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STANDARDIZED CARBON FOOTPRINT FOR A CUBESAT MISSION: A SUSTAINABILITY STUDY CASE ON EMERGING COUNTRIES WORKING ON SPACE TECHNOLOGY

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The space industry is becoming one of the most relevant and thriving industries of this decade. In fact, the space market is expected to become a multi-trillion-dollar industry in the following years.[2] On the other hand, the world is facing a climate change emergency, with 2020 being the hottest year on record. The concentration of greenhouse gasses has been rising steadily and mean global temperatures along with it.[16] If this trend continues Earth could have an average temperature up to 5,4 degrees Celsius warmer than today.[7] As a consequence, the frequency and magnitude of extreme weather events have increased. For these reasons, there have been recent studies analyzing the environmental impact of propellant choices[1] and rocket launches.[14] Nonetheless, emission allocation for products going into space or the organizational carbon footprint of space industry start-ups has not yet been reviewed. For this study, we aim to determine the carbon footprint of the launching of a CubeSat Mission by a Falcon 9 vehicle and allocate the corresponding emissions, in order to include in the organizational carbon footprint measurement of the Ecuadorian Space Technology Start-Up: Astralintu Space technologies. This resulted in 10.52 t CO2/ CubeSat launched (1U) corresponding to a total emission per launch of 493.46 t CO2. In addition, we have defined the emission sources relevant for scopes 1, 2, and 3 and as the next step of this study, we plan to complete the GHG Inventory of Astalintu Space Technologies under the ISO 14064:1 2018, serving as the main tool to comply with the commitments acquired as part of the national initiative Zero Carbon Ecuadorian Program and the United Nations Global Compact alliance. In addition, this study provides insights to determine the main sources of GHG emissions in space technology startups and serves as the basis for the development of effective carbon reduction initiatives and strategies.

keywords: Sustainability, CubeSat, Carbon Footprint, New Space, Emerging Countries, Sustainable Development Goals

1. Introduction

Climate change has become one of the most relevant risks for the international community, as it has caused great damage to biological, social, and economic systems in recent decades. Different countries have already presented in their annual reports the likelihood that the effects of climate change will have irreversible consequences, prompting the search for actions to reduce or mitigate the effects of climate change. Thus, in 2015, in the Paris Agreement, a consensus was reached to establish the goal of not increasing the temperature above 1.5°C.[9] In this scenario, global strategies such as adherence to the SDGs, have been adopted. The 30 SDGs seek the eradication of poverty, protect the planet and ensure sustainability. In addition to assigning responsibilities to each country and organization in order to meet the goals established in the fight against climate change.[9] It is increasingly evident that the quest for sustainability and sustainable development requires the integration of economic, social, cultural, political, and ecological factors. It requires the constructive articulation of top-down approaches to development with bottom-up, grassroots initiatives. It requires taking into account both local and global aspects and how they relate to each other. Finally, it requires broadening the spatial and temporal horizon to accommodate the need for intergenerational as well as intragenerational equity.[5] It is a fact that the space industry has been and will be the future of humanity, however, the chain of processes to obtain the appropriate materials to build rockets, satellites, and spacecraft, comes from highly polluting sources such as oil extraction and mining. These conditions, including the high cost of production, have forced the industry to reinvent itself every day, in order to be highly effective and remain at the forefront. This has given rise to the development of new technologies that are capable of enhancing both material and monetary resources through strategies such as programming, software development, and reengineering. In addition to venturing into the field of circular economy, looking for alternatives to fuels and construction material. However, one of the biggest challenges continues to be the CO2 emissions released into the environment. As we know, there is a global commitment to reduce greenhouse gas emissions, and to achieve this it is necessary to meet the established goals, therefore, this is an issue that cannot be ignored. This is why the leading companies in the industry are beginning to concretize ideas about reducing their emissions.[10] In the same way, it is a fact that the space industry plays a very important role in monitoring key factors to know the current state of the components of the global ecosystem. In words of the Director of the UN Office for Outer Space Affairs: ¨Space tools are highly relevant for the attainment of all 17 Sustainable Development Goals and their respective targets, either directly, as enablers and drivers for sustainable development, or indirectly, as an integral part of the indicators for monitoring the progress towards the implementation of the 2030 Agenda for Sustainable Development¨.[15] This shows that the industry has been making a commitment both in the short and long term. In the same way, this opens the door for emerging countries to access the development and technology opportunities that the space ecosystem can provide. There are many projects going on on a global scale, aiming to make space accessible for everyone and also to be a safe environment where everyone has an opportunity to make a contribution.[10] There are many projects on a global scale that are directed towards the control, monitoring, and early warning of drastic changes in the climate through the use of satellites and space technology. This leads to a useful tool for decision-making within government authorities, as well as other stakeholders. At the same time, it provides an idea of the impacts of climate change and where national strategies for both territorial and economic development should be guided in the case of emerging countries. In the same way, natural disasters can be foreseen in order to safeguard vital infrastructures such as hospitals and schools, as well as to ensure the safety and well-being of the population in case of risk.[6] For this study, we aim to determine the carbon footprint of the launching of a CubeSat Mission by a Falcon 9 vehicle and allocate the corresponding emissions, in order to include in the organizational carbon footprint measurement of the Ecuadorian Space Technology Start-Up: Astralintu Space technologies. In addition, we have defined the emission sources relevant for scopes 1, 2, and 3 and as the next step of this study, we plan to complete the GHG Inventory of Astalintu Space Technologies under the ISO 14064:1 2018, serving as the main tool to comply with the commitments acquired as part of the national initiative Zero Carbon Ecuadorian Program and the United Nations Global Compact alliance. In addition, this study provides insights to determine the main sources of GHG emissions in space technology startups and serves as the basis for the development of effective carbon reduction initiatives and strategies.

