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# Design of a Carbon Recovery System for George Mason University to Meet Net Zero Carbon Pledge

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**Abstract**: Eight hundred eighty American universities, including George Mason University (GMU), committed to achieving net zero carbon emissions by 2050. GMU's CO2 emissions increased from 100,567 mtCO2e in 2016 to 102,891.86 mtCO2e in 2019. GMU's mitigation strategy moves CO2 emissions from Scope 1 to Scope 2. Scope 2 requires the electric-power generation source to be based on renewables. Only 37% of GMU's power generation is currently from renewable sources. Even with an optimistic exponential rate of increase, only 68% of the power will come from renewable sources by 2050. To achieve the 2050 Carbon Zero pledge, GMU needs to recover CO2 from the atmosphere. Three designs were considered to remove 2050 CO2 emissions: A Liquid Direct Air Capture (LDAC) with the current rate of renewables, LDAC with exponential renewables, and Solid DAC with Geothermal power. Geothermal is the best option unless there is an improvement of 79% in the efficiency of LDAC technology.

*Keywords*: Carbon Dioxide (CO2), Carbon Recovery, Carbon Capture, Carbon Emissions, Direct Air Capture (DAC)

## 1. Context Analysis

George Mason University alongside 880+ American universities pledged net zero carbon emissions by 2050. GMU's CO2 emissions rose from 100,567 to 102,891.86 metric tons of CO2 (mtCO2e) from 2016 to 2019. GMU mitigation strategies resulted in moving emissions from Scope 1 to Scope 2. Scope 2 emissions are derived from their power utility. Regional power generation currently has 34% renewables, but even with an exponential increase, only 68% will be renewable by 2050. To meet the pledge, GMU needs to recover 17,923 mtCO2e with current renewables and 11,030 mtCO2e with exponential renewables.

### 1.1 The Energy Balance of Earth

Earth maintains a balance between the amount of incoming solar radiation from the sun and outgoing radiation reflected through the atmosphere. This is called Earth's energy budget. Within our atmosphere Carbon Dioxide molecules absorb and reflect back to Erath, some of the outbound radiation, keeping more energy and heat in the atmosphere and on Earth. The effect of Carbon Dioxide absorbing outgoing thermal radiation is called the greenhouse effect. Carbon Dioxide is removed from the atmosphere by natural processes such as photosynthesis, biodiverse soil, and carbon mineralization. These processes take CO2 out of the atmosphere and mitigate the greenhouse effect to a temperature hospitable for human life.

Human activities on Earth in the last 1000 years have raised the atmospheric CO2 levels to 400 parts per million. This is largely due to the CO2 released from burning fossil fuels to power manmade systems (Statista, 2023). This increase of CO2 in the atmosphere led to an increased greenhouse effect on Earth that has affected the Earth's energy balance. The Earth's surface temperature has risen by an average of 0.14° Fahrenheit per decade since 1880. In 2023 that is a 2° Fahrenheit increase since 1880.

### 1.2 GMU Carbon Zero Pledge

George Mason University signed the Presidents' Climate Commitment in 2007, which enforces Net Zero Carbon emissions by 2050. The commitment is composed of three parts: the pledge, a development of a comprehensive climate action plan, and the submission of an annual evaluation of progress. The Pledge requires Universities and Colleges committing to it to make incremental goals leading to a defined Net zero carbon emission target as soon as possible. The action plan gives a timeline for critical tasks that will ensure the success of the president's climate commitment goals.

George Mason University completed a Climate Action Plan in 2010 and is in the process of creating a new Climate Action Plan. GMU completed its initial campus-community resilience assessment and continues to submit annual progress evaluations yearly. GMU emitted 101,000 mtons CO2 in 2022, this 26% addition in carbon emissions compared to the target of 20% reduced by 2022.

## 1.3 GMU Scopes of Emissions

CO2 emissions are categorized into 3 scopes. These scopes break down and separate individual emissions depending on factors that are both in and out of the universities control. Scope 1 is direct emissions from owned or controlled systems. Scope 2 is indirect emissions from grid electricity. Scope 3 is all other indirect emissions like transportation and waste disposal.

