Electrifying and Decarbonizing the UM Bus Fleet

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12 December 2024

Abstract

To address climate change at a local level, the Ann Arbor City Council committed to charting a path for Ann Arbor to achieve carbon neutrality. The A^{2}Zero plan lays out a series of actions for the city to reach carbon neutrality by 2030.[1] The University of Michigan (UM) has also developed a Campus 2050 plan, which aims for the university to reach carbon neutrality by 2040.[2] One significant contributor to the campus and city emissions is the UM fleet of buses, which currently consists of 4 electric buses, 27 hybrid, and 29 diesel buses and emits an estimated 3 million kg CO_2 eq/year.[3] While the A^{2}Zero plan calls for full electrification of the UM bus fleet by 2030, UM would only need to reduce emissions by 33% over the next five years to be on track for its 2040 carbon neutrality goal.

This report analyzes the options for UM bus purchases over the next five years, specifically focusing on the cost and emissions tradeoffs in the context of these two carbon neutrality timelines. To remain on track for the 2050 Campus plan goals, the UM bus fleet could transition to 28 electric buses, 29 hybrid and 3 diesel buses to reduce emissions by 33% (to ~2 million kg CO_2 eq/year) at the lowest cost ($33,576,000) by 2030.[4]

Introduction

The Ann Arbor City Council developed a plan that is committed to charting a path for Ann Arbor to achieve carbon neutrality by the year 2030. A^{2}Zero was designed to develop actions that invest in the city of Ann Arbor to reduce greenhouse gas emissions in an effective and timely manner and serve as a model for addressing the climate emergency. Two of the strategies highlighted in the plan aim to reduce emissions from transportation by promoting the electrification of vehicles and promoting public transportation.[1]

In order to achieve these reductions in transportation emissions, The University of Michigan (UM) will have to play a large role. In 2018, the UM campus emitted the largest proportion (32%) of all greenhouse gasses in the city. One contributing factor is the UM fleet of buses, which currently consists of diesel, hybrid, and electric buses. The A^{2}Zero plan calls for UM to electrify their entire bus fleet, and power the buses partially with renewable energy sources like carbon-free solar power.[1] UM has also developed its own Campus Plan 2050, which targets reaching carbon neutrality by 2040. While the campus has indicated it plans to electrify its bus fleet before 2040, we consider that at the minimum, UM would need to reduce its emissions by 33% over the next five years to remain on track for its 2040 carbon neutrality goal.

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[1] City of Ann Arbor. (2020) A^{2}Zero Plan
[2] UM Campus Plan 2050: Blueprint for Our Future
[3] Fisher, A. (2023, June 22).
[4] Figure 1: Pareto frontier

Adherence to the differing timelines laid out in these plans will also introduce considerable tradeoffs between budget, emissions, public transit accessibility, and other community-wide considerations during this transition. Therefore, a multi-criteria decision analysis approach is relevant to determining the optimal combination of diesel, hybrid, and electric buses. Our team took the role of the UM Bus Fleet Manager to further investigate the relationship between the University of Michigan's bus fleet electrification efforts while minimizing cost.

Systems of Equations

Note: all variable descriptions , values, and sources are defined in Table 1 of the Methods section.

Objectives

1. Minimize emissions: $Z_1 = E_E + E_H + E_D$
   E_E - total emissions from electric buses (kg CO_2 eq)
   $$E_E = E_F * m * I_E$$
   E_H - total emissions from hybrid buses (kg CO_2 eq)
   $$E_H = H_F * m * I_H$$
   E_D - total emissions from diesel buses (kg CO_2 eq)
   $$E_D = D_F * m * I_D$$
2. Minimize cost: $Z_2 = C_E + C_H + C_D$
   C_E - total cost of electric ($)
   $$C_E = (E_B * P_E - E_S * S_E) + (E_F * m * M_E * l)$$
   C_H - total cost of hybrid ($)
   $$C_H = (H_B * P_H - H_S * S_H) + (H_F * m * M_H * l)$$
   C_D - total cost of diesel ($)
   $$C_D = (D_B * P_D - D_S * S_D) + (D_F * m * M_D * l)$$

