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A lifecycle cost analysis of transitioning to a fully-electrified, renewably powered, and carbon-neutral campus at the University of Dayton

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ABSTRACT

This paper analyzes the cost-effectiveness of converting the University of Dayton (UD) to a fully-electrified, renewably powered, carbon-neutral campus by 2025. The greenhouse gas (GHG) impact and 30-year lifecycle costs (LCC) of a scenario including four primary strategies for transitioning to carbon-neutrality were analyzed; scaling building energy efficiency was determined to reduce GHG emissions by 12% with $10 million LCC savings from business as usual, switching the campus fleet to electric vehicles would reduce GHG emissions by 0.4% with $2 million LCC savings, switching from on-site natural gas combustion to geothermal heat pumps would reduce GHG emissions by 15% with a $15.5 million LCC premium, and procuring renewable electricity through a power purchase agreement with a new-build renewable generator would eliminate the remaining 73% of GHG emissions with a $1.7 million LCC premium. In total, achieving a carbon-neutral campus would increase the 30-year LCC of UD's energy systems by 2.4%, from $211.8 million to $216.9 million. This is likely a reasonable investment to consider, given the uncertainties in future commodity pricing, the potential of future regulatory mechanisms like carbon pricing that would internalize the social cost of carbon, and the urgent need to reduce global GHG emissions.

Introduction

With global average temperatures about 1 °C above pre-industrial levels, the effects of climate change are already being realized in the United States through increased natural disaster events like wildfires, hurricanes, flooding, and drought [1]. In an effort to limit global warming and the effects of climate change, 196 countries signed the Paris Climate Accord in 2015 with a goal of limiting warming to well below 2 °C above pre-industrial levels and pursuing additional efforts to limit it to 1.5 °C above pre-industrial levels. In 2018, two important reports outlined the importance of achieving this goal: The Intergovernmental Panel on Climate Change (IPCC) special report outlined the importance of limiting global temperatures to 1.5 °C by outlining the social, environmental, and economic impacts of a 2 °C versus a 1.5 °C scenario [1] and the U.S. National Climate Assessment Report indicated current mitigation efforts are not sufficient to prevent severe damages to the U.S. citizen's health, environment, and economy [2]. To limit warming to 1.5 °C, urgent action is required to reduce global greenhouse gas (GHG) emissions 45% below 2010 levels by 2030 and eventually reaching zero net emissions by 2050 [1]. Since the energy sector is by far the largest contributor to global GHG emissions [3], the urgency to transform our energy systems cannot be overstated.

Universities can play an important part in reducing GHG emissions and transitioning to carbon-neutral energy systems. Universities account for about 2% of U.S. total GHG emissions – about equal to all commercial aircraft or landfills [4]; thus, achieving carbon-neutrality in the higher education sector could have a substantial climate impact [5,6]. The educational value of achieving carbon-neutrality is also immense, as these efforts serve as experiential learning opportunities for the citizens and climate leaders of tomorrow. Realizing their collective potential, in 2007 over 600 higher education institutions, representing over 30% of U.S. higher education enrollment [6], signed the American College & University Presidents' Climate Commitment (ACUPCC) and committed to carbon-neutrality "as soon as possible."

Initially, many institutions that joined the ACUPCC, including the University of Dayton (UD), did not invest serious thought into the question of how soon 'as soon as possible' is, and established carbon-neutrality target dates far in the future with only modest short-term goals. However, in response to the United States announcing its intention to withdraw from the Paris Climate agreement, over 300 universities signed the 'We Are Still In' pledge alongside cities, states, and corporations to galvanize enough action at the local level to still

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Nomenclature

Abbreviations

AASHE	Association for the Advancement of Sustainability in Higher Education
AC	Alternating current
ACUPCC	American College & University Presidents' Climate Commitment
AHU	Air handling units
BAS	Building automation system
BAU	Business as usual
Capex	Capital expenditures
CF	Capacity factor
C_p	Specific heat
DC	Direct current
DDC	Direct digital control
EEMs	Energy efficiency measures
ERS	Emission reduction strategies
E_t	Total energy savings
EV	Electric vehicle
FC_0	Upfront capex
FC_n	Annual cost savings
F_{oa}	Fraction outdoor air
GHG	Greenhouse Gas
HP	Heat pump
HP_t	Sum of supply and return fan horsepower
HVAC	Heating, ventilation, and air conditioning
ICE	Internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
ISO	Independent System Operator
ITC	Investment tax credit
kWh	Kilowatt-hour
LCC	Lifecycle costs
LED	Light emitting diode
MSRP	Manufacturer's suggested retail price
$MTCO_2e$	Metric ton of carbon dioxide equivalent
MWh	Megawatt-hour
N_l	Number of lamps
Opex	Operating expenditures
PJM	Pennsylvania, Jersey, and Maryland
PPA	Power purchase agreement
PV	Photovoltaic
Q_{sens}	Sensible energy
q	Airflow
r	Discount rate
RECs	Renewable energy certificates
RTO	Regional transmission organization
SCC	Social cost of carbon
SP	Static pressure
STARS	Sustainability Tracking, Assessment & Rating System
T_{ex}	Exhaust air temperature
T_{oa}	Outdoor air temperature
T_{ma}	Mixed air temperature
TMY3	Typical meteorological year, 3rd edition
T_{sa}	Supply air temperature
T_{ra}	Return air temperature
UD	University of Dayton
VAV	Variable-air-volume
V_{sa}	Volume flow rate of supply air
ΔW	Difference in wattage
Δt	Difference in time
ε	Heat exchanger effectiveness
η	Unit efficiency
μ	Unit average load
ρ	Density

achieve the United States' intended nationally determined contribution of a 26–28% reduction in GHG emissions below 2005 levels by 2025 [7]. This renewed call for immediate action has spurred more institutions, including UD, to analyze the technical, economic, and logistical feasibility of moving up their climate targets to accelerate their transition to carbon-neutrality.

As with any university exploring carbon-neutrality, it is important to understand the campus' unique challenges and advantages. UD faces various challenges of scale, with over 11,000 students, energy intense scientific research buildings (which are typically 55–115% more energy intensive than administrative campus buildings [8,9]), and most buildings 50+ years old that were designed under less stringent energy codes with now outdated heating, ventilation, and air conditioning (HVAC) systems. Also, Dayton's climate drives high winter heating loads and high summer cooling loads. These loads largely drive UD's annual natural gas consumption (around 365,000 MMBtu per year), electricity consumption (around 87,000 MWh per year), and corresponding scope 1 and 2 GHG emission breakdown, as seen in Fig. 1. On the other hand, UD has the advantage of proximity to a shallow and rapidly-replenishing aquifer, along with environmental regulations that would permit an open-loop geothermal heat pump (HP) system. Understanding UD's local context helped to form the four primary emission reduction strategies (ERS) that collectively constitute the scenario presented here for achieving carbon-neutrality: scale-able energy efficiency, electrified campus fleet, electrified geothermal heat pumps, and on- and off-site renewable electricity.

Due to concerns about the additionality of some approaches commonly used by universities, including the purchase of unbundled Renewable Energy Certificates (RECs) and carbon offsets, the approach analyzed in this study considers a complete transition from fossil fuels to a fully-electrified campus powered by new-build renewable generation facilities. The boundaries of this study include all scope 1 (direct emissions from owned sources – e.g. natural gas combustion and campus fleet) and scope 2 (indirect emissions from purchased energy – e.g. purchased electricity) emissions. Scope 3 emissions (all indirect emissions not included in scope 2 – e.g. commuting, waste, purchased goods and services) will be considered in the future, but are not part of this study.