Table 1. University Scope Breakdown

| University Emissions by Scope | | |
|---|---|---|
| Scope | Direct or Indirect | Example |
| 1 | Direct | Vehicle Fleet, Gas Boilers |
| 2 | Indirect | Electricity Purchased from the Grid |
| 3 | Indirect | Air Travel, Commuter Vehicles, Waste Disposal |

George Mason University started tracking carbon emissions through Second Nature (https://secondnature.org/) in 2006 (see Figure 3). An independent analysis was conducted focusing on the square footage of the George Mason Fairfax Campus buildings, the buildings' electricity usage, annual climate averages in the Fairfax area, the buildings' heating/cooling usage, and transportation used by the George Mason community. The results of this independent analysis were used to estimate the annual emissions associated with the three different scopes, which were contrasted with those of the independent analysis provided by Second Nature. This graph also shows that no significant progress has been made to reduce campus emissions even climbing higher than when reports were first being made in 2006. It should be noted that the only drop in emissions was during the 2018-2021 COVID-19 pandemic when George Mason (along with many other schools) began reducing on campus operations. However, after 2021 when the university began slowly resuming normal capacity, emissions have spiked to normal levels.

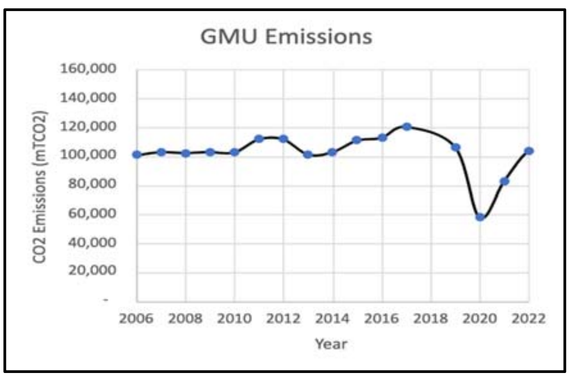


Figure 2. GMU Reported Emissions per Year (SecondNatureInc,2006)

### 1.3.1 GMU Scope 2 Emissions

A database of all main buildings on the Fairfax campus was used to establish the total area per building was given (called usable area). Electricity usage of the lights per building was estimated by averaging the lights per square foot in different spaces of the usable area. It was assumed that the 75-Watt lights would be on 17 hours per day. This revealed the daily kWh. Finally, the average production of CO2 was obtained (0.224kg/kWh) which allowed for the calculation of the $Yearly\ mtCO^2/kWh$.

In addition to lights and appliances, heating and cooling costs were analyzed. Data from the National Weather Service revealed the average daily temperature for the year 2019 (last year secondnature.org published data on $CO^2$ emissions from George Mason University). Heating Degree Days as well as Cooling Degree Days were calculated from the database, depending on whether the average daily temperature fell below or rose above 65°F (United States national average). The difference between the outside and inside temperatures, setting the latter at 72°F, was considered to calculate the amount of Kcal needed to heat or cool the buildings. Those Kcal were later transformed into kWh to find the daily kWh. In this calculation, a good

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insulation coefficient of 1.2 was considered. Similarly, to the electricity usage, the average $CO^2$ production (0.22436710kg/kWh) was applied to calculate the yearly $Yearly\ mtCO^2/kWh$.

### 1.3.2 GMU Scope 3 Emissions

An independent analysis was also conducted to measure GMU's scope 3 emissions which has been summarized in the figure below. Overall, these results show how most emissions originate from commuter students.

Table 2. Total scope 3 emissions in 2023

| Type of Emissions | Total Yearly Emissions (mTons) |
|---|---|
| Cars | 29,842 |
| Busses | 432 |
| International | 5,975 |
| Study Abroad | 3,302 |

Emissions from cars were calculated by multiplying the number of campus users that commute to campus (60% of the total student + staff population) by the average number of days a campus user will be driving to campus (4 days * 36 weeks) by the average kilograms of CO2 emitted per mile by a car (0.25) then dividing by 1000 to convert to mT CO2

Emissions from busses were calculated by taking the same commuting days as cars and multiplying by the average number of miles Mason transportation busses travel a day with the average $CO_2$ emissions made by busses then dividing by 1000 to convert to mT CO2.