Decision variables

- E_F - total number of electric buses in 2030
- H_F - total number of hybrid buses in 2030
- D_F - total number of diesel buses in 2030

Constraints

- Total number of buses must stay the same (to ensure that current accessibility/route frequency standards are maintained)
  - $E_F + H_F + D_F = E_i + H_i + D_i$ (# buses)
- Can't sell more buses than the initial starting amount
  - $E_S <= E_i$
  - $H_S <= H_i$
  - $D_S <= D_i$
- Non-negativity constraints
  - $E_B, E_S, H_B, H_S, D_B, D_S >= 0$

Methods

Table 1: List of variables used in our system and how they were developed

Variable	Description	Value	Units	How it was derived	Assumptions
m	miles traveled per bus per year	21666.7	mi/bus/yr	- Calculated # buses and distance traveled by each bus route per week using GIS and frequency data[5] - Extrapolated results to 1 year	- Value remains the same for electric, hybrid, and diesel - Does not account for buses being reused by different routes, going under maintenance, or not operating during holidays/events
I_E	emissions intensity for electric	0.71	kg CO_2 eq/mi	- CO2 emission factor for electric buses: 0.27 kg CO2/kWh[6] - Vehicle efficiency for electric buses: 2.62 kWh/mi[4] - Combined these two values	- Batteries are not charged by 100% renewable energy - Not considering life-cycle emissions
I_H	emissions intensity for hybrid	2.212	kg CO_2 eq/mi	“The figure of 2,212 grams of CO2 per mile was used which is the grams of greenhouse gas per mile emissions from a diesel hybrid bus.” [7]	
I_D	emissions intensity for diesel	2.68	kg CO_2 eq/mi	"Union of Concerned Scientists reported that while the average 40-foot diesel bus emits 2,680 grams of CO2 per mile (g/mi)...” [8]	
P_E	purchase price of electric	850,000	$	“The new 40-foot electric vehicle bus cost $850,000…” [9]	
P_H	purchase price of hybrid	700,000	$	- Average cost for the first 7 hybrid buses that UM purchased in 2012 was $525,000 each[10] - Used inflation calculator to adjust to 2024 dollars, resulting in $712,000 per bus	- Rounded down to $700,000 for simplicity and with the assumption that hybrid buses have become relatively cheaper due to manufacturing innovations

5 University of Michigan Logistics, T. & P. (2024).
6 Onolememen Jrn, O. M. (2021). Table 1
7 Mainzer, B. (2022).
8 Massoli, P. (2020, May 19).
9 Smart Energy Decisions. (2023, February 13).
10 Woodhouse, K. (2013, October 7).

P_D	purchase price of diesel	500,000	$	- UM spent $476,00 for diesel bus in 2022[7] - City of Ann Arbor assumes diesel bus costs $525,000[11] - Took midpoint of these two values	- Rounded down to $500,000 for simplicity
S_E	sale price of electric	127,500	$	- Residual value of electric buses stated to be 15% of its initial purchase value, so calculated as 15% of PE[12]	- In practice, scrap price would be determined by battery quality, but we're keeping it a constant value for simplicity
S_H	sale price of hybrid	105,000	$	- Calculated as 15% of PH[10]	- Residual value of electric/diesel buses stated to be 15% of its initial purchase value, so assumed the same for hybrid
S_D	sale price of diesel	75,000	$	- Residual value of diesel buses stated to be 15% of its initial purchase value, so calculated as 15% of PD[10]	
M_E	maintenance cost of electric	0.79	$/mi	- Listed as maintenance cost for electric buses[4]	
M_H	maintenance cost of hybrid	1.09	$/mi	- Rough estimate based on electric and diesel values[4]	- Assuming it lies roughly in between diesel/electric costs, could not find specific data
M_D	maintenance cost of diesel	1.29	$/mi	- Listed as maintenance cost for diesel buses[4]	
l	lifetime of bus	12	years	- Assumed to be 12-year lifespan for electric in Onolemenen 2021[4] and Johnson 2020[10]	- Assuming it is the same for electric, hybrid, and diesel for simplicity
E_i	initial number of electric	4	buses	"Four new battery-powered electric buses have arrived on the University of Michigan's Ann Arbor campus…"[13]	
H_i	initial number of hybrid	29	buses	"The U-M fleet also includes 29 diesel-hybrid buses…"[13]	
D_i	initial number of diesel	27	buses	"The U-M fleet also includes… 27 regular diesel-buses"[13]	

