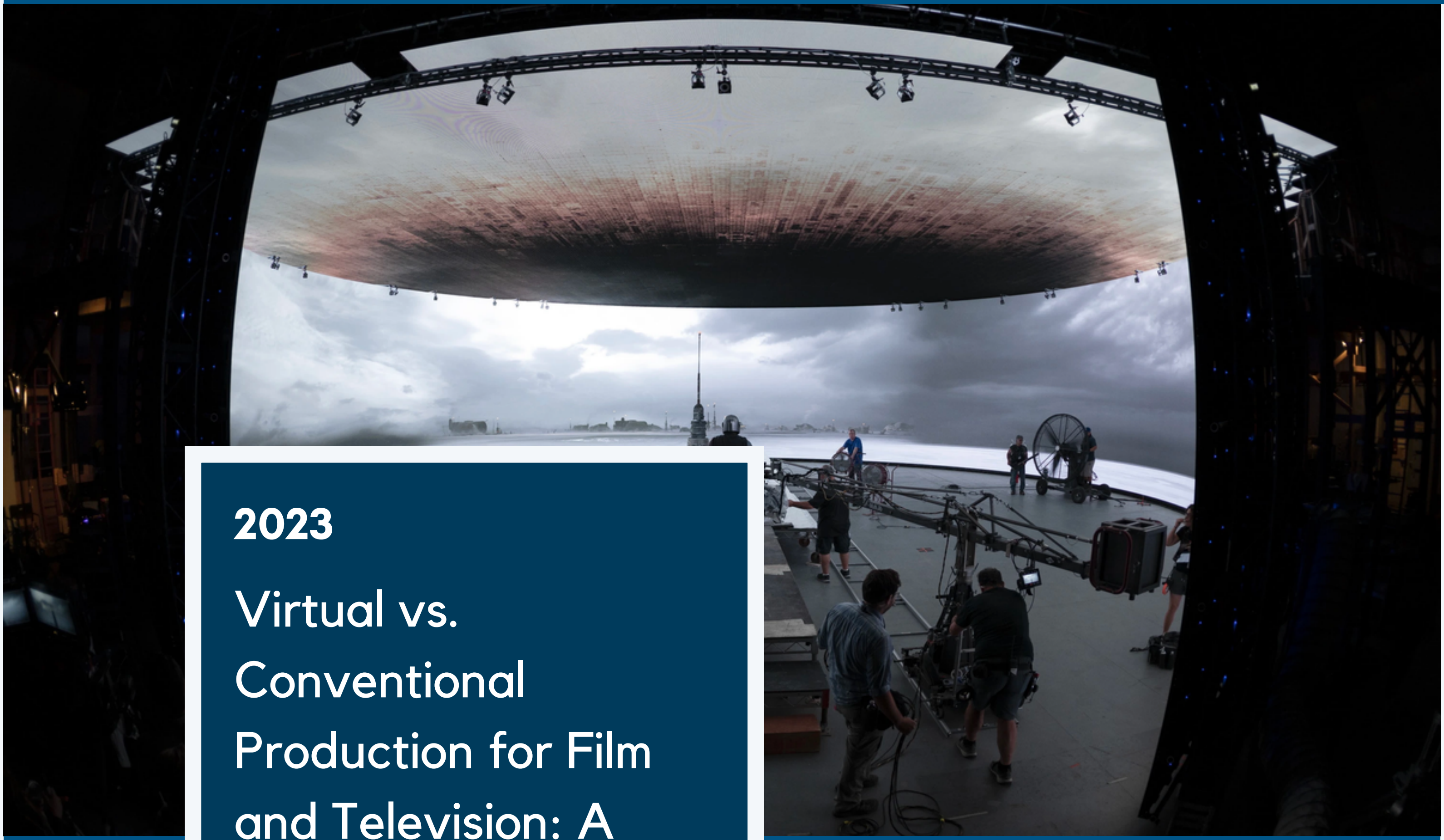

2023

Virtual vs. Conventional Production for Film and Television: A Comparative Life Cycle Assessment