Emissions from international students & study abroad were calculated by taking the total number of miles flown by plane to each country (x2 for study abroad students) and multiplying by the average CO2 an international travel plane will emit per mile then finally multiplying by the total number of students studying abroad or on school-sanctioned international travel. Note that two assumptions were made with this model: the CO2 emitted for an international travel plane was cut by 70% to account for the rest of the passengers not associated with GMU being present on the plane. The bus calculations account for study abroad/international travel students commuting back to GMU by bus. These results were used in our independent analysis figure and prove how CO2 emissions

## 1.4 Current Mitigations

Current CO2 mitigation strategies to meet the Presidents' Climate Commitment include LED lighting, electric vehicle adoption, and electric boilers, shifting scope 1 & 3 emissions to scope 2. This does not eliminate emissions produced by these systems but instead sways emissions from direct (Scope 1) to indirect (Scope 2) (Zero Waste Task Force, 2021).

## 1.5 Dominion Power Distribution & Projections for 2050

George Mason has a contract with Dominion Power to provide electricity for George Mason's power consumption. They had 23,359 MW of electricity purchased in Virginia in 2020. This energy is supplied to George Mason via the PJM Interconnection. The bar graph shown is a breakdown of the Natural Resources Converted into electricity by Dominion Virginia Power in the most recent year recorded, 2020.

Table 3. Dominion Energy Breakdown

| Percent of Energy Production | | | |
|---|---|---|---|
| Nonrenewable | | Renewable | |
| Source | Percent | Source | Percent |
| Natural Gas | 43.4 | Nuclear | 17.7 |
| Coal | 27.5 | Hydro | 4.5 |
| Oil | 4.7 | Wind | 1.2 |
| Waste | 0.5 | Solar | 0.6 |

The resources in red show the non-renewable resources that makeup 76% of Dominion Power's energy production. These resources produce CO2 when converted to electricity.

Dominion Power has set its own Net Zero Carbon pledge for 2050. They promise this will be fulfilled by massive solar and wind energy adoption. With 0.6% solar and 1.2% wind energy production in 2020, little progress has so far been made.

An analysis was performed of Dominion Power's projected Carbon intensity of energy production in 2050.

Table 4. Dominion Energy's Renewable Energy Market Penetration

| Rate of Introduction of Renewables | | |
|---|---|---|
| Year | +10% Every Decade (Current) | Exponential Growth |
| 2020 | 31% | 31% |
| 2030 | 34.8% | 41% |
| 2040 | 38.3% | 53.6% |
| 2050 | 42.1% | 68.1% |

Even under optimistic projections by 2050, the energy grid will still be reliant on nonrenewable sources of energy to power GMU's campus.

### 1.6 George Mason University GHG Projections for 2050

A projection of CO2 emissions is shown in Figure 7. Currently, Dominion Energy is introducing renewable energy into the total power market which can be seen as a linear growth. The current linear growth was based on past trends that Dominion has introduced renewables into their power grid. This projection model assumes that more students will be enrolled at GMU at an equal rate and that renewables will continue to penetrate the market at an equal rate. If Dominion Energy were to be more aggressive and drastically improve the state of renewable energy and become less dependent on fossil fuels, the projected GMU emissions would differ slightly (shown as the exponential rate). This exponential rate more closely matches the future goals that Dominion Energy wishes to accomplish with its energy grid by 2050. As shown in Figure 7, due to the increasing number of students attending GMU per year, campus emissions will still continue to climb as activities such as commuter travel, study abroad travel, and electricity needs will increase. Both graphs do not achieve Net Zero emissions by 2050.