11 City of Ann Arbor. (2020), p.34
12 Johnson, C., Nobler, E., Eudy, L., & Jeffers, M. (2020), p. 17-18
13 Fisher, A. (2023, June 22).

Results and Discussion

Pareto Frontier

To create the Pareto Frontier, the endpoints of the range of feasible values needed to be determined. These were found by separately solving for the optimal solutions of the two objective functions*. This gave a range of values for the two objective functions to work between. The Pareto Frontier was further defined by using the constraint method and giving the cost objective a maximum value. The cost was constrained to values ranging from $24,000,000 to $48,000,000 using intervals of $6,000,000. This provided an additional 6 points for the Pareto Frontier. The constraint method was also used on the objective of minimizing emissions. A maximum emissions constraint was set at 2,012,804 kg CO_2 eq, which represents a 33% reduction in emissions. The solution that satisfied this constraint indicates the minimum cost required to keep UM on track to reach its 2040 carbon neutrality goal. This provided 9 points in the Pareto Frontier to work from as detailed in Table 1 below. **We used the GRG nonlinear solution method in the newer version of Solver in Excel.*

Table 2: Pareto Frontier values for decision variables (cols 1,2,3) and objective functions (cols 4,5).

Electric (# buses)	Hybrid (# buses)	Diesel (# buses)	Emissions (kg CO_2 eq)	Cost ($)	% Emissions Reduction
4	29	27	3,019,207	18,096,002	0%
13	29	18	2,628,505	24,000,000	13%
22	29	9	2,231,451	30,000,000	26%
28	29	3	1,994,807	33,576,000	34%
32	28	0	1,842,898	36,000,000	39%
38	22	0	1,647,736	40,000,000	45%
41	19	0	1,550,154	42,000,000	49%
50	10	0	1,257,411	48,000,000	58%
60	0	0	923,000	54,854,000	69%

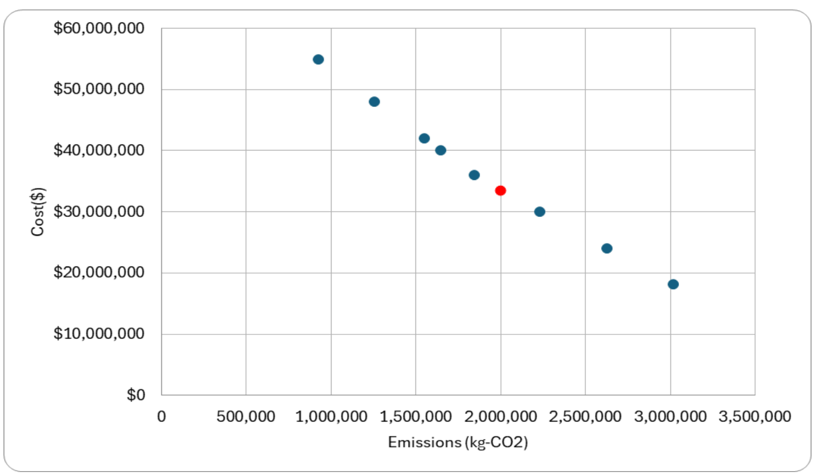

Figure 1: Scatter plot of the Pareto Frontier comparing the two objective functions. The red point represents the solution that minimizes cost and still reduces emissions by 33% by 2030.