FINAL REPORT

Prepared for: Sustainable Production Alliance

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Abstract

This report presents a comparative Life Cycle Assessment (LCA) of two methods of production of film and television, the conventional method and the emerging method of virtual production. The study quantifies the environmental benefits of using virtual production technology compared to a conventional method of production. The comparative LCA methodology uses a cradle-to-grave approach, and it focuses on sectors that exhibit significant differences in products used and practices in two methods of production–raw material use, transportation, computing, and energy usage. The scenes assessed vary to address different benefits of virtual production including a scene that would be shot across the country with transportation required for principal actors, a moving car scene that would traditionally be shot in the desert over the course of days, and a sci-fi scene that would require an extensive set build with large material usage. The results show that virtual production has reduced CO_2 emissions compared to traditional filming methods across the board, while the degree of benefits vary based on scene composition for each sector. Total emissions saved range from 1141 kilograms of CO_2 per minute for Scenario 2, to 5777 kilograms per minute for Scenario 1, and finally 20783.5 kilograms for Scenario 3. Results are further categorized by sector and minute of film as scene length varied between scenes.

Introduction

The film and television industry has the ability to immerse viewers in new stories and fantastical worlds through elaborate set builds or filming on-location. However, the environmental impacts associated with these practices cannot be overlooked. In recent years, filmmaking technology has greatly evolved to now encapsulate not only traditional techniques, but also fully virtual productions which have the ability to completely transform the industry and affect its carbon footprint. This report aims to quantify the carbon dioxide emissions generated through both methods of film making in an effort to create a roadmap for productions to identify and, in turn, decrease their emissions.

According to a report by UCLA titled Sustainability in the Motion Picture Industry (2006), economic activity in Greater Los Angeles related to the film and TV industry produces the greatest conventional pollutants when compared to other highly polluting sectors (Corbett & Turco, 2006). A large portion of the emissions generated come from things like set building, running the HVAC for production stages, running diesel generators and computing power. The environmental impact of these productions also extends beyond just production as sets are commonly discarded after use, as they are unique to each production and therefore recognizable, ending up in landfills and contributing to waste. Additionally, on-location production is known to be a major contributor primarily stemming from its extensive use of resource-intensive processes. Aside from the emissions generated though flying cast and crew out to a given location, energy usage on these sets is substantial due to the use of diesel generators, lighting, cast trailers and hair and make-up trailers. Each location also has different local environmental regulations, and access to resources like recycling bins, environmental information, or green infrastructure might not always be readily available (Corbett & Turc, 2006). Astonishingly, in 2020 it was estimated that the average major motion picture generates about 2840 tons of CO_2 during production, which is equivalent to 11 one-way trips from the Earth to the moon (Arup and BFI, 2020). Recognizing this impact and working towards innovative solutions to lower the industry's environmental impact is vital. One such technology that has the ability to vastly reshape how films and television are produced today is through the use of Virtual Production (VP).

In Virtual Production, floor to ceiling 180 or 360 LED walls, also called LED volume walls, surround the stage and display a computer-generated backdrop in real-time, streamlining the production process while delivering backdrops that are nearly indistinguishable from sets or on location shoots. Virtual Production can help reduce the amount of material consumption and travel time between off set locations, in theory making it a more sustainable alternative to conventional shooting practices. Additionally, there is an industry wide consensus that VP allows for shooting approximately 30% more material in the same amount of time as conventional. Productions such as Disney's The Mandalorian and HBO's House of the Dragon have spearheaded the shift towards using VP in the modern era of digital VFX.

However, this is an emerging technology that has not been heavily studied and there is no concrete evidence on the extent to which VP affects greenhouse gas emissions and whether or not it is in fact more sustainable. Working with the Sustainable Production Alliance–a coalition of sustainability professionals at various media studios such as Disney, Amazon, Paramount and more–in this report we analyze Life Cycle Assessment data from various academic and governmental sources to address this gap. Through conducting a comparative life cycle analysis, we aim to identify differences in environmental impact between shooting conventionally or on location, and through using VP. We investigate the differences in emissions generated between using the LED volume and shooting conventionally for three different filming scenarios: an on-location scene that could be shot in a studio with VP, an extensive set build of a science fiction fantasy scene, and a car chase scene which involves an on location shoot. Each scenario encapsulates different instances VP can be used for. Our goal is to ultimately pave the way to more environmentally conscious filming practices.

Literature Review

Sustainable Production Alliance's Green Production Guide

Over the course of this report, we build off the work of the Sustainable Production Alliance and their Green Production Guide (GPG). The GPG is a public-facing website intended to inform and encourage the film, television, and streaming content industry to reduce its carbon footprint. The website offers spreadsheet tools, vendor databases, and sustainability reports to updates on the latest news on sustainability in the entertainment industry (GPG, 2022).