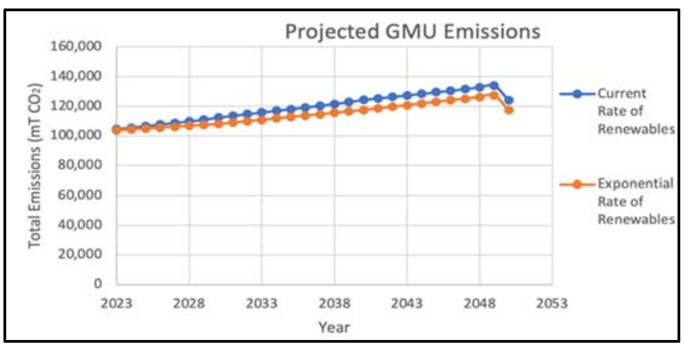


Figure 3. GMU Emissions Through 2050 with Current & Exponential Renewable Rate

### 1.7 Summary

George Mason University made a commitment to have Net Zero Carbon emissions by 2050. GMU uses electricity mostly CO2 producing non-renewable sources from Dominion Power. GMU mitigates emissions by replacing fossil fuel-powered systems with electrically powered systems. With current rates of renewable energy adoption, Dominion Power will not reach net zero CO2 emissions of electricity supplied to the grid by 2050. Even if the energy grid were to go completely renewable, GMU still produces CO2 from scopes 1 & 3 making a need for the campus to remove Carbon Dioxide from the atmosphere to meet the President's Climate Commitment of Net Zero emissions by 2050.

## 2. Performance Gap (AS-IS), Problem and Need Statement

GMU is estimated to have annual CO2 emissions of 106K mT/CO2 produced from all 3 scopes. Efforts to reduce emissions leave a substantial amount of CO2 that must be removed from the atmosphere. The left-over CO2 emissions create a performance gap, which leads to a problem: switching to electric-powered systems shifts scope 1 emissions to scope 2. Due to fossil fuels being required; emitting CO2 into the atmosphere, mitigation strategies are not effective enough to reach the 2050 net zero pledge. Even if renewables were to dominate the energy market today, scopes 1&3 emissions will still prevent the university from achieving its goal as they do not rely on the power grid. As a result, to meet the net zero pledge, CO2 emissions must be taken out of the atmosphere or through ambient air by DAC and storage. It is not possible to achieve net zero emissions without Carbon Recovery.

## 3. Concept of Operations

The Concept of Operations is to remove CO2 from the atmosphere using Direct Air Capture (DAC). In the DAC processes, chemically filled designed contactors are used to repeatedly capture CO2 from the air and release high-purity CO2, which can then be stored or utilized in various ways.

## 4. Requirements

Seventy-two requirements were defined for the Carbon Recovery System. A sample of the project requirements are highlighted below.

- R.1 The system shall provide a net removal of at least 130,000 $mTCO_2$ per year.
- R.2 The system shall operate entirely on property owned by George Mason University.
- R.3 The system shall have an operational availability of at least 95%.
- R.4 The system shall have a safety fail rate of no less than $10^{-6}$ per year.
- R.5 The system shall be operated, maintained, and accessible only to authorized personnel.

## 5. Design

Three designs that meet Net Zero Carbon Dioxide emissions for George Mason University were developed. 1) an LDAC system assuming the current rate of renewables in the energy grid, 2) an LDAC system assuming the more aggressive rate of renewables in the energy grid, and 3) an SDAC system that will be powered by a geothermal plant.

GMU requires over 100,000 mT of CO2 removed per year to reach net zero CO2 emissions. This scale of carbon recovery cannot be met with any natural processes for carbon removal. The CO2 must be directly pulled from the air. Two major methods of Direct Air Capture are Solid and Liquid Direct Air Capture.

### 5.1 Liquid Direct Air Capture System for GMU with Existing & Exponential Rate of Renewable Introduction

Given the existing (shown top) and exponential (shown bottom) rate of renewable energy introduction, the LDAC system modeled fulfilling Net Zero CO2 emissions operates at the following parameters.

