The Earth's atmosphere contains a relatively low concentration of carbon dioxide (CO_2) but plays an outsized role as one of Earth’s most potent greenhouse gases (GHGs). GHGs allow solar radiation to pass through the atmosphere and reach the Earth’s surface, but block some of the longer wavelength light reradiated from the surface, resulting in a greenhouse effect [1]. A familiar example of a greenhouse effect is the heating of the interior of a car parked in the sun, where the glass windows let the visible light from the sun through, but block the infrared light reradiated from the surfaces inside the car [2]. CO_2 in Earth’s atmosphere is not inherently bad. In fact, without CO_2, the natural greenhouse effect of our atmosphere would not be sufficient to maintain a global surface temperature above freezing [1]. However, by releasing tens of billions of tons of CO_2 into the atmosphere annually, humans are amplifying the natural greenhouse effect, leading to an unprecedented rise in global temperatures [1]. Although CO_2 is released through natural processes, it is estimated that two-thirds of the aggregate warming effect of man-made greenhouse gases can be attributed to CO_2, with methane (CH_4) accounting for about half of the rest [1, 3, 4]. To incorporate the influence of other GHGs besides CO_2, the analysis presented here will use carbon dioxide equivalent (CO_2e), as it is the “prevailing ‘currency’ of greenhouse gases and global warming” [5]. This metric gives a more comprehensive assessment of the overall anthropogenic warming impact of our activities and operations. In general, through the burning of fossil fuels, humanity has upended the equilibrium of CO_2 and other GHGs in our atmosphere, far surpassing the natural rate of processing, leading to a precipitous rise in global temperatures with significant and potentially catastrophic consequences for plants, animals, and people.

Researchers, scientists, and government organizations have been working to identify the main sources of GHG emissions and find the best approaches to promptly reduce emissions. In the United States, President Biden announced in April 2021 that the U.S. is preparing “to achieve a 50–52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution in 2030” [6]. In addition, the U.S. rejoined the Paris Climate Accords, setting “a course for the United States to tackle the climate crisis at home and abroad, reaching net zero emissions economy-wide by no later than 2050” and “limiting global warming to 1.5 °C” [6]. In this year’s report, the Intergovernmental Panel on Climate Change (IPCC) stated that “there is a more than 50% chance that global temperature rise will reach or surpass 1.5 °C between 2021 and 2040” [7]. The IPCC found that, although the U.S. and other countries have made progress in reducing GHG emissions, it was not nearly enough. The report found that the pledged emissions reductions submitted by countries party to the agreement would reduce GHG emissions only 7% from 2019 levels by 2030 — well short of the 43% reduction over that time period needed to limit temperature rise to 1.5 °C [7]. As global GHG emissions have continued to increase over the past decade, corporations, such as the regional power provider Duke Energy in the U.S., are taking their own measures to transition to clean energy and reduce emissions.

An American-based company, Duke Energy, is headquartered in Charlotte, North Carolina, serving 7.9 million customers across six states [8]. The corporation is one of the United States’ largest electricity providers, collectively owning 51,000 megawatts (MW) of energy capacity [8]. According to Duke Energy, their main responsibility is providing their customers with “reliable, affordable, and increasingly clean energy that keeps communities moving forward” [8]. In Duke Energy’s Sustainable Financing Framework report from October 2021, they addressed the challenges of climate change by setting “enterprise-wide emission reduction goals, accelerating toward net-zero carbon emissions from electricity generation by 2050” [8]. The report also states that Duke Energy is “on track to cut carbon emissions by at least 50% by 2030” [8]. Considering that an estimated 25% of GHG emissions in the U.S. come from electricity generation

[9], Duke Energy has a key role in reducing America's carbon footprint by transitioning away from fossil fuels and increasingly adding clean energy sources to their portfolio.

Coal and natural gas are carbon-based energy sources that are burned to generate electricity. These non-renewables release large amounts of carbon dioxide when they are burned, and Duke Energy has taken an aggressive approach to phase out their use. Since 2010, the company has retired 56 coal units – the largest carbon emitter in their portfolio – helping to reduce carbon emissions 44% from 2005 levels [10]. The corporation has announced additional goals such as reaching 16,000 MW of renewable generation capacity by 2025 [10] (from 10,000 MW in 2021), which would include solar, wind, and hydroelectric sources. This would equate to roughly 30% of their current total generation capacity. In the longer term, Duke Energy aims to integrate a combination of zero-emission energy sources, to achieve a significant reduction in GHG emissions. By 2030, Duke Energy claims that around 55% of their generation will be carbon-free [10]. If Duke Energy can achieve this, it will represent a significant accomplishment and meet the emission reduction targets set forth by both President Biden and the Paris Climate Accords.

