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Carbon Lifecycle Analysis of South Pole's Diesel Fuel vs Proposed Renewable Energy Sources

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ABSTRACT

In this study, a carbon emissions lifecycle analysis is performed to assess the environmental impact of diesel fuel usage versus the implementation of renewable energy sources at the Amundsen Scott South Pole Station. Currently, the station operates on diesel fuel, with an average cost of $40 per gallon delivered, significantly impacting both operational costs and carbon emissions due to the remote location. The analysis quantifies the carbon emissions from the transport and use of diesel fuel against those associated with the initial shipment of the renewable energy infrastructure. By comparing these scenarios, the research highlights the potential environmental benefits of adopting renewable energy at one of Earth's most isolated outposts.

INTRODUCTION

This report aims to analyze the environmental implications of transporting diesel fuel to the South Pole compared to the adoption of renewable energy alternatives. The Antarctic region, with its extreme conditions and remote location, holds unique challenges for logistical operations, specifically, in terms of fuel transportation and energy supply. The reliance on diesel fuel not only poses significant logistical challenges, but also raises concerns regarding carbon emissions and environmental impact. The project's scope encompasses a comprehensive review of existing literature related to the transportation of resources to the Antarctic, an evaluation of the environmental footprint associated with such activities, and the potential environmental benefits of transitioning to renewable energy sources. To achieve this, Argonne National Lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model software data was used to compare the carbon emissions and fuel efficiency associated with the current diesel-based operations, against hypothetical renewable energy pathways.

LITERATURE REVIEW

Following a series of insightful meetings with the project team, a comprehensive collection of resources was assembled. Most literature focused on the transportation modalities and economics of delivering diesel fuel, specifically AN8, to one of the most remote and environmentally sensitive regions on Earth. AN8 is a special type of diesel fuel commonly used in military operations for its lower freezing point and higher efficiency. Its procurement, primarily from Australia and Greece, presents the first step in a complex logistical chain that extends to the South Pole [3]. This logistical problem begins at Port Hueneme, California, where the fuel is loaded for the subsequent leg of its transportation. From California, two primary routes emerge, transportation via commercial air or surface methods and the more substantial U.S. Fuel Tanker Ship route. The first leg of the trip covers a distance of 6,900 miles to Christchurch, New Zealand [2]. The commercial transportation options, while viable, differ significantly in terms of carbon emissions and logistical constraints from the tanker ship route. Upon reaching Christchurch, the fuel's journey splits once again with options including continued sea transport via U.S. Fuel Tanker Ships and U.S. Icebreaker Ships, or air transport via C-17 or LC-130 aircraft. Icebreaker ships are required for this portion of the journey as thick ice commonly crowds the water pathways needed to be traveled by the tanker ships. Typically, large cargo and fuel are transported by sea, with air transport only used for more "last-minute" trips. The final leg of the fuel's journey, from McMurdo Station to the South Pole Station, relies on a ground traverse covering 1,030 miles. This section is particularly noteworthy for its reliance on specialized vehicles such as the Case Quadtracs, the Prinoth BR350 bulldozer, and AGCO MT865s, each with specific fuel consumption rates and operational parameters that further complicate the carbon emission calculations. Originally, this final portion of the trip was done through LC-130s, a highly inefficient use of fuel; however, this new method, coined SPoT, was recently proposed and is now used widely. Figure 1 visually depicts the entire trip from start to finish.

Figure 1: Map of Shipping Logistics

METHODOLOGY

After getting a better idea of logistics and the various paths one could take, our final modeled path was from Port Hueneme, California, to Christchurch, New Zealand, via a tanker, followed by the continuation to McMurdo Station with the assistance of an icebreaker, and culminating with SPoT to the South Pole Station. The needed 124,000 gallons of fuel needed for the South Pole Station to operate was evaluated using the above shipping path and compared to the emissions released from the shipment of renewable energy infrastructure which was modeled through a different path, due to weight and size constraints. These two options were first calculated using a simple Python script, then using specific data from a software called Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies, short for GREET. The steps taken in each phase, along with the pros and cons of each phase are thoroughly analyzed below.

Base Code Development

In the initial phase of the analysis, two rudimentary programs were developed to provide a high-level overview of the carbon emissions associated with each segment of the journey. The first program focused on aggregating the carbon emissions from each vehicle involved in the transportation chain, providing a very rough estimate of the emissions for the entire trip from California to Antarctica. The second program was designed to evaluate the fuel efficiency of the SPoT segment, utilizing operational data to estimate fuel consumption and associated emissions. The data can be shown in Figure 2. However, there were many simplified assumptions and a lack of comprehensive lifecycle considerations, leading to a desire for more in-depth analysis.