The GPG includes three powerful excel tools: a sustainable practices checklist, a carbon footprint calculator, and a plywood tracking worksheet. First, the Production Environmental Actions Checklist (PEACH) is intended to help productions plan, implement, and track sustainable practices on set (GPG, 2021). The completed checklist generates a production score based on how many sustainable actions were completed, weighted based on the relative impact of the action. The Production Environmental Accounting Report (PEAR) measures the carbon emissions of a production based on utilities, transportation, travel, waste, and donations. Once completed, the PEAR generates a completed emissions report which includes the total CO_2 emissions for the production in metric tons, a graph of CO_2 emissions by source (utilities, fuel, air, or housing), CO_2 emissions per episode, and a waste diversion rate (GPG, 2021). Lastly, the Production Lumber Material (PLUM) tool tracks a production's usage of plywood. The completed table tracks plywood usage and focuses on whether it is responsibly sourced (GPG, 2021). The three tools in the GPG toolkit—PEACH, PEAR, and PLUM—foster greater awareness of a production's sustainability and highlight areas in which a production can further green their content.

In addition to tools, the GPG features relevant reports focusing on high impact areas in the film, television, and streaming industry. In 2021, SPA prepared the report *Close Up: Carbon emissions of film and television production*, which outlined the average carbon emissions from productions between the years 2016 and 2019. The report analyzed data from the PEARs of 161 feature films and 266 television series from SPA member companies. Results showed that average carbon footprints varied significantly depending on the type of feature film or television series. For feature films, the average CO_2 equivalent (CO_2e) emissions per feature was 3370 metric tons, 1081 metric tons, 769 metric tons, and 391 metric tons for tentpole, large, medium, and small feature films, respectively (SPA, 2021). For television series, the average CO_2e emissions per episode were 77 metric tons, 26 metric tons, 18 metric tons, and 13 metric tons for 1 hour scripted drama, 1/2 hour scripted single camera, 1/2 hour scripted multi-camera, and unscripted, respectively (SPA, 2021). These differences in average CO_2e emissions were largely attributed to the length of filming as well as the number of filming locations.

Another interesting result was that fuel consumption was the largest contributing factor to the carbon footprint of all types of feature films (tentpole, large, medium, and small) as well as one-hour scripted dramas and single-camera television series (SPA, 2021). Based on these findings, SPA recommended that film and television productions prioritize energy efficiency and a transition away from fossil fuels toward clean, renewable energy sources. Some suggestions in the report included investing in more LED lighting, off-grid solar trailers, electric vehicle technology, renewable diesel fuel, electrical grid tie-ins, and battery generator technology. One noted limitation to electrification on production, however, was the lack of access to grid power on sound stages (SPA, 2021).

In 2021, SPA surveyed 50 soundstage facility owners to determine the practices production facilities were currently undertaking to become more sustainable and to identify key challenges in implementation (SPA, 2022). According to the report, the majority of soundstage facilities had low adoption rates of sustainability best practices where 60% of facilities reported having "Low" or "Moderate" adoption (SPA, 2022). This indicated that there was significant potential to make soundstage facilities more sustainable. To help facilities identify specific sustainable practices to prioritize, the report included a facilities priorities checklist. SPA recommended that all facilities adopt the immediate actions and near-term goals outlined in this checklist in order to reduce their environmental impacts. These reports prepared by SPA highlight high impact areas of production and are important first steps in developing effective solutions to address the entertainment industry's significant carbon footprint. Moving forward, it will be important that SPA continues to conduct similar reviews to monitor the progress of the entertainment industry, or lack thereof, towards greater sustainability.

Sustainability Practices in Film Production

One sector of film production that can be targeted to implement more sustainable practices is energy. Clean energy and power is defined as "energy that comes from renewable, zero emission sources that do not pollute the atmosphere when used" (TWI, 2022). The Sustainable Production Alliance (SPA) is particularly focused on the adoption of clean energy and power at soundstage facilities. When looking at the environmental impacts of virtual production and the amount of power required to run its technology and software, it becomes even more vital to develop useful clean energy practices. Clara George, a Vancouver-based Producer who is a Green Production Guide task force member, explains that what has historically been used on production lots and on location – fuel, gas diesel, natural gas, and propane – is what creates GHGs. Therefore, SPA aims to replace fossil fuel with clean energy, with a focus on fixed production facilities given their multi-season use by episodic productions and companies' frequent reuse of stages (GPG, 2020).