Given its significance, there is an abundance of literature and ongoing research devoted to solving the problem of decarbonizing the electric grid worldwide. The simplified analysis presented here demonstrates how Duke Energy can substantially reduce their carbon footprint while limiting price increases for their customers, doing their part to limit global temperature rise to 1.5 °C. The following section provides a summary of the analysis, which encompasses two decision variables, two objective functions, and several constraints to achieve an optimal compromise solution between meaningful emissions cuts and minimum expense. Please note that all data is contained within the *SCHMIDT-Emily.xlsx* file but will present a short synopsis now.

Decision Variables

- x_i = Number of *i* electricity generation plants opening [10]
- y_i = Number of *i* electricity generation plants closing [10]

From Duke Energy's 2021 ESG Report, there are eight energy types (*i*) represented within their generation portfolio, however, fuel cells and oil will not be covered in this project given their very low usage (<0.2% of total electricity generated) [10]. In addition, the current number of plants for each energy type may not be completely accurate as data was pulled from different time periods from Duke Energy's various online reports and websites. However, the number of current plants operated by generation source had very little effect on the results of the analysis.

Objective Functions

Duke Energy has announced its commitment to decarbonizing its power production by selectively building and decommissioning certain energy plants, based on their CO_2e emissions. The primary objective function holds immense significance, as it describes the number of generation facilities by type to be opened or closed based on their corresponding CO_2e emissions. The optimal solution will dictate the number and type of plants to be built or decommissioned by the conclusion of the project (five years) that will minimize Duke Energy's GHG emissions. This solution provides the most aggressive decarbonization scenario for Duke Energy (working within the given constraints) but does not account for cost or other considerations.

1. Minimize CO_2e: $\sum_i x_i c_i g_i - \sum_i y_i c_i g_i$
    - x_i = Number of *i* energy plants opening [10]
    - y_i = Number of *i* energy plants closing [10]
    - c_i = CO_2e emission for plant type *i* [11]
    - g_i = Electricity generated per plant [10]

The second objective function pertains to the levelized cost of electricity (LCOE). According to the U.S. Department of Energy, LCOE "measures lifetime costs divided by energy production" [12]. This measurement is advantageous because it considers capital costs, operations and maintenance costs, market matching costs, and external costs of each energy source [12]. By minimizing this metric, Duke Energy can offer their customers electricity at the lowest possible expense, regardless of GHG emissions.

2. Minimize LCOE Cost: $\sum_i x_i d_i g_i - \sum_i y_i d_i g_i$
    - x_i = Number of i energy plants opening [10]
    - y_i = Number of i energy plants closing [10]
    - d_i = LCOE for plant type i [13, 14]
    - g_i = Electricity generated per plant [10]

Constraints

To meet Duke Energy's targets, there are multiple constraints that require fulfillment between the two objective functions. The initial three constraints signify the linking constraints, while the remaining ones represent general limitations.