Review of the scientific literature on the techno-economic implications of carbon-neutral campus energy systems as defined here (i.e., without unbundled RECs or offsets) reveals a limited amount of studies. The most relevant study is by Wiryadinata, Morejohn, and Kornbluth at the University of California, Davis, who examined three pathways to eliminating fossil fuels in their energy systems: biomass-based, electrification with storage, and a combination of both [10]. They found that the biomass-based system could have a lower lifecycle cost (LCC)

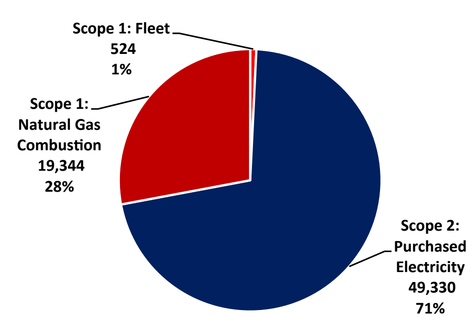

Fig. 1. University of Dayton's Fiscal Year 2017/18 Scope 1 & 2 GHG Emissions ($MTCO_2e$).

than business as usual, while the biomass-electrification combination and electrification with storage pathways incurred higher LCCs. However, it is important to note the higher costs embedded in their analysis are due to the authors' stipulation that the supply of renewable energy needed to match the campus demand profile (rather than simply meeting annual demand), and due to the roughly 75% higher electric rates in California compared to Ohio [11].

Two other studies related to carbon-neutral universities are also of note. Baitule and Sudhakar examined the feasibility of implementing a 5 MW solar PV system at Maulana Azad National Institute of Technology in India to cover all campus electric loads [12]. Without campus heating loads, this analysis did not have to deal with the complexity of fuel switching from natural gas to geothermal heat pumps and focused solely on the techno-economic assessment of a large campus solar PV system. Opel et al. analyzed the Leuphana University of Lueneberg's efforts to attain net climate-neutrality by becoming a net exporter of renewable electricity produced by their biomethane combined heat and power system [13].

The present paper seeks to add to the limited literature by providing an economic analysis of transitioning UD's campus energy systems to a fully-electrified, renewable powered, and carbon-neutral campus. In the section entitled "Additionality in the carbon-neutral context," additionality in the context of a carbon-neutral campus is explored while explaining the motivation for eliminating the purchase of unbundled RECs or carbon offsets as potential solutions. In the section entitled "Methodology," the methodology in determining the impact of each ERS is outlined, as well as the economic inputs for the LCC analysis. In the section entitled "Results," the overall LCC results of a fully-electrified and carbon-neutral campus will be compared to BAU. Finally, in the section entitled "Conclusion & Discussion," the implications of this study and its limitations are discussed.

Additionality in the carbon-neutral context

Some institutions have already become recognized leaders in their pursuit of carbon-neutrality, employing many different strategies. While various strategies are technically recognized as equal in the accounting methods promulgated by authorities such as the U.S. Federal Trade Commission, Second Nature, and the Association for the Advancement of Sustainability in Higher Education's (AASHE) Sustainability Tracking, Assessment & Rating System (STARS), it is important to consider the different climate impacts of these strategies. A question of particular interest is whether actions a campus takes to reduce its emissions inventory actually lead to a reduction in the total amount of GHGs entering the climate system: that is, are the reductions additional?

Out of over 400 institutions reporting to AASHE's STARS, as of October 2019 only two universities – American University (U.S. doctoral) and Thompson Rivers University (Canadian masters) – reported 100% of their building energy coming from renewable sources, thus having rights to claim carbon-neutral campus energy systems. These two campuses took different approaches to carbon-neutrality: Thompson Rivers directly purchases 100% renewable power through a green energy retailer and utilizes 100% renewable, landfill-based, natural gas; whereas half of American University's renewable electricity claims result from their purchase of unbundled RECs and *all* of their natural gas usage is offset through carbon offsets. Many other universities have made progress towards carbon-neutrality, using both direct and indirect approaches.

These different strategies will not only have different climate impacts but also different long-term implications for fossil fuel infrastructure. Thus, two fundamental questions about claiming carbon-neutrality arise: whether unbundled and bundled RECs should be differentiated when claiming renewable energy generation, and whether purchasing carbon offsets for campus fossil fuel combustion should be considered equivalent to switching to a renewably powered energy system.

Unbundled RECs

Due to the nature of the electricity grid, it is not possible to trace the physical flow of electrical power from a particular generation facility to a particular load (such as a campus). Thus, to enable end users to procure and make legitimate claims about the use of renewable electricity, the US Environmental Protection Agency (EPA) developed the concept of Renewable Energy Certificates, or RECs, where 1 REC is created for every 1 megawatt-hour (MWh) of renewable electricity generated. The RECs mechanism was developed with the intention of spurring growth in the market of renewable electricity generation. In principle, as demand for renewable electricity increases, the price of RECs should rise, and there will be more incentive to develop new renewable electricity generation facilities. RECs can either be purchased along with the renewable electricity, in which case they are referred to as "bundled," or they can be sold separately from the electricity as "unbundled" RECs.

Unfortunately, the market for RECs is not yet fully functioning as intended in all parts of the country. In regions of the country (e.g., the Northeastern U.S.) that have effective regulations (such as Renewable Portfolio Standards) requiring utilities to source a significant fraction of their electricity from renewables, the compliance markets work relatively well, and the prices of RECs have risen to a point where they effectively stimulate new generation to meet the demand. However, in regions such as Ohio where there are not similarly effective regulations ("voluntary" markets), there is little demand for RECs. Worse yet, in regions like the Midwestern US with good wind resources and voluntary markets, large wind farms are economically attractive to build (especially when factoring in the federal Production Tax Credit) even without the sale of RECs. In these areas with low demand for RECs, the prices are quite low and consequently are not effective in stimulating the market for renewable electricity. A detailed study that included extensive interviews with market participants concluded that unbundled RECs do not actually lead to the development of new renewable electricity generation [14]. If the purchase of unbundled RECs does not stimulate new renewable generation, then it is far from clear that it leads to additional GHG reductions.

There is, however, another mechanism for end users not only to claim that they are using renewable electricity, but also to be confident that their actions lead to additional decreases in GHG emissions: a Power Purchase Agreement (PPA) "bundled" with its corresponding RECs from a new (additional) renewable energy generation facility. A PPA contract with a new build, where the end user purchases a specific fraction of the renewable generator output at a fixed price per MWh independent of time of day or day of year, has a much clearer climate impact because new projects generally cannot obtain the financing necessary to build out the renewable facility until they can show financiers that they have a sufficient income stream to service the loan. As an end user, entering into a PPA with a new build can be the action that makes the project actually come online because, given the uncertain nature of the electricity market, the best way to demonstrate a sufficient income stream is to identify "offtakers" who have agreed to purchase the electricity from the facility for an extended period of time (typically 15–25 years).

Many universities, including Boston University and Ohio State University, have taken this route, as have large corporations. PPAs can include financial delivery of power through an Independent System Operator (ISO) or Regional Transmission Organization (RTO), or they can be "virtual" agreements involving a contract for differences, where the project developer sells the power on the wholesale market and settles with the PPA customer on the difference between the agreed-upon contract price and the actual market price. Regardless of the structure, the purchaser receives the RECs for accounting purposes, and can make unambiguous claims to have caused additional reductions in GHG emissions.

For a university such as UD that is looking to ensure that its actions lead to a clearly identifiable and additional climate impact, a bundled PPA with a new renewable electricity generation facility appears to be a more effective strategy to address the emissions from purchased electricity than unbundled RECs. Thus, the authors recommend universities procure renewable energy through a bundled renewable PPA, and the following research focuses on its cost-effectiveness.