2. Methods

2.1 *Standardized Mission and payload configuration*

The calculations for this study were based on the CubeSat Missions by a Falcon 9 vehicle. This reusable two-stage rocket manufactured by SpaceX has been used in 170 launches as of August 2022, becoming a reliable transport of payload to space.[18] The specifics of the rocket are described in Figure 1.

Falcon 9 has a maximum capacity for payloads of 22.8t to LEO and 8.3 t to GTO. It can launch multiple satellites in a single mission and is one of the vehicles used for the rideshare missions offered by SpaceX.[18] The payload configuration assumed for this study is described in Figure 2 and the volume dimensions of the Falcon 9 faring is shown in Figure 3.

Moreover, the mission of the study focuses on the emission of CubeSat launches. CubeSats have standard dimensions of “Units” corresponding to 10 cm x 10 cm x 10 cm. They can be 1U, 2U, 3U, or 6U and typically weigh less than 1.33 kg.[13]

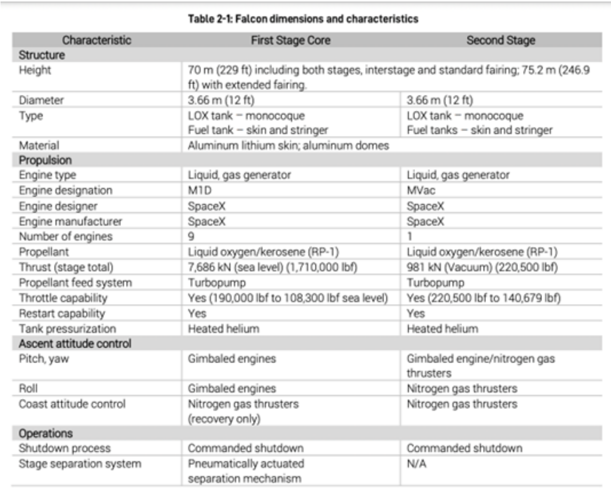

Table 2-1: Falcon dimensions and characteristics

Characteristic	First Stage Core	Second Stage
Structure		
Height	70 m (229 ft) including both stages, interstage and standard fairing; 75.2 m (246.9 ft) with extended fairing.	
Diameter	3.66 m (12 ft)	3.66 m (12 ft)
Type	LOX tank – monocoque Fuel tank – skin and stringer	LOX tank – monocoque Fuel tanks – skin and stringer
Material	Aluminum lithium skin; aluminum domes	
Propulsion		
Engine type	Liquid, gas generator	Liquid, gas generator
Engine designation	M1D	MVac
Engine designer	SpaceX	SpaceX
Engine manufacturer	SpaceX	SpaceX
Number of engines	9	1
Propellant	Liquid oxygen/kerosene (RP-1)	Liquid oxygen/kerosene (RP-1)
Thrust (stage total)	7,686 kN (sea level) (1,710,000 lbf)	981 kN (Vacuum) (220,500 lbf)