1. Δ Electricity Generated: In 2021, Duke Energy's ESG Report stated that they generated 215,770,000 megawatt hours (MWh) of electricity [10]. This first constraint dictates the bounds within which the optimal solution can change the total amount of electricity generated. It is assumed that electricity generation will remain relatively constant throughout time, which is a realistic assumption, given annual growth of just 0.15% over the last decade [15]. Therefore, the allowed change in total electricity generated from the opening and closing of new plants is between 0 and 1%.
    - $\sum_i x_i e_i - \sum_i y_i e_i \geq 0.0$
    - $\sum_i x_i e_i - \sum_i y_i e_i \leq 0.01$
        - e_i = Current electricity generated per energy type i [10]
2. Δ Base Load: The base load refers to the lowest level of electricity demand on an electrical grid over a 24-hour period. "Base load power sources are those plants that can generate dependable power to consistently meet demand", and thus, are considered the fundamental building blocks of a robust electrical system [16]. These include coal, natural gas, hydroelectric, and nuclear plants. As such, this second constraint is in place to ensure that the power grid has a stable base load capacity to meet demand at all times. The allowable change in base load capacity for the optimal solution is between -1% and 1%. The value for the fraction of each source that is considered base load power is estimated with data from Electricity Generation Baseline Report [17]. It is important to note that as power storage for renewables improves, base load constraints will become less relevant.
    - $\sum_i B_i(x_i e_i) - \sum_i B_i(y_i e_i) \geq 0.01$
    - $\sum_i B_i(x_i e_i) - \sum_i B_i(y_i e_i) \leq -0.01$
        - B_i = Base load capacity factor percentage [18]
3. Capital Cost Budget: Duke Energy has projected spending $63 billion in CapEx over the next five years, 82% of which is expected to go towards transitioning their power generation to low- and zero-carbon resources [10]. Since time is not considered within these objective functions, $63 billion will be used as a constraint specifically geared towards the cost of opening and closing plants. In practice, employing this constraint alongside LCOE is somewhat flawed as construction costs are included as a part of the LCOE. However, this capital cost budget should help give a reasonable indication of the transition in electricity generation mix that is possible over five years for Duke Energy.
    - $\sum_i x_i p_i + \sum_i y_i p_i \geq 50{,}000{,}000{,}000$
    - $\sum_i x_i p_i + \sum_i y_i p_i \leq 63{,}000{,}000{,}000$
        - p_i = cost of opening or closing plant i [19, 8, 20, 21, 22, 23]

4. Closing Plants: Duke Energy cannot close more plants than it owns.
   - $\sum_i y_i \leq u_i$
     - u_i = Number of current plants owned by Duke Energy [8, 20, 21, 22, 23]
5. Hydroelectric plants: The United States has 1,490 hydropower plants across the country [6]. As a result, there is a very limited number of water ways that can still be dammed. This constraint dictates that no additional hydroelectric plants can be built and that only existing plants can be upgraded with modern equipment and/or added capacity.
   - $x_c \leq 13$ [21]
6. Multiplicity Factor: To avoid Excel Solver recommending to open and close the same type of plant, this constraint ensures that a plant can either be opened or closed.
   - $x_i * y_i = 0$
7. For all x_i *and* y_i, decision variables need to be integer values.
8. For all x_i *and* y_i, decision variables need to be positive values or zero.

Summary Table

Resources		*[10] Page 35*	*[10] Page 35*	*[10] Page 35*	*Table 1*	*Table 2*	*[8, 20, 21, 22, 23]*	*[19] Table 2, Page 3*	*[17] Approximated*
Decision Variables	**X, Y**	**Xi, Yi**	**Electicity Generated (MWh (thousands))**	**Generation Capacity (MW)**	**CO2 Emissions (kg/MWh)**	**LCOE (US$/MWh)**	**Number of Plants**	**Plant Cost (US$)**	**Baseload**
Opening Plant Xi	XA	Solar	4,325	1,973	53	36	23	$112,632,565	0
	XB	Wind	7,387	2,987	12	38	21	$209,232,238	0
	XC	Hydo-electric	2,870	1,339	9	93	13	$547,548,000	0.75
	XD	Nuclear	75,328	8,907	6	167	11	$4,891,562,455	1
	XE	Coal	48,181	15,652	924	108	11	$5,230,613,818	0.65
	XF	Natural gas	77,679	19,788	458	60	40	$536,254,800	0.25
			215,770	50,646			119		
Closing Plant Yi	YA	Solar	4,325	1,973	53	36	23	$12,389,582	0
	YB	Wind	7,387	2,987	12	38	21	$23,015,546	0
	YC	Hydo-electric	2,870	1,339	9	93	13	$60,230,280	0.75
	YD	Nuclear	75,328	8,907	6	167	11	$538,071,870	1
	YE	Coal	48,181	15,652	924	108	11	$575,367,520	0.65
	YF	Natural gas	77,679	19,788	458	60	40	$58,988,028	0.25
			215,770	50,646			119		

To obtain further details regarding the data, summary table, and resources outlined above, refer to *SCHMIDT-Emily.xlsx* (Data tab: Column B, Rows 48 – 59). This file also includes how the optimization problems were formulated and the approach used to solve them.