Carbon offsets

Most universities also have a large portion of its GHG emissions from on-site fossil fuel combustion that are not straightforward to eliminate through changes in procurement strategies like PPAs. As an alternative to difficult and expensive capital projects to eliminate such emissions, many campuses purchase carbon offsets. In principle, the purchase of carbon offsets funds a project that leads to a reduction in GHG emissions which counterbalances the campus's emissions.

The challenge with using carbon offsets to achieve carbon-neutrality is ensuring that the offsets truly lead to additional reductions that would not have occurred if the offsets were not purchased. A number of verification and certification programs have emerged for carbon offsets that attempt to ensure that offsets are real, traceable, permanent, not double-counted, and additional [15]. However, given the wide variety of offset projects and certification programs that are available today, it can be challenging for a campus to be confident that the purchase of offsets makes the sought-after impact.

Indeed, even the term *additionality* is subject to different interpretations. Carbon offset verification programs, in the laudable interest of being objective and quantitative, have developed highly technical methodologies to define whether a particular project is additional. However, carbon offset projects are accepted by these programs in cases where they represent "best in class" performance even when the projects would have been conducted in the absence of the revenue from the sale of offsets. In such cases, the projects might be considered *relatively* additional, in that they go above and beyond what is legally required; but they cannot be considered *absolutely* additional in the sense that the project would not have occurred without at least the expectation of the revenue from selling offsets.

Thus, even though the advancement of certified carbon offset programs has helped to alleviate some of the concerns about the credibility of offset projects, the largely unregulated market still presents challenges in tracing a dollar spent to the emissions offset and ensuring the climate impact claimed is realized. For these reasons certain administrative bodies such as the Science Based Targets initiative do not recognize carbon offsets when achieving GHG reduction goals [16].

Another concern with the use of carbon offsets is that they do not address the systemic dependence on fossil fuels, and this reliance may create long-term negative ramifications. By definition, carbon offsets are purchased as a response to an institution's spending on carbon-emitting activities. Worsham and Brecha explain how these purchases serve to reinforce the techno-institutional mechanisms that support fossil fuel-based economies, lock in fossil fuel infrastructure, and lock out lower-carbon alternatives [17]. As an alternative to the purchase of carbon offsets, universities like UD have an opportunity to invest in renewably powered energy systems on their own campus and in their own communities. This can be seen as an indirect investment in the technical competencies that vendors, contractors, and university staff will need to compete in a low-carbon economy, and a direct investment in the university's ability to use its campus as a lab for experiential learning. Furthermore, it clearly demonstrates that the university is taking a leadership role in addressing the climate crisis and charting a pathway to global carbon-neutrality.

Thus, given these concerns, this paper does not consider carbon offsets as an effective strategy in reducing emissions and will instead focus on the cost-effectiveness of transitioning from campus fossil fuel combustion to a renewably powered and electrified campus.

Table 1
Emission reduction strategies by scope and category.

GHG Emission Scope	Emission Reduction Strategy
Scope 1 & 2	Building Energy Efficiency
	Lighting
	AHU fan controls
	AHU outdoor air conditioning
	Thermostat controls
Scope 1	Fleet
	Electric Vehicles
	Fuel Switching
	Geothermal HP
Scope 2	Renewable Energy
	On-campus Lrg. Rooftop PV
	On-campus Parking PV
	On-campus Res. Rooftop PV
	Off-campus RE PPA

Methodology

A university can employ many measures to reduce their GHG emissions in pursuit of carbon-neutrality. For this paper, ERSes were limited to projects that already had been implemented on other campuses and that Facilities Management or contractors could realistically implement by 2025. Each ERS was categorized by emission – scope 1 or 2 – and technology – building energy efficiency, fleet conversion to electric vehicles (EVs), fuel switching to electrification through geothermal HPs, and renewable generation energy – as seen in Table 1.

For each ERS, two primary metrics were determined: total emission reduction potential and difference in net present lifecycle cost (LCC) from BAU over their lifespan. Net present LCCs were calculated using Eq. (1):

$$LCC = \frac{FC_0}{(1+r)^{t_0}} - \frac{FC_1}{(1+r)^{t_1}} - \frac{FC_2}{(1+r)^{t_2}} - \cdots - \frac{FC_n}{(1+r)^{t_n}} \tag{1}$$

where FC_0 is upfront capital expenditures (capex) in year 0, FC_n is annual cost savings from BAU in year n, r is the discount rate, and t is the year.

Lifecycle costs are highly sensitive to assumptions and parameters. For a carbon-neutrality analysis, the most sensitive inputs are the current and future rates of electricity and natural gas, discount rate, and lifespan of the project. In this analysis, future rates were calculated by applying an electricity escalation rate of 1.3% per year, based on conversations with UD's market advisor, and a natural gas escalation rate of 2.45% per year, based on 10-year Henry Hub natural gas futures pricing [18], to UD's 2019 electric and natural gas rates. A discount rate of 4% and a lifespan of 30 years were chosen since they are currently used for long-term campus construction and infrastructure projects. These parameters appear to be conservative, in the sense that they are likely to make BAU more economically attractive than the carbon-neutral pathway.

The two primary varying inputs in calculating the LCC – upfront cost and annual energy cost savings – encompass the majority of this analysis. The methodology in determining those two values and the associated emission reductions varied by ERS, each of which will now be outlined.

Scope 1 & 2: building energy efficiency

In U.S. commercial buildings, the largest typical energy users are heating and cooling (34%), ventilation (10%), and lighting (10%) [19]. In buildings without refrigeration or cooking appliances, as in many campus buildings, these services make up an even larger share. This held true during energy audits of UD campus buildings, as the largest energy efficiency opportunities with high economic returns were observed in lighting upgrades, pre-conditioning outdoor air in air handling units (AHU), AHU fan controls, and thermostat controls. This methodology details the steps taken to calculate first the total campus-wide potential energy and emission reductions from these energy efficiency measures (EEMs), and second the capex and annual energy cost savings inputs for Eq. (1) to calculate their LCC.

Lighting

Lighting energy can be reduced by replacing old lamps with more energy efficient light emitting diode (LED) lamps and installing occupancy sensors to reduce run time. To calculate lighting's total energy and emission reduction potential on campus, lighting audits were completed in over 90% of the campus building square footage to count and categorize lights by type and location, as seen in Table 2. Operating hours in each location were estimated from light loggers placed in typical locations over a two-week interval. Thus, total annual proposed energy savings, E_t, for each lamp in each location was calculated using Eq. (2):

$$E_t = N_l \times \Delta W \times \Delta t \times 8760 \quad (2)$$

where N_l is the number of lamps, ΔW is the difference in wattage between fluorescents and their equivalent LEDs and Δt is the reduction in operating time using occupancy sensors. The totals were then scaled up to the remaining 10% of building area by assuming constant energy savings potential.

LED lighting upgrades are a popular EEM due to their high economic returns and significant reduction in energy. To calculate UD's specific lighting LCC, the overall capex input and 10-year lifespan were based on recently verified campus projects. The costs per lamp were based on recent campus projects and broken down by material and labor costs and rebates, as seen in Table 3. Annual cost savings were determined by applying UD's forecasted all-in marginal electric rate ($/kWh) to the total energy savings from LED replacements since both demand and energy would be reduced, and UD's forecasted off-peak $/kWh rate to energy savings from occupancy sensors since savings are more likely to occur during off-peak hours when buildings are less occupied.

Air handling units – pre-conditioning outdoor air

Most campus buildings are conditioned with AHUs. In the cooling season, cold water from a chiller plant is pumped through cooling coils in the AHUs to cool and dehumidify supply air. Likewise, in the heating season, steam heat from a boiler plant is sent to heating coils in the AHUs, variable-air-volume (VAV) boxes, or perimeter heating coils. Two EEMs were assessed to estimate the total potential to reduce this heating and cooling energy use by pre-conditioning outdoor air: identifying and fixing malfunctioning economizers in AHUs with mixed air dampers and adding heat recovery units to 100% outdoor air AHUs.

