIG proposal is compatible with a carbon tax or a cap-and-trade system, complimentary programs like BIG can decrease the efficacy of a cap-and-trade system if its cap has not anticipated the program and if the trading system does not have exogenous bounds on the trading price [23,75]. And fourth, while hydrocarbon producers may be able to avoid paying GHG-induced liabilities to the government through BIG, producers still incur the investment costs associated with BIG. These producers are likely to pass these costs on to their customers and such carbon-specific costs are likely to be regressive [17,25]. Under BIG, as compared to a traditional carbon tax, there are less options for mitigating these potentially-regressive outcomes since the investment costs do not flow through the government. Nevertheless, as the potentially-regressive investment costs (i.e., not including reinvestment) are minor ($2.7/ton CO2e) when compared to other GHG-mitigation options, more detailed models of BIG should nevertheless be pursued. Moreover, our BIG proposal, to foster decarbonization within existing energy firms and within the same regions as fossil fuel extraction, mitigates many distributional justice concerns associated with other energy transition proposals [8,15–17].

The first-order model used to demonstrate BIG’s potential is intentionally coarse and leaves room for improvement in several domains. First, the presented model does not account for changes in GHG emissions associated with changing economic activity, weather, policy, or technology. Accounting for such changes could be improved in future work. Second, carbon management schemes can induce unexpected secondary effects [24,29]. Accounting for such effects of BIG will be an important next step in assessing its feasibility. Third, the BIG model uses the average electricity production of wind turbines, the average electricity demand of each eGRID subregion, and the average GHG intensity of each eGRID subregion. Accounting for hourly, daily, seasonally, and yearly variations in these averages will be important in future, more detailed BIG models. And fourth, the model of BIG did not capture the additional benefits of job creation due to BIG’s effect on the wind turbine industry; such benefits should be included in future models. In addition to addressing these limitations in future models, the viability of BIG could be efficiently explored through pilot projects, which would evaluate and evolve the BIG idea and its associated policies.

5. Conclusions

We present a hypothesis that oil and gas companies can profitably invest in renewables, while offsetting the carbon they produce, thereby achieving an economic Black Into Green transition. The hypothesis is tested with an example of BIG in ND and demonstrates that, over a period of 40 years, by investing a reasonable fraction (< 10%) of the revenue from ND’s oil and gas production, the GHG emissions from ND’s oil and gas production and consumption can be completely offset for only $9.9/ton of CO2e. Reinvesting $0.03/kWhwind proved key to funding BIG with a reasonable fraction of hydrocarbon revenues. Should either a carbon tax or a cap-and-trade system be implemented with an equivalent liability of at least $9.9/ton of CO2e, ND’s oil and gas companies should invest BIG.

More broadly, this example from ND demonstrates that the collocation of abundant wind, oil, and gas resources can allow for the extraction of all three resources in a carbon-neutral way, all while mitigating distributional injustices traditionally associated with green energy transitions [8,15–17]. Accordingly, BIG should be evaluated in more detail and applied to other locations. Specifically, follow-on studies of BIG’s feasibility in Nebraska and Wyoming are recommended. Additionally, where hydrocarbons are extracted on federal lands, a unique policy opportunity exists to leverage the existing royalty structure to render such resource extraction carbon neutral and to encourage carbon producers to decarbonize their business.

The presented BIG example demonstrates that by investing in renewables directly, companies can keep the avoided liabilities as assets on their balance sheets, evolve into thriving green energy producers, and support ‘jobs & environment’ in a BIG way.

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Declaration of interest: D.V. manages an investment firm whose investments often include publicly traded companies from the energy
and utility sectors. The authors declare that these interests have not influenced our results.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.03.158.

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Glossary

**BIG**: ‘black into green’

**Btu**: British thermal units

**CapX**: capital expenditures

**CO2e**: carbon dioxide equivalent

**EPA**: Environmental Protection Agency

**GHG**: greenhouse gas

**GJ**: gigajoules

**kWh**: kilowatt hour

**kWhnet**: kilowatt hour of wind-generated electricity

**MW**: megawatts

**ND**: North Dakota

**NPV**: net present value

**SM**: supplemental materials

**t**: ton

**W**: watts.