The primary objective for Duke Energy is to minimize CO_2e to reduce their GHG emissions as much as possible. Considering the available data and constraints, Duke Energy can achieve a reduction of 60.6 million tons of CO_2e by opening two solar plants, 124 wind plants, and six nuclear plants, while closing 11 coal and 19 natural gas plants. This strategy would result in a reduction of 75.0% in total emissions from the current electricity generation mix. Interestingly, this plan would only result in a 4.8% increase in LCOE. If enacted as a part of a five-year CapEx plan, Duke Energy can decrease its carbon emissions by 75% while keeping additional LCOE costs below 5% [10]. The major caveat with this approach is the construction of new nuclear plants currently takes about a decade, and this analysis suggests building six. This is unreasonable in the given timeframe, and stopgap solutions would be required, especially to account for the nuclear plants' large base load capacity.

The secondary objective of Duke Energy's optimization approach was focused on minimizing costs, again with the capital cost constraint of $63 billion. This analysis shows that a 3.2% reduction in LCOE is attainable, a modest cost discount, which could ultimately translate into benefits for Duke Energy's customers or their bottom line. The 3% reduction in LCOE corresponds to a cost decrease of $748.5 million per year and would hardly justify the $63 billion investment. Furthermore, this scenario would result in a 41.3% rise in the company's CO_2e emissions — a staggering increase considering the relatively meager cost savings. The additional CO_2e emissions in this scenario are attributable to the opening of several coal plants while closing solar, wind, and nuclear. Initially, it may be surprising that the most cost-effective solution is closing solar and wind (very low LCOE) and building coal plants (high LCOE), but this is a result of the base load constraint. To fulfill the base load requirement, Duke Energy must consider that four sources can be used: nuclear, coal, hydroelectric, and natural gas. Since nuclear is the most expensive power source in terms of the LCOE, the most cost-effective solution prioritizes closing these plants. In this case, four nuclear facilities are to be closed, but the base load constraint requires that this is replaced with another base load source. The reason Duke Energy would build coal and hydroelectric plants over natural gas despite the latter's lower LCOE is because they have much higher base loads (65% and 75%, respectively). To satisfy the base load constraint, if Duke Energy were to close 1,000 MW of nuclear with a base load capacity of 100%, it would need to concurrently install 4,000 MW of natural gas with its 25% base load. To ensure no change in the total generation capacity (the first constraint), 3,000 MW of solar and wind with a 0% base load capacity would then need to be closed. So, although installing hydroelectric and coal power is more expensive, it actually results in less of the very inexpensive solar and wind being closed due to their ability to meet higher base load demands. To summarize, a limited reduction in LCOE of around 3% is possible, but this solution is not pragmatic assuming Duke Energy's commitment to reducing their GHG emissions.

As previously discussed, Duke Energy aims to reduce CO_2e emissions by at least 50% by 2030 [8]. With this five-year outlook, it is intriguing to analyze how this could be achieved through the two objective functions. In this next analysis, the reduction in CO_2e is constrained to be at least half of current emissions, i.e., mandating at least a 50% decrease in CO_2e. The second objective function is then solved to find the minimum cost for which this is possible, with all the other constraints still in place. Here, the most cost-effective solution shows that Duke Energy can achieve a 64.2% CO_2e reduction, while increasing cost by just 3.2% over five years. This would be a significant accomplishment as Duke Energy can exceed their emissions reduction goal by a considerable margin with a minimal increase in cost.

Throughout this analysis, modifications were made to meet specific criteria by adjusting certain constraints. Consequently, it became evident which elements have a more significant effect on the objective functions. Notably, the base load for each energy type had the most substantial influence. In the three previously discussed optimization scenarios, the base load values remained unchanged. The present estimates are approximations based on the Electricity Generation Baseline Report [17]. Historically, nuclear, hydro, and coal were the primary sources for base load power because they were reliable and inexpensive. More recently, the natural gas supply in the U.S. has grown markedly [24] – with a corresponding fall in price [25] – due to the commercialization of hydraulic fracking [26]. As a result, natural gas has been increasingly used as a base load power source. Additionally, solar and wind were initially assigned a 0% base load capacity in this analysis, as they cannot be relied upon to provide electricity around the clock. However, as energy storage technologies continue to advance, companies like Duke Energy will be able to release power generated from wind and solar over longer time periods. In the near future, it is likely that wind and solar will be able to contribute to a portion of the grid's base load power. For the sensitivity analysis presented here, the base load values of natural gas, solar, and wind will be increased to see how the optimal solutions respond. In addition to changing base load capacities, a final scenario was simulated where no hydroelectric power could be added to the grid. This may be a more realistic interpretation of the constraints on hydroelectric power discussed earlier. All the results from this sensitivity analysis are provided below.