Functional economizers modulate the exhaust-air damper, mixed-air damper, and outside-air dampers to vary the fraction of outdoor air to minimize cooling and heating energy usage. However, several studies have indicated that economizers consistently fail in the field; failure rates have been reported ranging from 37 to 80% resulting in additional cooling energy of up to 35% [20–23]. To estimate the number of AHU economizers malfunctioning at UD, and the corresponding proposed energy savings from correcting malfunctioning controls, twelve AHUs in five diverse buildings were initially analyzed [24]. Using six months of trended temperature data from the twelve AHUs, their hourly fraction outdoor air, F_{oa}, was calculated using Eq. (3):

$$F_{oa} = \frac{T_{ma} - T_{ra}}{T_{oa} - T_{ra}} \quad (3)$$

where T_{ra} is the return air temperature, T_{oa} the outdoor air temperature, and T_{ma} the mixed air temperature. The calculated F_{oa} was then compared to the optimal fraction outdoor air, $F_{oa,ideal}$, calculated using Eq. (4):

$$\begin{aligned} &\text{if } T_{oa} > T_{ra}\ then && F_{oa,ideal} = F_{oa,min} \\ &\text{Else if } T_{ra} > T_{oa} > T_{sa}\ then && F_{oa,ideal} = 1 \\ &\text{Else if } T_{oa} < T_{sa}\ then && F_{oa,ideal} = \frac{T_{sa} - T_{ra}}{T_{oa} - T_{ra}} \end{aligned} \quad (4)$$

where the supply air temperature, T_{sa}, is equal to T_{ma} when T_{oa} is less than T_{sa}, the $F_{oa,ideal}$ is 100% outdoor air when it is between T_{ra} and T_{sa}, and $F_{oa,ideal}$ is the minimum allowable F_{oa}, $F_{oa,min}$, at outdoor air temperatures above T_{ra}. Plotting F_{oa} and $F_{oa,ideal}$ versus T_{oa} identified that all twelve AHUs were malfunctioning to some degree. Thus, the potential sensible cooling energy savings, $Q_{sens,c}$, from correcting the control algorithm was estimated when F_{oa} was outside of a reasonable control band of ± 5% using Eq. (5):

$$Q_{sens,c} = V_{sa} \times \rho \times c_p \times (T_{ma} - T_{sa}) \quad (5)$$

where V_{sa} is the volume flow rate of supply air, ρ and c_p are the density and specific heat of air, T_{sa} is the supply air temperature and T_{ma} is the mixed air temperature. Across all twelve AHUs, average cooling savings from correcting these economizer malfunctions were calculated at 17% [24]. These results were scaled up to calculate the entire campus potential by applying 17% savings to annual campus chiller electrical usage serving economizer-based AHUs, provided by the MEP Associates analysis discussed in Section "Scope 1: on-site thermal combustion to open-loop geothermal heat pump." Since heating savings were not calculated in the case study since it occurred during the cooling season, heating savings were conservatively estimated at 5% based on available literature and applied to annual heating usage in all campus economizer-based AHUs [25–27].

In addition, in 100% outdoor air AHUs, cooling and heating energy savings can be realized from retrofitting these units with heat recovery units. The energy savings in retrofitting the four largest airflow exhaust systems from lab space and fume hoods whose exhaust systems were near the supply air duct were analyzed. Using hourly typical meteorological year (TMY3) temperature data for Dayton, OH, the annual cooling savings, when T_{oa} is greater than exhaust temperature, T_{ex}, and heating savings, when T_{oa} is less than T_{ex}, was calculated using Eq. (6):

$$Q_{savings} = \sum_0^{8760} \varepsilon \times V_{ex} \times \gamma \times \rho \times c_p \times |(T_{oa} - T_{ex})| \quad (6)$$

where ε is the heat exchanger effectiveness (50%), V_{ex} is the design exhaust airflow (ft^3/h), γ is the assumed percentage of exhaust air to design exhaust (75%), ρ is the density of air (lb/ft^3), c_p is the specific heat of air (Btu/lb-F), T_{oa} is outdoor air temperature, and T_{ex} is exhaust air temperature (70 °F). Then, the realized cooling and heating energy savings were calculated by dividing by the chiller plant efficiency for cooling savings and steam combustion and distribution efficiency for heating savings.

These heating and cooling savings were then converted to the appropriate units to determine the annual cooling and heating cost savings and GHG savings. Annual energy cost savings were determined by

Table 2
Lights categorized by lighting type and location.

	Lighting Counts				Lighting Operating Time	
	4′ T8 Tube	2′ T8 Tube	2′ T8 U-Bend	Plug-in CFL	Without Sensors	With Sensors
Lobby/Study Areas	5,103	101	439	983	80%	70%
Halls/Stairwells	6,222	534	554	1,240	100%	70%
Offices	7,510	98	0	111	33%	27%
Classrooms	7,914	416	50	199	40%	35%
Dorm Rooms	2,246	1,718	0	216	30%	30%
Dining Halls	174	0	0	159	70%	70%
Mech. Rooms	2,799	0	0	18	100%	68%
Restrooms	1,241	48	0	1,295	90%	10%
Total	33,209	2,915	1,043	4,221		

Table 3
Lighting energy and economic details.

	Wattage	Material Costs	Labor Costs	Rebates	
		per item	per item	per item	per connected Watt
4′ LED T8	11.5	$7.5	$28.1	$1.5	n/a
2′ LED T8	9	$8.5	$28.1	$1.5	n/a
2′ LED U-Bend	17	$16.0	$28.1	$1.5	n/a
PL-LED	11	$11.0	$28.1	$3.0	n/a
Occ Sensors	n/a	$50.0	$43.0	n/a	$0.04

applying the all-in marginal electricity rates ($/kWh) and marginal natural gas rate ($/MMBtu). The capex for identifying and fixing economizer controls in all 130 applicable AHUs was estimated from a material and labor $/AHU quote from a similar recent campus project. The capex for the heat recovery units was separately estimated based on an economic study of run around heat recovery units [28]. The savings were assumed constant across the LCC 30-year lifespan.

Air handling units - fan controls

Most UD campus buildings employ VAV systems for heating, cooling and ventilation. In these systems, AHUs push air to zone VAV boxes where dampers modulate airflow. Two avenues to reduce AHU fan energy usage were explored: properly scheduling AHUs off during unoccupied periods and reducing static pressure (SP) in over-pressurized ducts. While simple, in many retro-commissioning projects identifying incorrectly scheduled or unscheduled AHUs leads to large savings with small upfront cost [29]. During the same UD AHU study previously mentioned, properly scheduling AHUs during unoccupied periods resulted in an average fan energy savings of 35% [24]. To identify the total potential of AHU fan energy savings from properly scheduling all units, an audit of all AHU schedules in the building automation system (BAS) was completed. Out of 136 AHUs audited, 50 (37%) were identified with incorrect schedules. For these units, proposed energy savings from properly scheduling the units was calculated using Eq. (7):

$$E_t = \frac{HP_t \times 0.746\frac{\text{kW}}{\text{HP}} \times \mu \times \Delta t \times Y}{\eta} \tag{7}$$

where E_t is total annual energy savings (kWh), HP_t is the sum of supply and return fan horsepower, μ is the estimated average load of the unit during operation, Δt is the difference in scheduled operating hours, Y is the increase in fan energy from increasing to zone temperatures during initial start-up, and η is the efficiency of the fan.