Propellant feed system	Turbopump	Turbopump
Throttle capability	Yes (190,000 lbf to 108,300 lbf sea level)	Yes (220,500 lbf to 140,679 lbf)
Restart capability	Yes	Yes
Tank pressurization	Heated helium	Heated helium
Ascent attitude control		
Pitch, yaw	Gimbaled engines	Gimbaled engine/nitrogen gas thrusters
Roll	Gimbaled engines	Nitrogen gas thrusters
Coast attitude control	Nitrogen gas thrusters (recovery only)	Nitrogen gas thrusters
Operations		
Shutdown process	Commanded shutdown	Commanded shutdown
Stage separation system	Pneumatically actuated separation mechanism	N/A

Fig. 1: Falcon 9 Characteristics. Retrieved from Falcon Payload User's Guide[17]

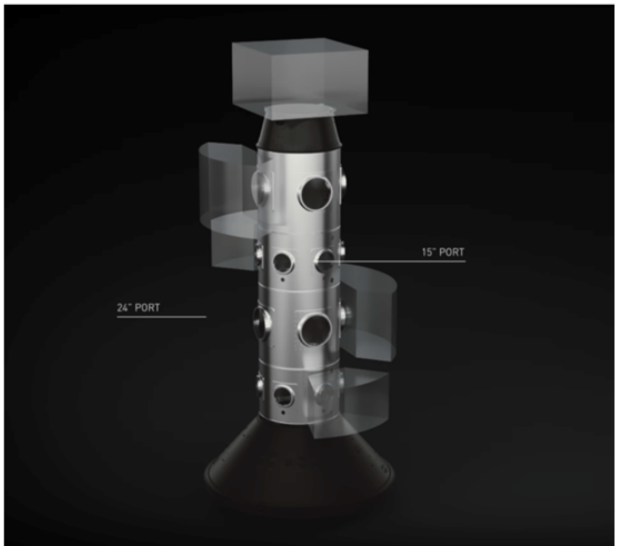

Fig. 2: Payload Configuration on a Transporter Mission. Credits: SpaceX[12]

2.2 *Greenhouse Gas Emission Estimation*

The theoretical stoichiometric equation for rocket-grade kerosene (RP-1) combustion was utilized to estimate the emissions of the launch. Since RP-1 is a complex mixture of different components, this study assumes the stoichiometric values and properties presented by the National Institute of Standards and Technology[11] in the report: Thermophysical Properties Measurements and Models for Rocket Propellant RP1: Phase 1. The mentioned report was based on a mixture that approximates the behavior of an investigated sample of RP1. In this regard, the chemical properties assumed for the estimation of CO2 in this study are presented in Table 1.

Once defined the chemical formula, the emissions were calculated based on the theoretical combustion equation shown next a) C11.8H23+b O2cO2+d H2O (1)

Where a, b, c, and d are the stoichiometric coefficients of the balanced equation shown below.