Figure 2: SPoT Table of Information

Year	SPot Fuel Delivered (lb)	SPot Cargo Delivered (lb)	Total lb Delivered	LC130 Flights Offset	LC130 Fuel Burned (gal.)	SPoT Fuel Burned (gal.)	Fuel Saved (gal.)
‘08-’09	805k	129k	934k	35.6	178k	64k	114k
‘09-’10	662k	39.4k	702k	27.4	134k	61k	72.8k
‘10-’11	667k	0	667k	26.1	127k	57.2k	70k
Avg	**712k**	**56k**	**768k**	**30**	**146k**	**60.7k**	**85.6k**

Adoption of LCA Tools: OpenLCA and GREET

To address the need for more precise and holistic analysis, the project explored two advanced LCA tools: OpenLCA and GREET. These tools are equipped to conduct more detailed and rigorous assessments of environmental impacts across the entire lifecycle of a product or process, including the extraction, production, transportation, usage, and disposal phases. OpenLCA, which was created in 2006, was first considered for its versatility and widespread use in environmental impact assessments, offering a robust platform for modeling complex systems and processes [11]. GREET, on the other hand, is renowned for its comprehensive database and sophisticated modeling capabilities, particularly in the analysis of energy systems and transportation fuels. Furthermore, it is a software developed by Argonne specifically, thus experts who specialize in GREET are abundant. As such, GREET was naturally used to model the carbon emissions of both scenarios. However, after many failed attempts to create new modes of transportation and transportation processes where the software insisted on crashing, it was then recommended to use GREET’s Excel version in which data could be extracted and calculated separately within a Python program.

Calculation Approach

After extracting the needed data from the T&D and Fuel_Specs tab in the GREET1 Excel file, two Python programs were created to easily plug and calculate emissions. The first one, a Jupyter notebook, is used to cleanly call functions, evaluate numbers, and in the same file, explain results. The second program contained the various custom functions, data, and metrics used to calculate the emissions associated with each scenario. The main goal was to abstract and create Python functions so that information regarding cargo load, miles traveled, etc. could easily be plugged in and spit out the emissions associated with the trip. There were many initial questions about the scope of the emissions and the team decided to do both embodied and the transportation of the diesel vs renewable sources. This documentation encompassing the development process, assumptions, and data sources ensures transparency and reproducibility of the results. Specifically, each function targets specific scenarios, such as truck and ocean tanker journeys, both loaded and unloaded, the production of energy components and diesel, and also converts the emissions into CO2-equivalent terms to provide a uniform metric of climate impact, reflecting the varying potentials of different greenhouse gases to warm the atmosphere over a hundred years. Each function and how they work are detailed below:

calculate_truck_emissions function estimates emissions from trucks over designated distances by considering loaded and empty trips. Using established energy consumption metrics, it calculates the diesel consumed per mile and, by employing emissions factors, determines the pollutants emitted.

$$E_{\text{loaded}} = \left(EF \times \frac{EI_{\text{loaded}} \times W_{\text{cargo}}}{BTU_{\text{gallon}}} \times BTU_{\text{gallon}} \times D \right) \times Q$$

$$E_{\text{empty}} = \left(EF \times \frac{BTU_{\text{empty}}}{BTU_{\text{gallon}}} \times BTU_{\text{gallon}} \times D \right) \times Q$$

Where:

- EF = Emissions factor for CO2, CH4, and N2O (grams per mmBtu) [12]
- EI_loaded = Energy intensity for the loaded trip (Btu per ton-mile) [2]
- W_cargo = Weight of the cargo (tons)
- BTU_gallon = Energy content of a gallon of diesel (138,700 Btu) [5]
- BTU_empty = Energy consumption for the empty trip (Btu per mile) [12]
- D = Total distance of the round trip (miles) [2]
- Q = Quantity of trips [2]

calculate_tanker_emissions function assesses maritime emissions by accounting for variations in fuel efficiency between loaded and return voyages. It adjusts for the maritime transport specifics, such as the type of fuel used and the different operational efficiencies when loaded versus empty.

$$E_{\text{tanker\_loaded}} = \left(EF \times \frac{EI_{\text{tanker}} \times W_{\text{cargo}}}{BTU_{\text{gallon\_resid}}} \times BTU_{\text{gallon\_resid}} \times D \right) \times N$$

$$E_{\text{tanker\_empty}} = \left(EF \times \frac{Energy_{\text{hp}} \times HP \times LF}{V_{\text{avg}}} \times \frac{1}{BTU_{\text{gallon\_resid}}} \times BTU_{\text{gallon\_resid}} \times D \right)$$

Where:

- EI_tanker = Energy intensity for tanker loaded trip (Btu per ton-mile) [12]
- BTU_gallon_resid = Energy content of a gallon of residual oil (149,700 Btu) [3]
- Energy_hp = Energy consumption per horsepower-hour (Btu/hp-hr) [12]
- HP = Horsepower of the tanker
- LF = Load factor for the empty back-haul [12]
- V_avg = Average speed of the tanker (mph) [12]

- N = Number of tankers [2]
- D = Distance of the one-way trip (miles) [2]

calculate_co2_equivalent function quantifies the combined climate impacts of CO2, CH4, and N2O emissions. It converts these into a standardized metric of CO2-equivalent.

$$CO2_{\text{eq}} = (m_{CO2} \times GWP_{CO2}) + (m_{CH4} \times GWP_{CH4}) + (m_{N2O} \times GWP_{N2O})$$

Where:
- m_CO2, m_CH4, m_N2O = Masses of CO2, CH4, and N2O (in kilograms)
- GWP_CO2, GWP_CH4, GWP_N2O = Global warming potentials of CO2, CH4, and N2O (1, 29.8, and 273, respectively) [12]

calculate_fuelused_emissions function aggregates the emissions from both trucks and tankers based on their fuel consumption.

$$E_{\text{fuel}} = (EF_{\text{diesel}} \times Fuel_{\text{diesel}} + EF_{\text{resid}} \times Fuel_{\text{resid}})$$

Where:
- EF_diesel, EF_resid = Emissions factors for diesel and residual oil (grams per mmBtu)
- Fuel_diesel, Fuel_resid = Total fuel consumption in mmBtu for diesel and residual oil, respectively [12]

calculate_emissions_from_diesel function focuses on the emissions associated with diesel production.

$$E_{\text{pollutant}} = EF_{\text{pollutant}} \times \frac{G_{\text{diesel}} \times BTU_{\text{per gallon}}}{10^6}$$

Where:
- EF_pollutant = Emissions factor for each pollutant (CO2, CH4, N2O) in grams per mmBtu
- G_diesel = Total amount of diesel used (in gallons)
- BTU_per_gallon = Energy content of diesel per gallon (138,700 Btu) [5]

embodied_renewable_emissions function computes the upfront emissions from the production of solar panels, wind turbines, and battery systems, as well as diesel.

$$E_{\text{embodied}} = (\text{Capacity}_{\text{solar}} \times \text{EF}_{\text{solar}}) + (\text{Capacity}_{\text{wind}} \times \text{EF}_{\text{wind}}) + (\text{Capacity}_{\text{BESS}} \times \text{EF}_{\text{BESS}})$$

Where:
- E_embodied = Total embodied emissions from production (in grams of CO2 equivalent)

- Capacity_solar = Target capacity of solar panels (in kW)
- EF_solar = Emissions factor for solar panel production (in grams CO2e per kW) [6]
- Capacity_wind = Target capacity of wind turbines (in kW)
- EF_wind = Emissions factor for wind turbine production (in grams CO2e per kW) [6]
- Capacity_bess = Target energy capacity of battery energy storage systems (in kWh)
- EF_bess = Emissions factor for battery system production (in grams CO2e per kWh) [6]

transportation_scenario_emissions calculates the total emissions associated with transporting various energy components including solar panels, wind turbines, battery energy storage systems (BESS), and diesel. It uses previously described functions along with weights and transportation modes to estimate emissions for each component.

sum_emissions function aggregates emissions data across multiple sources, providing a consolidated view of emissions for various pollutants.

consolidate_scenario_emissions function integrates emissions data from transport and production, yielding a total emissions figure for key pollutants across all evaluated scenarios.

However, despite these calculations, various assumptions are still made which are discussed in the next section.

ANALYSIS AND RESULTS

Figure 3 illustrates the range of renewable energy scenarios explored in the original techno-economic paper [1]. Each scenario presents distinct advantages and drawbacks, with some prioritizing certain renewable sources over others, while some emphasize a predominant reliance on diesel.

Figure 3:Different Renewable Energy Scenarios

	B	**C**	**D**	**E**
PV System Size (kW-DC)	0	180	120	200
Wind System Size (kW)	780	570	600	580
BESS Power (kW)	200	180	180	200
BESS Energy (kWh)	3310	3410	12570	2210
Fuel Consumption (gallons)	9500	5600	0	8500

Figure 4: CO2 Emissions and Payoff Period Table

	Diesel (1 year)	**B**	**C**	**D**	**E**
CO2 (in kg)	292,222	1,329,610	1,397,310	3,354,551	1,168,613
Payoff (in years)	0	4.55	4.78	11.48	4.00