Decision Variables	X, Y	Xi, Yi	Baseload	Compromise Final Scenario	Altered Baseload	Base Load - Gas Increase	Altered Baseload	Base Load - Solar and Wind	Baseload	No Hydro Plants
Opening Plant Xi	XA	Solar	0.00	203	0.00	130	0.40	167	0.00	205
	XB	Wind	0.00	16	0.00	3	0.45	67	0.00	16
	XC	Hydo-electric	0.75	1	0.75	0	0.75	0	0.75	0
	XD	Nulear	1.00	5	1.00	7	1.00	2	1.00	4
	XE	Coal	0.65	0	0.65	0	0.65	0	0.65	0
	XF	Natural Gas	0.25	0	0.70	0	0.25	0	0.25	0
Closing Plant Yi	YA	Solar	0.00	0	0.00	0	0.40	0	0.00	0
	YB	Wind	0.00	0	0.00	0	0.45	0	0.00	0
	YC	Hydo-electric	0.75	0	0.75	13	0.75	13	0.75	2
	YD	Nulear	1.00	0	1.00	0	1.00	0	1.00	0
	YE	Coal	0.65	9	0.65	9	0.65	11	0.65	6
	YF	Natural Gas	0.25	20	0.70	16	0.25	9	0.25	23
LCOE				$738,886,152.05		$2,536,801,971.77		-$1,883,037,518.71		$616,808,621.65
CO2e				(51,915,202,008.60)		(49,085,559,806.21)		(49,353,931,613.09)		(42,468,979,819.14)
LCOE Change				3.19%		10.96%		-8.13%		2.66%
CO2e Change				-64.18%		-60.68%		-61.01%		-52.50%

Sensitivity Analysis Key Takeaways

The sensitivity analysis was performed using the “compromise” conditions where CO_2e reduction was mandated to be at least 50% and the objective function was solved to minimize LCOE.

1. There was an 11% increase in cost from the existing LCOE in the scenario where natural gas base load was raised to 70%. This decreased CO_2e by 61% compared to 64% for the original compromise case. The higher cost for a similar reduction in emissions is a result of the larger base load capacity that is closed in this scenario. To compensate, several high-cost nuclear plants are opened, leading to a higher LCOE.
2. The scenario where wind and solar power can be used for a sizeable fraction of the base load proved to be the most interesting in the sensitivity analysis. Here, a 61% reduction in emissions coincides with an 8% drop in LCOE. This highlights the importance of advancements in electrical storage technology which would allow the incorporation of low cost and zero emission sources as a considerable portion of the electric grid.
3. The final scenario where no hydroelectric plants were allowed to be opened showed a similar LCOE but a smaller reduction in emissions (52.5% rather than 64%). This outcome occurs because the solution calls for closing two hydroelectric plants while keeping three coal plants that were closed in the initial compromise scenario open. Considering that the original compromise solution only called for one hydroelectric plant to be opened, this substantial effect on emissions is surprising. However, it is likely that for a small increase in LCOE, similar cuts in CO_2e to the initial solution could be realized.

To effectively address the problem of man-made climate change, it is necessary to mobilize global assets and pursue specific objectives. This requires the cooperation of various entities, including governments, corporations, and individuals, to reduce GHG emissions. An analysis on this issue is complex and poses several challenges, including resource constraints and computational limitations that require the exclusion of certain elements. Here, a five-year CapEx plan has been discussed, but an explicit time dimension is not included, which would necessitate annual forecasts. The assumption of constant electricity generation does not account for fluctuations in demand but is not unreasonable [15]. Additionally, the location of power plants, their optimal capacity, and their environmental impact (aside from GHG emissions), were not considered. This may affect the utility of certain facilities and pose ecological risks. The inclusion of these variables may be of interest for future research. Despite these limitations, the analysis showed that Duke Energy could achieve a 64.2% reduction in carbon emissions over five years, with only a 3.2% increase in cost, by implementing a plan that balances steep emissions cuts with the minimum possible expense. In doing so, Duke Energy would exceed their stated climate goals, those set forth by the U.S. government, and those recommended by the Paris Climate Accords to ensure our planet stays below the critical 1.5 °C warming threshold.

Resources

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