As outlined in SPA's Green Production Guide report, the benefits of investing in clean energy include cost savings, energy autonomy, and the added value of energy conscious optics. However, additional considerations include the varied up-front installation costs and regional hurdles such as climate and fossil fuel powered grid sources. SPA reported that 86% of respondents did not have on-site renewable energy, however 62% procured renewable energy through a supplier or utility.

In response to these findings, SPA first suggests all respondents strive to supply enough clean energy to productions to prevent the use of fossil fuel generators. This standard suggests the possibility for energy harnessed off-site to contribute less GHG emissions than fossil fuel generators. Although the sources of public utility off-site energy vary by region, Los Angeles County is significant to compare, as it is home to the most square footage of soundstages in the world at 5.4 million square feet (Robb, 2022). In Los Angeles, energy is 34% renewable, 27%

natural gas, 14% nuclear, and 21% coal (LADWP, 2019). Renewable energy consists of geothermal, eligible hydroelectric, solar, and wind. Given the composition of LADWP electricity, it can be deduced that public electricity produces less emissions than fossil fuel generators, even if the generators use the lowest GHG emitting fossil fuel–natural gas.

Adopting and supplying new clean energy technology is another way soundstage facilities can lower their emissions. In addition to the physical space, filming facilities rent out equipment to studios or connect them with suppliers. They can source and provide greener rental options, as well as change their rules to allow the use of green equipment in their spaces. Cleantech rentals include solar panel chargers, mobile batteries, and electric and hybrid vehicles. The upfront costs are sometimes more expensive than alternatives, but through LCA it is shown that cleantech often is an investment that pays off well before the end of its life cycle.

The life cycle assessment of suggestions in SPA's Green Production Guide helps to clarify and quantify the difference in GHG emissions between the suggested practices and the status quo alternatives. Reviewing the quantifiable differences in environmental impact between clean energy practices and their fossil fuel predecessors explains the environmental and financial impacts clean energy can have for facilities, thus increasing the likelihood of implementation (Morgil et al., 2006).

Material use is another sector of interest when investigating sustainable practices in the film and TV industry. In physical production, sets are imperative and a significant component of the materials used and wasted during filming. Virtual production presents an opportunity to eliminate or reduce set materials, thereby reducing their life cycle impacts.

According to a report by the Screen New Deal created with the aim to provide a path to sustainable film production, there is an average of 47,000 tons of total waste generated per tentpole film production. Unfortunately, the measures in place to deal with this statistic fall short. According to a report done by the Sustainable Production Alliance (SPA), S*oundstage Facility Survey Key Takeaways*, only 26% of productions provided studio-managed material reuse programs, and only 38% provided food donation programs. This is an area that can be developed to improve the sustainability of physical production operations (SPA, 2022).

One suggestion for improving the issue of waste management on set is forging connections with local partners to reuse set material and donate food. An example of this is having a designated space at production facilities for set and other miscellaneous materials to be kept, so they can be systematically put toward developing local material reuse partnerships. However, one thing to keep in mind is that the life cycle impacts of reusing material, or partnering with organizations to reuse material, is highly dependent on the nature of material reused and the energy required to transport it to the final destination.

Life Cycle Analysis and its Historical Use

Life cycle assessment revolves around the idea that the environmental impacts of any good or service must be assessed from the most basic level to the final stages of that good or service; this includes raw materials, transportation, use, waste removal, and any other steps involved in creating, using, and removing a good or service. Life cycle assessment has been characterized as a decision-support tool rather than a scientific measurement tool (Hertwich and Hammitt, 2001a). LCA will be vital to this project as it's a holistic method of getting the closest possible estimate of the environmental impacts of both physical and virtual production. We hope that the LCA study we provide to the Sustainable Production Alliance will be able to inform the decision-making of filmmakers when determining how a scene or entire production should be shot.