2) C11.8H23+35.1 O223.6 CO2+23 H2O (2)

After determining the CO2 emissions per ton of RP1 this value was used to estimate the corresponding value of a launch assuming the propellant consumption detailed in Table 2.

2.3 *Greenhouse gas emissions allocation by volume of a Falcon 9 fairing*

To achieve a standardized measure of carbon emissions for a CubeSat Mission it is necessary to allocate the total emissions of the launch to the corresponding payload of interest, in this case, a CubeSat (1U). Various methodologies have been developed to estimate the "shared" emissions of products and people traveling in the same vehicle. For this study, the emission allocation was based on the International Civil Aviation Organization (ICAO) methodology.[8] This methodology intends to estimate passengers' emissions from flights as accurately as possible considering freight, mail and other passengers are part of the same flight. The equation used in this study is derived from the passenger emission equation in the ICAO methodology as follows:

ICAO equation

"CO2 per pax = 3.16 * (total fuel * pax-to-freight factor)/(number of y-seats * pax load factor)

Where:

Total fuel = The weighted average of the fuel used by all flights departed from the origin airport in order to reach the destination airport. The weighting factor is the ratio of the number of departures for each equivalent aircraft type, to the total number of departures.

Pax-to-freight factor = is the ratio calculated from the ICAO statistical database based on the number of passengers and the tonnage of mail and freight, transported in a given route group.

Number of Y-seats = the total number of economy equivalent seats available on all flights serving the given city pair.

Pax load factor = the ratio calculated from the ICAO statistical database based on the number of passengers transported and the number of seats available in a given route group.

3.16 = constant representing the number of tonnes of CO2 produced by burning a tonne of aviation fuel."

Reference: ICAO[8]

2.4 *Standardized CubeSat Carbon Footprint Calculation Equation*

CO2 per U = RP1 emission factor (total fuel U to payload factor)(U payload capacity U load factor) (3)

Where:

Total fuel = The average of the fuel used by Falcon 9. (ton RP1)

U-to-payload factor = is the ratio calculated based on the number of U and the tonnage of other noncommercial payloads, transported in a given route group. We assume it is 1 meaning the fairing corresponds solely to the commercial payload.

U payload capacity = the total number of U's capable of flying in the Falcon 9 fairing.

U load factor = the ratio calculated on tons transported and tons are available in a Falcon 9 fairing.

RP1 emission factor = constant representing the number of tonnes of CO2 produced by burning a tonne of RP1 (ton CO2/ ton RP1)

In terms of the calculation, the total fuel was assumed to be the propellent mass described in Table 2 and the U payload capacity was calculated integrating the volumetric space available in the Falcon 9 fairing. This space then was divided by the volume of the CubeSat 1U to determine the total number of Us capable of flying in Falcon 9.

On the other hand, the U load factor was estimated based on the total payload launched this August corresponding to the heaviest payload ever launched by a Falcon 9 rocket.[3]

3. Results and Analysis

3.1 *GHG Calculation Factors*

The factors needed for the emission allocation were calculated separately as described in the methods sec-

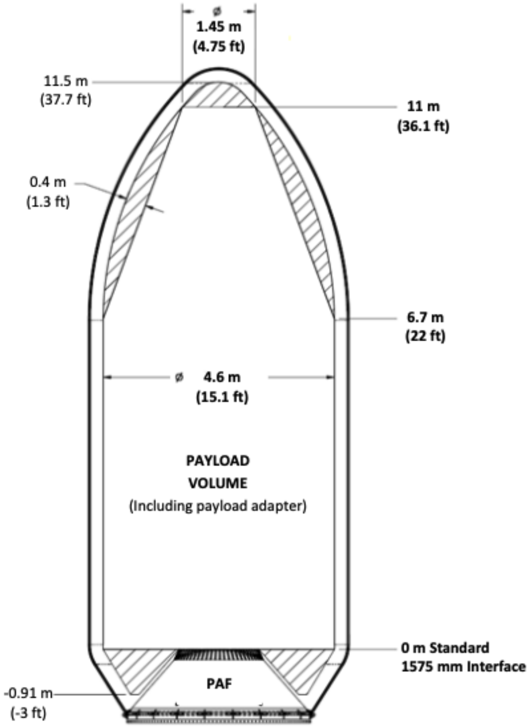

Fig. 3: Falcon fairing and payload dynamic envelope taken from[17]