The second AHU fan EEM explored was implementing SP reset controls on all AHUs with supply fans of 10 horsepower or greater. AHU fan power is the product of SP rise across the fan, Δp, and airflow, q, divided by the fan, belt, and motor's collective efficiency, η, as shown in Eq. (8).

$$P = \frac{\Delta p \times q}{\eta} \tag{8}$$

Recent research has reported that resetting SP in response to VAV damper position can lead to savings ranging from 20% to more than 50% [30–34]. Our campus AHU case study identified eleven of the twelve AHUs analyzed as over-pressurized and reported average measured savings of 33% [24]. The total campus energy savings potential was calculated by applying a conservative estimate of 20% savings to the annual fan energy usage of all AHUs with supply fan motors 10 horsepower or greater. Annual usage was calculated using a modified Eq. (7) without Y and annual hours instead of Δt. This was applied to the AHU fan energy usage post-scheduling, so as to not double count savings.

Since both EEMs are controls based, there is little upfront cost in modifying the BAS. Nevertheless, labor costs were based off previous BAS quotes for similar projects. While scheduling requires no material costs, best practices when implementing SP reset algorithms require direct digital control (DDC) VAV dampers networked into the BAS and approximately 25 of the 136 AHUs analyzed were still serving old pneumatically-controlled VAV dampers. Thus, for these units the capital cost of converting VAVs serving the ten most critical zones of each AHU was calculated using a $1200 price tag from previous facilities management projects. Annual electrical savings were then applied to electric rates ($/kWh) for scheduling, since there would be no demand savings, and overall electric rates (both $/kWh and $/kW-mo) for SP reset controls that would realize both energy and demand savings. Savings were projected for 30 years for both EEMs to calculate their LCCs.

Thermostats

The University of Dayton owns nearly 700 residential houses and apartment units, most of which are unoccupied during winter and summer breaks. Typically, the temperature set-points in these units are not set back to their full potential due to humidity concerns or general lack of manpower. This methodology describes the steps taken to calculate the energy, emissions, costs savings, and capex to upgrade to wi-fi connected "smart" thermostats that allow for remote monitoring and controls.

Energy savings from remotely setting back and monitoring thermostat temperatures in these units were estimated using Energy Explorer software [35]. In Energy Explorer, monthly electricity and natural gas usage were regressed against monthly outdoor air temperature to disaggregate energy usage into weather-dependent and weather-independent usage. The three resulting parameters are the change-point temperature (°F), heating slope (MMBtu/°F), and cooling slope (kWh/°F). By setting back the thermostats 8°F over summer and winter breaks, the change-point temperatures also shift 8°F. Energy savings could then be calculated by applying the new change-point temperature with Dayton's TMY3 data.

Annual cost savings were determined by multiplying electric and natural gas savings by their corresponding electric and natural gas residential energy rates. Capex for the nearly 700 smart thermostats was taken from a quote from a local smart thermostat supplier, and local utility rebates for smart thermostats were subtracted.

Scope 1: electric vehicle fleet

While the campus vehicle fleet represents only about 1% of campus emissions, the economic feasibility of converting to EVs was explored because of its high campus visibility, replicability on other campuses, and indicative nature of the broader global climate challenge to transition to EVs. During the past decade the transportation sector surpassed the electric power sector as the largest source of carbon emissions in the US economy [19]. As in all sections, the capex, opex, and lifespans were determined to input into the LCC analysis.

Fuel consumption data was obtained on the 145 internal combustion engine (ICE) vehicles that make up the university's fleet. The first step in determining the capex differential from BAU to convert these to EVs was categorizing by vehicle type and whether they were over-sized or correctly-sized for their operational function, as seen in Table 4. A

Table 4
Campus fleet breakdown by vehicle type and size for operational function.

Use Type	Over-sized	Correctly-sized
Cargo	59	11
Heavy utility	14	4
Light duty	1	1
Light passenger	13	3
Light utility	1	0
Passenger van	9	18
Safety	9	1
Truck	1	0
Total	107	38

Table 5
Upfront costs for replacing ICEs with carbon-neutral fleet.

Service Category	Total	Typical Make & Model	Package	MSRP (pre-tax credit)	Total Upfront Purchase Cost
Oversized Vehicles					
Cargo	59	GEM eL XD	Technician Package - Cool Weather	$ 21,277	$ 1,255,343
Heavy utility	14	GEM eL XD	Construction Package - Cool Weather	$ 19,984	$ 279,776
Intra-campus	1	EZ GO Freedom Golf Cart - Electric	Base	$ 7,000	$ 7,000
Light passenger	13	GEM e4	Shuttles & Tour Package - Cool Weather	$ 17,966	$ 233,558
Light utility	1	GEM eL XD	Construction Package - Cool Weather	$ 19,984	$ 19,984
Passenger	9	GEM e6	Shuttles & Tour Package - Cool Weather	$ 22,489	$ 202,401
Safety	9	GEM e2	Public Safety Package - Cool Weather	$ 14,283	$ 128,547
Utility cart	1	GEM eL XD	Construction Package - Cool Weather	$ 19,984	$ 19,984
Correctly Sized Vehicles					
Cargo	11	Zenith Electric Cargo Van	Base	$ 46,900	$ 515,900
Heavy utility	4	Chevy Colorado - Diesel engine + $1000 biodiesel conversion	4WD – 2018	$ 29,500	$ 118,000
Intra-campus	1	EZ GO Freedom Golf Cart - Electric	Base	$ 7000	$ 7000
Light passenger	3	Chevy - Bolt EV	Base – 2019	$ 36,620	$ 109,860
Passenger	18	Zenith Electric Passenger Van	Base	$ 46,900	$ 844,200
Safety	1	Jaguar I-PACE	Base – 2019	$ 69,500	$ 69,500
Total	145				$ 3,811,053

vehicle was deemed over-sized if it was found to be a "low-performing" vehicle – if its operational fuel economy was less than 70% of its rated city fuel economy – or a "low-utilization" vehicle – if consuming less than 100 gallons of fuel per year. The rationale for these criteria was as follows: if an ICE vehicle performs significantly (chosen as 30% in this case) below its rated fuel economy, it's reasonable to conclude that it spends a lot of time idling or making very short trips on a cold engine. If the vehicle performs adequately in fuel economy but consumes very little fuel (chosen as 100 gallons in this case), it's reasonable to conclude that it's driven infrequently and is a candidate for elimination through fleet consolidation. This step was essential to properly identify the appropriate replacement EV for each fossil fuel vehicle. For oversized vehicles, an adequate EV replacement was chosen given the desired operational function the vehicle serves. For correctly-sized vehicles, an EV replacement closely resembling its fossil fuel counterpart was chosen, as seen in Table 5. Electric equivalents were found for every vehicle category except for one, of which there are 4 vehicles, where a biodiesel vehicle had to be inserted, as seen in Table 5.

Another important determinant of the capex for an EV conversion was the year the vehicles would be replaced. Vehicle lifetime was assumed to be 10 years, thus once each fossil fuel vehicle reached 10 years (all vehicles 10+ years old replaced in year 1), it was replaced with a new version of a similar make and model in the BAU scenario and replaced with the appropriate EV in the carbon-neutral scenario. The capex for all make and models was determined using manufacturer's suggested retail price (MSRP) 2019 values, as seen in Tables 5 and 6. Additionally, in 2025 all remaining fossil fuel vehicles less than 10 years old were replaced to achieve full campus electrification by 2025.

The second primary capex requirement for an EV fleet is the charging infrastructure. Since most of the campus fleet sits unoccupied overnight and seldom travels off-campus, Level-1 pedestal chargers (120 V, 2–5 miles/hour charging) were assumed adequate. With two outlets per charger, 73 chargers were required to accommodate the fleet. The total cost per charger was estimated to be $2000 assuming they would be located within 50 feet of an electrical service and no major electrical upgrades would be necessary [36].