Figure 4 presents the calculated CO2 emissions for each scenario based on the methodology outlined earlier. These calculations consider round-trip emissions, setting the stage for a detailed analysis of the most effective scenarios along with their respective advantages and disadvantages. However, it is critical to first examine the assumptions underpinning these calculations due to their potential impact on the accuracy of the results. A key assumption involves the limitations of the GREET model, which does not allow for the addition of new vehicle types. Consequently, specialized vehicles like Icebreakers, used in the second leg of transport, are modeled as Ocean Tankers. This also applies to other specialized vehicles like Case Quadtracs, Prinoths, and LC-130s, which are all approximated as heavy-duty trucks within the model. Such simplifications mean that the unique fuel efficiencies and emissions profiles of these specialized vehicles are not individually accounted for, which could lead to significant discrepancies between modeled and actual emissions. Another critical assumption is the constancy of fuel efficiency and emission rates regardless of the load carried by the vehicles. In practice, carrying overloaded cargo—exceeding the vehicles' rated maximum load—would likely alter fuel consumption rates and emissions. Nonetheless, the model assumes unchanged variables even when vehicles carry more than their maximum load capacity. This assumption extends to the calculation of emissions, where the model uses a BTU/ton-mile metric for trips to the destination, but calculates return trip emissions based on fuel efficiency with an empty load. This approach does not account for changes in fuel efficiency that might occur due to variations in load weight on the return trip. Furthermore, for transporting wind turbine components, it is estimated that seven LC-130 trips are necessary from McMurdo to the South Pole, due to outside research [4]. These assumptions realistically lead to the underestimation or overestimation of the actual environmental impact.

DISCUSSION AND CONCLUSION

While it is clear that renewable energy sources initially emit more greenhouse gases than one year of diesel fuel transportation, the payoff periods are relatively short. This finding indicates that once the initial environmental cost is overcome, renewable energy systems can offer substantial long-term benefits in terms of reduced CO2 emissions and fuel savings. Specifically, the Diesel scenario, with CO2 emissions of 292,222 kg and no renewable energy component, serves as the baseline for comparison. It records the lowest CO2 emissions because it only accounts for operation, not manufacturing or setup processes. Scenario B combines a medium-sized photovoltaic system with a significant wind power component and a balanced battery storage system. This scenario has a relatively high CO2 output but offers a moderate payoff period of 4.55 years, suggesting a quicker transition to beneficial returns compared to larger setups. Scenario C features no photovoltaic input but utilizes a large wind system and a massive battery storage capacity. It emits the highest CO2 among the renewable scenarios but transitions to net benefits in 4.78 years. The absence of photovoltaic components might be a factor in its slower transition compared to Scenarios B and E. Scenario D is the most environmentally demanding scenario, with the highest CO_2 emissions and the longest payoff period of 11.48 years. It utilizes a large photovoltaic system and wind power but has an enormous battery storage capacity. Scenario E has a robust setup with the largest photovoltaic system, substantial wind power, and the lowest battery storage energy. It achieves the quickest transition to net benefits among the scenarios with a payoff period of 4 years. Given the data, Scenario E appears to be the most advantageous in balancing initial CO_2 emissions with a quick transition to environmental and economic benefits, making it potentially the best option among the renewable setups. This scenario efficiently leverages a larger photovoltaic capacity with balanced wind and battery storage components to maximize benefits while minimizing the payoff time.

Overall, the higher emissions from renewable installations are most likely linked to the manufacturing and setup processes, which often involve significant energy inputs derived from non-renewable sources. Additionally, these emissions cover only the transportation and manufacturing of the panels, not the installation and maintenance of them—similar to the diesel scenario, where only transportation and extraction of the fuel are measured, not the actual combustion of the said 124,000 gallons of fuel. However, over time, the absence of ongoing fuel combustion, typical in diesel systems, leads to a net positive environmental impact for renewable systems. For the next steps and to further refine this analysis, it would be beneficial to collect more detailed data about each component of both renewable and diesel systems, including specifics on manufacturing processes, transportation, and operational efficiency. Reducing the number of assumptions by incorporating real-world operational data from existing systems could also enhance the accuracy of the findings. Moreover, having concrete emissions data for the specified vehicles used in the Antarctic, along with accurate metrics on how overloaded vehicles' efficiency and emissions are affected, would be more accurate. After this, it might be interesting to extend the timeframe of the CO_2 emissions analysis to include not just the initial manufacturing and installation but also long-term operational maintenance and eventual decommissioning. This would provide a more comprehensive view of the total environmental impact. Ultimately, by improving data quality and expanding the scope of analysis, one can achieve a more accurate understanding of the environmental payoff of renewable energy systems compared to traditional diesel-based systems, thereby supporting better-informed decisions for sustainable energy development.

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APPENDIX

Link to Code: https://github.com/WynonaL/southpole.git

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