tion. The emission factor of RP-1 that resulted from the theoretical stoichiometric balance was 3.17 ton CO2/ ton RP-1. On the other hand, we assumed a total payload capacity of 64.[4] Moreover, the U load factor was estimated to be 0.7324. A summary of these findings is shown in Table 3.

3.2 *Standardized Carbon Footprint of CubeSat Missions*

Based on the calculated factors in the previous section, the standardized CO2 emissions for a CubeSat Mission (1U) is 10.52 t CO2. The corresponding emissions for common CubeSat dimensions are shown in Table 4.

From these results, it is important to note that the carbon emission factor of RP1 is similar to the one for aviation fuel used by ICAO (3.17 vs 3.16). This similarity was expected since both fuels are types of kerosene. Although they have different mixtures of various hydrocarbons the molecular mass of both compounds does not differ significantly.

Moreover, even if the emission factor is similar the overall emissions of a launch vs a flight are significantly greater. The theoretical total emissions per launch of a Falcon 9 were estimated to be 493.46 t CO2 [*], whereas the total emissions of a 10-hour flight (LHR-HKG) were calculated to be 146.06 t CO2[†]. This indicates that launching a rocket would be similar to traveling almost for 36 hours straight by plane.

3.3 *Challenges and Data Limitations*

The main challenges of this research are related to uncertainty and data availability. First, the combustion equation could become more specific because RP1 is a mixture of several hydrocarbons, not just one. Second, in this case a NIST equation was used but could be refined if more information is available. The equation used for this study assumes complete combustion of RP1, it would be more accurate to know how much of this fuel goes through incomplete combustion. These assumptions could cause a certain level of uncertainty in the results. Besides, the U load factor could be improved by doing a historical recap of how full the rocket launches have been in the last years. Finally, considering the guidelines of ISO 14964, the analysis for the CubeSat Carbon Footprint should be extended by considering the whole life cycle approach.

4. Conclusions and Discussions

As a conclusion of this study, it was found that 1U emits 10.52 CO2 emissions. The estimation of these data becomes useful information for the calculation of CO2 emissions within the CubeSat Missions launches. In the general equation it is assumed that there is a complete combustion process of the RP1, therefore it was estimated that 3.17 tons of CO2 are produced for every ton of RP-1 fuel used. A set of data can be found in Table 4. About the Standardized CO2 emissions for CubeSat Missions in a Falcon 9, where the values of CO2 emissions are calculated in relation to the number of units of CubeSats sent in a regular launch. Additionally, the methodology described in the calculations and factors of the ICAO helps us to better understand the physical-chemical process in which the burning of the fuel (chemically similar to aircraft fuel) and the generation of greenhouse emissions takes place. Since the original application of this tool is to know about the emission generated on aircraft flights, it is important to know that the equations are structured with the available data from the launch service provider. That is why we consider the availability of information, a core step, in order to calculate with more accuracy the volume of emissions generated into the environment. This study also opens up a starting point, where the industry can invest in the development of new technology and management processes where the implementation of effective mitigation strategies in order to minimize the environmental impact generated by CO2 and greenhouse gas emissions is a reality. This means that from startups to leading companies in the space industry, can adapt to meet the goal of a zero-emission scenario and make space accessible, safe, and sustainable for all.

4.1 *Outlook*

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[*] Considering an emission factor of 3.17 tCO2/ t RP-1 and total fuel used as 155.87 t/launch (Table2)

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