The net fuel cost savings from switching to an EV fleet were then determined. Under the BAU scenario, future annual fuel usage was assumed to be consistent with the 2017 usage totaled from UD's vehicle fuel transaction database. For simplicity, the thermodynamic work required for the EV fleet was assumed to be the same as the ICE fleet. Thus, the total kWh consumed by the EV fleet was calculated using a unit conversion from gasoline and diesel energy to kWh after applying thermodynamic efficiencies of ICEs (20%) and EVs (80%). Annual EV fuel costs could then be calculated by multiplying the annual kWh usage by the off-peak electricity rate, assuming charging during unoccupied evening hours.

Lastly, maintenance savings were based on referenced average maintenance costs of $112 per year for EVs and $280 per year for ICEs [37]. The second and third fleet generations were conservatively assumed to be EVs under the BAU scenario and thus no additional cost savings were included beyond the first fleet generation for the 30-year LCC.

Scope 1: on-site thermal combustion to open-loop geothermal heat pump

The campus's heating and cooling system, consisting of a central

Table 6
Upfront costs to replace current campus vehicles with a new similar make and model.

Service Category	Total	Typical Make & Model	Package	MSRP (pre-tax credit)	Total Upfront Purchase Cost
Cargo	70	Ford Transit Cargo Van	Base – 2019	$ 32,380	$ 2,266,600
Heavy utility	18	Chevy Silverado Truck	Base – 2019	$ 28,300	$ 509,400
Intra-campus	2	EZ GO Freedom Golf Cart - Gas	Base	$ 7000	$ 14,000
Light passenger	16	Chevy Traverse	Base – 2019	$ 29,930	$ 478,880
Light utility	1	Ford Ranger Pick-up	Base- 2019	$ 24,300	$ 24,300
Passenger	27	Chevy Express 12 Passenger Van	Base – 2019	$ 34,900	$ 942,300
Safety	10	Ford Explorer	Base – 2019	$ 32,365	$ 323,650
Utility cart	1	Club Car Carryall	Base – 2019	$ 6824	$ 6824
TOTAL	145				$ 4,565,954

steam plant for heating with individual chillers per building, posed a unique technical and economic challenge for retrofit to a carbon-neutral system. Given the complexity of the numerous possible retrofit options (i.e., central vs. subcentral district heating and cooling vs. individual building retrofit options), a professional engineering firm (MEP Associates) with extensive experience in converting campuses to geothermal heat pump systems was retained. This section outlines the general methodology used by MEP to identify the energy and emissions reductions, as well as the anticipated capex and opex inputs needed for the LCC analysis.

A site characterization study was first conducted to identify the most viable options of combining an Earth coupling with a suitable HVAC retrofit to a low-temperature heat pump system. Given that UD sits atop a prolific and rapidly recharging aquifer system known as the Great Miami Buried Valley Aquifer, the selected geothermal option was a groundwater-coupled system utilizing this buried aquifer. The conceptual system includes a separately-housed heat exchanger that couples an open groundwater loop sourced by a well field adjacent to the Great Miami River to a closed-loop pipe distribution network of process water. The process water would be pumped from the pump-house through the closed loop system to three central heat pump plants that would distribute hot and chilled water to buildings, in addition to a few outlier stand-alone buildings equipped with individual heat pumps.

Along with the site characterization study, MEP Associates calculated a campus thermal energy load profile to form the basis of design of the geothermal system and the associated implementation costs. Using monthly natural gas data from the previous four years, and a steam plant efficiency of 75% and steam distribution losses of 15%, the usable campus heating energy was determined. This monthly end-use heating usage was then correlated to historical ambient temperature data to derive the campus heating load profile. Similarly, the campus cooling load profile was estimated from monthly building electricity usage in conjunction with estimated quantities of non-cooling electricity usage since building level chillers or direct expansion cooling assets were not metered (UD does not have a central chiller plant).

Examination of the campus load profiles revealed opportunistic use of a central geothermal heat pump system retrofit, owing to load diversity amongst buildings. Of note was the use of steam re-heat of chilled air in summer, allowing for a heat pump system to take advantage of simultaneous heating and cooling loads with little modification of HVAC systems in individual buildings, as seen in Fig. 2. Based on peak diversified load analysis, the required well yields and process water flow rates could be determined, which was the primary factor in sizing the ambient loop branch pipes and number of required groundwater wells. The load profiles also dictated the sizing of the water-to-water heat pumps, distribution piping (hot and chilled water),

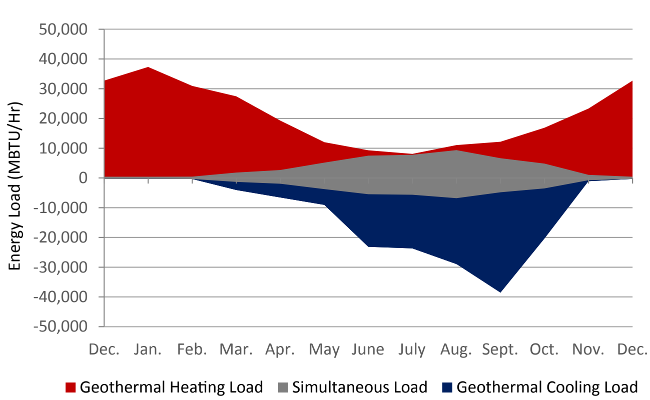

Fig. 2. UD main campus heating and cooling load energy profile.

building conversions, and central plant building conversions.

Using previous geothermal project and campus energy conversion experience, MEP estimated a total capex for all material, installation, and labor. Opex, along with anticipated heat pump replacement costs 15 years after implementation, were also estimated based on MEP's previous experience.

The economic implications of the conversion of smaller natural gas appliances used in kitchens and clothes dryers were not considered, as they are assumed to be negligible in comparison to the thermal energy conversion costs. The analysis does, however, include the generation of domestic hot water by the heat pump system.

Scope 2: electricity generation

On-site generation: solar PV

The horizontal solar irradiance in Dayton, Ohio is 4.05 kWh/m^2/day insolation, which ranks 8th out of 9 U.S. insolation levels created by NREL [38]. Nevertheless, the potential solar collector area of non-shingled campus buildings, south-facing roofs of student housing, and east-west lengthwise parking rows was measured to estimated total on-site solar potential. From this unshaded and unobstructed square footage, the rated capacity in kW that would fit on 65% of this space (due to dimension mismatch and spacing) was estimated using 330 W direct current (DC) 1.68 m^2 panels. Residential systems were sized to generate not more than 80% of each home's typical annual electricity to prevent annual overproduction with potential future energy efficiency upgrades. The alternating current (AC) capacity factor (CF_{AC}) was calculated using a 10° south tilt for flat roofs, 20° south tilt for parking canopies, and 30° tilt for residential south facing roofs plus 14% system losses and a 96% DC-to-AC inverter efficiency [39]. Total energy potential could then be calculated using equation (9):

$$E_t = Rated\ kW\ Capacity \times 8760 \times CF_{AC} \tag{9}$$

The solar PV capex for campus buildings and parking canopies was based on estimates from Melink Corporation, and for residential rooftops from Solar Integrated Resources, both local solar developers with previously installed campus solar PV projects. Large campus building rooftop solar was estimated to cost $1.50/W assuming 500–1000 kW system size, residential costing $3.00/W for 5–20 kW projects, and parking canopies costing $2.40/W for 500–1000 kW projects. Since these quotes did not include the U.S. federal 30% investment tax credit (ITC), the on-site LCCs may be conservative estimates should UD pursue third-party ownership to take advantage of the ITC.