Table 5. Proposed System Specifications for LDAC in Current & Exponential Rate of Renewables

| Energy Production | | | LDAC Parameters | | | | Annual Operating Costs | | Carbon Capture Credits | |
|---|---|---|---|---|---|---|---|---|---|---|
| Renewable Energy Production | Metric ton $CO_2$ / kWh | Energy Required (kWh) | Metric tons of CO2 captured | kWh / metric ton $CO_2$ captured | tons of water / $tCO_2$ captured | Additional Emissions ($mTCO_2$) | Cost per kWh | Cost per ton of water | USD per ton of $CO_2$ sequestered | USD per ton of $CO_2$ used |
| 42% | 0.2047 | 189,316,940 | 124,139 | 0.2047 | 5 | 38,755,537 | $0.06 | $7.48 | $180 | $130 |
| 68.11% | 0.1128 | 178,804,839 | 117,246 | 0.2047 | 5 | 20,163,899 | $0.06 | $7.48 | $180 | $130 |

### 5.2 Solid Direct Air Capture System for GMU with Geothermal power plant

Given the existing rate of renewable introduction, the SDAC system modeled fulfilling Net Zero CO2 emissions operates at the following parameters.

Table 6. Proposed SDAC with Geothermal Plant

| Energy Production | | | SDAC Parameters | | | | Annual Operating Costs | | Carbon Capture Credits | |
|---|---|---|---|---|---|---|---|---|---|---|
| Renewable Energy Production | Metric ton $CO_2$ / kWh | Energy Required (kWh) | Metric tons of CO2 captured | kWh / metric ton $CO_2$ captured | tons of water / $tCO_2$ captured | Additional Emissions ($mTCO_2$) | Cost per kWh | Cost per ton of CO2 Captured | USD per ton of $CO_2$ sequestered | USD per ton of $CO_2$ used |
| 42% | 0.2047 | 0 | 124,139 | 0 | 5 | 0 | $0.02 | $8 | $180 | $130 |

## 6. Conclusion

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The requirements needed to build an LDAC and Geothermal SDAC are displayed. LDAC is not carbon negative from the large energy requirements needed, which are satisfied by Geothermal because the thermal energy requirement is fueled by the Earth. However, the capital cost for geothermal is $14M.

In order to build this model, it would require around $100M, however, all use cases for renewable energy suggest that there would be a 312% increase in emissions for linear and current and a 162% increase for exponential. Overall, Liquid Direct Air Capture is not currently feasible due to the amount of energy needed and carbon emitted from this energy. LDAC machines require a significant amount of energy to operate, generating more emissions than the machines can capture which defeats the purpose of the system which is why this design will not be considered.

Despite the steep initial cost of building a geothermal plant to capture ambient emissions, no energy requirement and the carbon-negative status of this system (taking more carbon out than the system produces) is the factor that makes SDAC machines the most viable.

Table 7. Use Case Data

| | Current Rate of Renewables | | Exponential Rate of Renewables | |
|---|---|---|---|---|
| | (Use Case 1) LDAC | (Use Case 3) SDAC (Geothermal) | (Use Case 1) LDAC | (Use Case 3) SDAC (Geothermal) |
| Tons Captured per Year | 124,139 | 124,139 | 102,891 | 102,891 |
| mTon Emitted | 38,286,745 | 0 | 20,163,899 | 0 |
| Land Required (acres) | 10.16 | 4.96 | 11.58 | 4.11 |
| Energy Required (kWh) | 156,912,890 | 49,655,600 | 178,804,839 | 41,156,400 |
| Energy Cost | $9,414,733 | $0 | $10,728,290 | $0 |
| Water Cost | $3,848,432 | $0 | $4,385,352 | $0 |
| Unit Requirement | 1 (Large Plant) | 414 | 1 (Large Plant) | 343 |
| Credits for 50/50 Sequester/Sell | $10,870,989 | $2,886,231 | $12,387,673 | $2,392,215 |
| Total Acquisition+ Operating Cost | $99,289,815 | $322,398,556 | $113,142,390 | $267,215,861 |

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