To further illustrate the Pareto Frontier a scatter plot was created to show the relationship between the two objective functions. From the plot in Figure 1, it can be observed that the two objective functions of minimizing emissions and minimizing cost share a near linear relationship. This eliminates the ability to graphically remove any non-inferior solutions since it is an inverse relationship between the two objectives. However, when the constraint of reducing emissions by 33% is taken into account, 3 solutions can be removed.

Making a decision

This leaves a range of solutions ranging from the minimum emissions reduction goal (1,994,807 kg CO_2 eq) with an associated cost of $33,576,000. This solution has two binding constraints. The first is the assumption that the bus fleet will remain the same at 60 buses. The second of which is the maximum allowable emissions of 2,012,804 kg CO_2 eq. All of the constraints (besides the non-negativity constraints) have allowable decreases equal to their b-value and shadow prices of 0. This makes sense because realistically, the only constraints in our problem that could be altered are the two binding constraints.

If it is assumed that the range of costs being dealt with is an exorbitant amount relative to the budget, the most likely decision to be made based on this model would be the solution that just meets the 33% emissions reduction as detailed below.

Emissions = 1,994,807 kg CO_2 eq
Cost = $33,576,000
Electric buses = 28
Hybrid buses = 29
Diesel buses = 3

However, if the range of costs are in fact much more agreeable for the University's budget, then alternate solutions that cost more and reduce the emissions more could be considered. The decision is all dependent on the budget.

Additionally, the further trade-off between emissions and cost could be compared to the costs of other emissions reductions that are a part of the broader A^2Zero and Campus 2050 plans. The price per emissions reduction could be calculated for this method and could possibly be cheaper than other areas where improvement may be more difficult to come by at this point in time. This could help achieve broader emissions goals in a more cost-effective way. Additionally, if further goals are intended to be planned and achieved in succeeding years and decades, getting ahead of schedule of emissions goals is possible.

Limitations & Discussion

If it is desired, it is possible to expand upon this work and create a more thorough and comprehensive system of equations. According to this system set-up, the emissions are based on the kg CO_2 eq released over one year and the cost is based on the purchase or sale of buses between the current and the year 2030 as well as the maintenance cost over the bus lifetimes. Both of these objectives could be expanded upon by, for example, including full life cycle emissions associated with each type of bus. Another important addition would be to include annual projections for the carbon intensity of UM's electricity supply factoring in the Campus Plan 2050's goals to reduce emissions from purchased power to net zero by 2025.

Overall, both objectives could be altered to more accurately assess the emissions and cost of the transition from the current state to the future state. This could be done by the introduction of additional decision variables that reflect the specific gain and loss of buses and which year that takes place in. This could then allow for the calculation of the approximate emissions for the bus fleet in each year of the transition as well as the associated maintenance costs of each year. Furthermore, the cost of fuel could also readily be included.

Conclusion

Both the city of Ann Arbor and the University of Michigan have established goals for achieving carbon neutrality, but their timelines differ, with the A^2Zero plan targeting 2030 and the UM Campus plan targeting 2040. Electrification of the UM bus fleet will help reduce emissions for both the city and the campus, however it also carries significant cost implications for the university. We find that if we allow cost to drive the decision, UM would have to transition to 28 electric, 29 hybrid, and 3 diesel buses by 2030 at a minimum cost of over $33 million to remain on track for the Campus Plan 2050 carbon neutrality goal. If UM were willing to adhere to the A^2Zero's plan to electrify the entire UM bus fleet, however, it would increase the cost to nearly $55 million. By evaluating the set of non-inferior solutions that minimize both cost and emissions, we are able to present UM with options for decarbonizing their bus fleet along a spectrum with either plan at the extremes. Future work could factor in the timing in which the buses are purchased and sold, the fuel costs associated with each option, and the emissions impacts of an increasingly renewable electricity supply to provide UM with a more comprehensive assessment of bus fleet decarbonization options.

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