Annual cost savings were calculated based on energy, demand, and Pennsylvania, Jersey, and Maryland (PJM) capacity cost savings. For residential rooftop solar PV, total energy cost savings were simply the annual electricity generated multiplied by the marginal energy rate ($/kWh). For large campus rooftop and solar parking, cost savings included energy as well as demand and PJM capacity cost savings that were determined by multiplying the PV system's rated capacity generating (kW) at peak demand and capacity hours by the demand and capacity charges ($/kW-mo). The generating capacity of the PV system at those hours was calculated using TMY3 and measured hourly building demand. The analysis showed that an average of 26% of the PV system's rated capacity was generating during PJM capacity hours and 31% of its rated capacity was generating during monthly peak demand hours. Total cost savings were then projected for 30 years assuming a 0.50% annual degradation rate to calculate the LCC [40,41].

Off-site generation: renewable power purchase agreement

This study investigated the economic implications of both physical and virtual new build renewable energy PPAs with bundled RECs. In a physical PPA, the end user must be in the same RTO or ISO market as the developer for the end user to receive a credit each hour for the power added by the renewable generator. Depending on the load shape of the generator and the end user's demand, in a given hour the end user can, if necessary, import and pay for additional power from the grid, or if the project generation exceeds the end user's needs the user can sell the balance of power on the real-time market. A virtual PPA, on the other hand, can be inside or outside the end user's RTO because it is solely a financial transaction between the end user, guaranteeing a price per MWh generated and the developer, who sells the generated output on the local wholesale power market. Because of this flexibility and simplicity, a virtual PPA was chosen for this analysis.

Evaluating the LCC of a virtual PPA is challenging, as it depends on market conditions at the time of the agreement, and cannot be estimated confidently without actually seeking bids. Thus, the actual life cycle cost of a PPA might end up being positive or negative, depending on the terms and realized future market conditions. Furthermore, there is little publicly available information, outside of Level Ten Energy's general pricing index, about the pricing and long-term economic implications of PPAs because it is a competitive market and there are no requirements to disclose pricing of contracts [42]. However, recent experiences of other universities presenting at the 2018 AASHE conference [43,44] indicated that UD's load, about 80,000 MWh annually, would position UD well for a competitive bid. Further conversations with industry experts (Edison Energy, Renewables Advisory, private communication) in late 2018 suggested that the un-discounted LCC for a 15-year 80,000 MWh wind contract in Ohio's PJM RTO market would most likely be between +6 M and −$1 M. For the purposes of this analysis, a cost of $2 million was adopted. This $2 million loss was assumed to be evenly distributed over its 15 year period to estimate a discounted LCC. The total carbon-neutral PPA's LCC was then calculated by scaling up to the actual annual energy usage after the anticipated reduction in electricity from EEMs and additional electricity from geothermal HPs.

Results

To determine the most cost-effective pathway to a carbon-neutral, fully-electrified campus, the discounted LCC of each ERS was divided by its lifecycle emission reduction to better compare the relative economic impact between and within each of the four categories: EV fleet, energy efficiency, fuel switching to geothermal HPs, and renewable electricity. This metric can also be contextualized in reference to carbon offset pricing, which range from $0.50-$50/metric ton of CO_2 equivalent ($MTCO_2e$) depending on project type, location, and third-party certification [45]. The inter-category comparison indicates that an EV fleet and energy efficiency generate cost savings over their lifespans, while geothermal HPs and renewable energy systems have cost premiums over their lifespans, as shown in Fig. 3. An EV fleet has the most LCC savings per emission reduction, at $392/$MTCO_2e$, largely due to downsizing to appropriately-sized EVs from over-sized gasoline vehicles and utilizing low off-peak electricity rates during charging. The conversion to geothermal HPs carries a LCC premium of $31/$MTCO_2e$ relative to our BAU natural-gas-fired steam boiler system. However, this premium is very sensitive to the future price of natural gas; if UD's natural gas contract price from even two years ago was adopted as the base year price rather than today's historically low price, the LCC of converting to geothermal HPs would approximately break-even with BAU.

The intra-category comparisons in Fig. 3 show that while all EEMs save money over their lifetimes, the controls-based EEMs have greater economic returns per emissions reduction (LCC savings of $52-$61/$MTCO_2e$) than a material upgrade like lighting (LCC savings of $34/$MTCO_2e$). It also shows that an off-campus renewable PPA, at a LCC premium of $1/$MTCO_2e$, is more cost-effective than on-campus solar PV, whether on large campus rooftops (LCC premium of $14/$MTCO_2e$), residential rooftops (LCC premium of $39/$MTCO_2e$), or parking lots (LCC premium of $65/$MTCO_2e$). This disparity between on-campus and off-campus renewables is likely attributed to the scale differential between on- and off-site projects, in addition to the extremely low electricity rates paid by large universities like UD (around half the Ohio commercial average [11]) and in the state of Ohio (6% lower than US commercial average [11]), since cost savings of on-campus, behind-the-meter, solar PV systems are directly tied to electricity rates.

Guided by the intra-category comparisons, the final carbon-neutral pathway selected for the LCC analysis includes a fully-electrified fleet, all EEMs, fuel switching to geothermal HPs, and an off-campus renewable PPA for all remaining electricity. Their overall economic and emission reduction impacts are shown in Figs. 4 and 5. While the EV fleet was the most relative cost-effective ERS, it has the smallest impact in total emission reduction and thus results in a small overall LCC savings. Conversely, an off-campus PPA would reduce the largest share of emissions, by about 73% (Fig. 4 and Table 7), but have a small overall LCC premium of $1.7 million (Fig. 5 and Table 7) since its emissions-relative economic impact is about break-even at $1/$MTCO_2e$. Energy efficiency measures have both a sizable impact on reducing

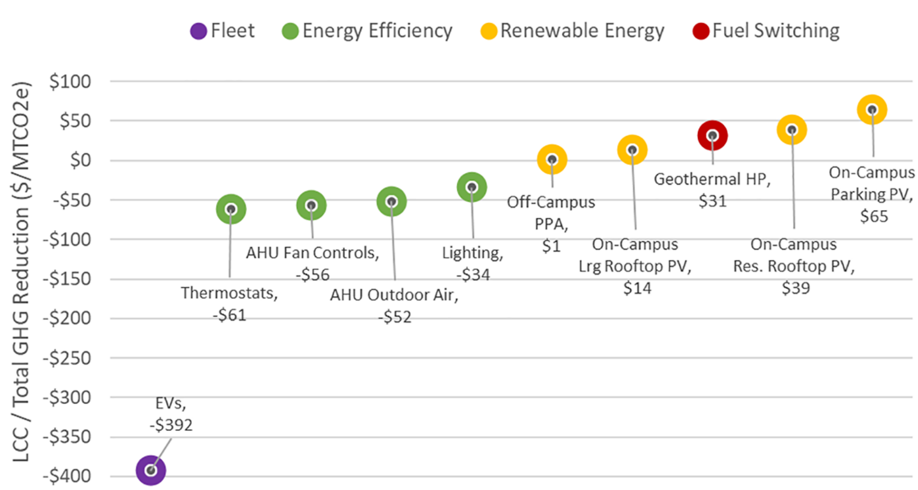

Fig. 3. Intra- and inter-category comparison of the cost-effectiveness of each emission reduction solution.

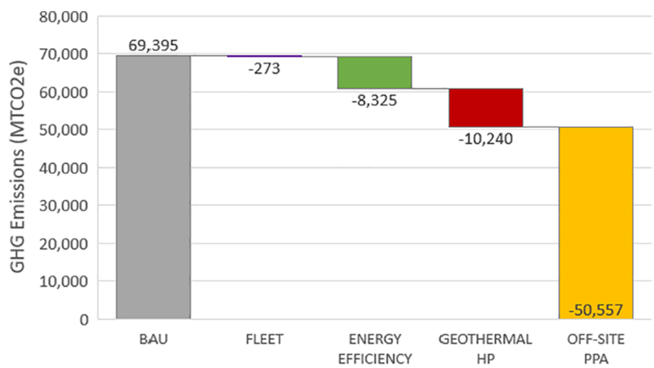

Fig. 4. Carbon-neutral pathway broken down by emission reduction category.

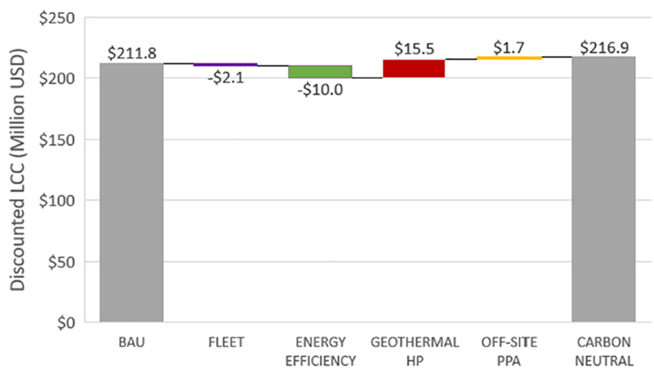

Fig. 5. Carbon-neutral discounted lifecycle costs from BAU broken down by emission reduction category.

emissions, by 12% (Fig. 4 and Table 7), and the largest LCC savings of $10.0 million (Fig. 5 and Table 7). While fuel switching to geothermal HPs has the second largest reduction in emissions at 15%, it also has the highest overall LCC premium of $15.5 million (Fig. 5 and Table 7).

In summary, a fully-electrified, carbon-neutral, campus would have a discounted LCC of $216.9 million, which is a 2.4% increase over the BAU LCC of $211.8 million. This discounted LCC is driven from the cash flow analysis, as seen in Fig. 6, which accounts for BAU delta for all ERS

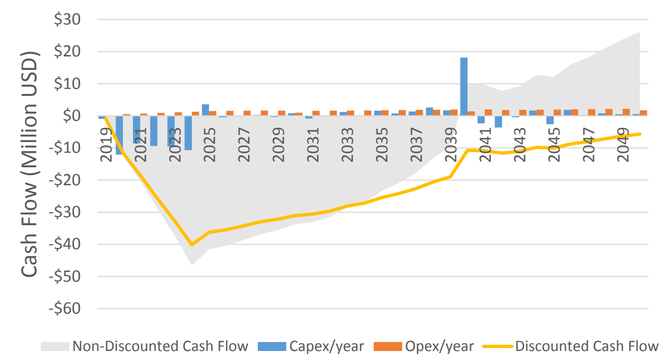

Fig. 6. 30-year cash flow of carbon-neutral, fully-electrified, campus by 2025.

capex and opex over the 30-year lifespan. Achieving carbon-neutrality by 2025 requires high capex in pre-2025 years, primarily for geothermal HPs, with savings spread out fairly evenly for post-2025 years. The high capex savings estimated in 2040 stem from not having to replace chillers, and capex requirements in the following years stem from geothermal HP replacements. Fig. 6 also helps to visualize the signifcant impact of the discount rate, from a $5.1 million discounted LCC loss versus $25.5 million non-discounted LCC savings, due in large part to significant cost savings in later years.

Conclusion & discussion

Transitioning to a fully-electrified and renewably powered campus by 2025 would increase UD's energy related 30-year LCC by only 2.4% over BAU. The $5.1 million LCC increase results from EV fleet savings of $2.1 million that reduces GHG emissions by 0.4%, energy efficiency LCC savings of $10.0 million that reduces GHG emissions by 12%, an off-site PPA increasing the LCC by $1.7 million that reduces emissions by 73%, and switching from natural gas steam boilers to geothermal HPs that increases the LCC by $15.5 million and reduces GHG emissions by 15%. While geothermal HPs have a large negative economic impact, they are essential to achieve full electrification and eliminate on-campus natural gas combustion.

In the authors' view, this $5.1 million cost premium is a small price to pay when contextualized against the negative externalities imposed by GHG emissions and other economic advantages of electrification and

Table 7
Energy reduction, emission reduction, and economics of each emission reduction solution.

Emission Reduction Solution	Annual Energy Reduction			Annual Emission Reduction		Upfront Cost		Discounted LCC	
	Gasoline	Electric	Nat Gas	Total		Relative	Total	Relative	Total
	gal	GWh	MMBtu	$MTCO_2e$	%	$/$MTCO_2e$	$	$/$MTCO_2e$	$
Building Energy Efficiency									
Lighting[1]	0	4.7	0	2,672	3.9%	$273	$728,191	−$34	−$1,423,199
AHU Fan Controls[1]	0	4.8	0	2,752	4.0%	$174	$480,246	−$56	−$4,053,258
AHU Outdoor Air[1]	0	1.4	27,739	2,262	3.3%	$211	$166,719	−$52	−$3,384,553
Thermostat controls[1]	0	0.4	7,546	639	0.9%	$43	$10,357	−$61	−$1,117,323
Fleet									
Electric Vehicles[1,2]	58,847	−0.4	0	273	0.4%	−$1,172	−$613,901	−$392	−$2,054,977
Fuel Switching									
Geothermal HP[1,2]	0	−13.1	332,982	10,240	14.8%	$1,082	$19,110,674	$31	$15,505,447
Renewable Energy									
On-campus Lrg. Rooftop PV	0	8.5	0	4,819	7.0%	$2,187	$10,536,135	$14	$1,627,516
On-campus Parking PV	0	7.4	0	4,197	6.1%	$3,635	$15,254,617	$65	$7,024,058
On-campus Res. Rooftop PV	0	0.9	0	515	0.7%	$4,487	$2,312,637	$39	$524,556
Off-campus RE PPA[1, 3]	0	0.0	0	50,557	73.1%	$0	$0	$1	$1,650,629

[1] Selected for carbon-neutral pathway.
[2] Emission reductions are less than current scope 1 emissions due to additional electricity usage prior to sourcing from 100% renewable.
[3] Emission reductions are greater than current scope 2 emissions due to net increase in electricity usage prior to sourcing 100% renewable.

carbon-neutrality. If UD were to internalize the social cost of carbon (SCC) using either the U.S. Interagency Working Group's SCC recommendation ($42/MTCO$_2$e in 2020 at a 3% discount rate) or IPCC SCC to limit global warming to 1.5 °C ($862/MTCO$_2$e in 2030[1]), the BAU would increase by $56 million and $1006 million respectively [1,46]. The economic impact of achieving a fully electric and renewably powered campus also goes beyond the LCC. With fossil fuel pricing, availability, and carbon regulations uncertain, shifting from fossil fuel-based energy systems to fully electric and renewably powered energy systems hedges against these uncertainties and makes the university more resilient.

This study limited its scope to the economic implications of a fully-electrified, carbon-neutral campus, and thus did not include other components central to university planning such as potential logistical barriers and campus disruption, educational advantages, and other potential carbon-neutral pathways. The results were also limited by assumptions of future energy rates and markets and varying levels of uncertainty and sensitivity in each ERS analysis. While a sensitivity analysis on the discount rate and energy rates was not completed due to the difficulty of separating the geothermal HP analysis from the other ERSes, the discount rate and natural gas price required for the geothermal HP LCC to break-even were determined to be 1% and $5.80/MMBtu respectively.

While these results are indicative of the geological, climactic, regulatory, and economic frameworks specific to Dayton, the approach outlined here may serve as a useful case study for other universities and organizations exploring their own transition to an electrified and carbon-neutral future. Further research could advance this work by exploring the economic implications of other carbon-neutral pathways in addition to full electrification, such as fuel switching to biomass steam boilers. Finally, because of the large upfront cost and additional LCC associated with geothermal HPs, further financial considerations, such as rebates and incentives, from policy makers are recommended to cost-effectively fuel switch to geothermal HPs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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