The general framework of life cycle assessment established by the ISO revolves around interpreting data at each key point. The key points include goal and scope definition, inventory analysis, and impact assessment. Within this framework the direct applications of the LCA interpretations include product development and improvement, strategic planning, public policy making, and marketing (ISO, 2006). These applications further solidify LCA's role as a decision-support tool rather than a scientific measurement tool, as LCA aims to provide more information on product or service development, use, and removal in order to allow for better decision making for industry, government, and consumers.

It is important to take note of both the strengths and weaknesses of life cycle assessment. LCA's effectiveness as a decision-making support tool is entirely dependent on the accuracy of measuring at each and every step, as well as the scope of the study, and how similar options are compared. The key to a successful LCA study is selecting the correct comparative inputs and outputs for a functional unit.

Objective

This project conducts a comparative life cycle assessment between three different shooting scenarios. In our comparative LCA, we identify the difference in carbon emissions between a conventional shoot and a virtual production shoot for the following scenarios:

Image 1: (*How I Met Your Father*, Ep 1, 21:03)

Scenario 1 is a 2.38 minute scene from episode 1 of *How I Met Your Father*. The use case is to eliminate travel of the whole production across the country from Los Angeles to New York City to film on the Brooklyn Bridge. The conventional shoot takes place on the Brooklyn Bridge and the virtual production shoot takes place in a soundstage in Los Angeles.

Image 2: (*The Old Man*, Ep 7, 36:56)

Image 3: (*The Old Man*, Ep 7, 40:06)

Scenario 2 is a 6 minute sunset driving scene from episode 7 of *The Old Man*. The use case is to film a time-sensitive sunset scene using vehicles. The conventional shoot takes place on location in the Antelope Valley. The virtual production shoot takes place in a soundstage, but a small crew travels to the Antelope Valley to capture background for the LED walls.

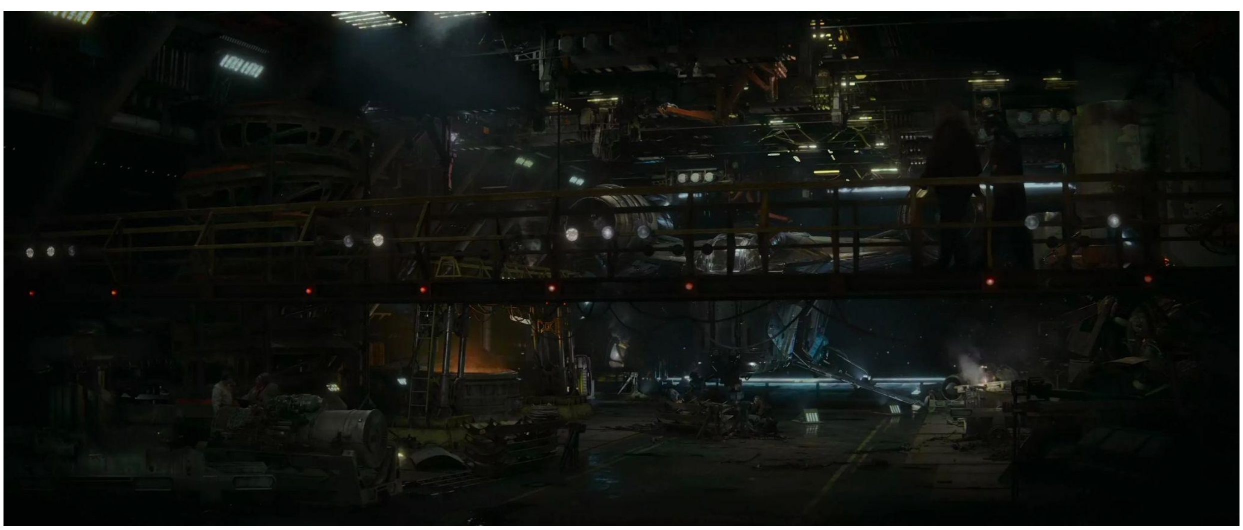
Image 4: (*The Mandalorian*, S1, E6, 42:07)

This is the most complex of the three scenarios. It is a 5.42 minute scene from season 1 episode 6 of *The Mandalorian* with the Roost hangar environment. The use case is to create a fantasy or “hard-to-create” physical set. Both conventional and virtual production shoots take place in studio.

Methods

Life Cycle Assessment, Data Analysis & Model Construction

A comparative life cycle assessment compares the life cycle impact of virtual and physical production using the life cycle assessment framework (refer to the figure below).

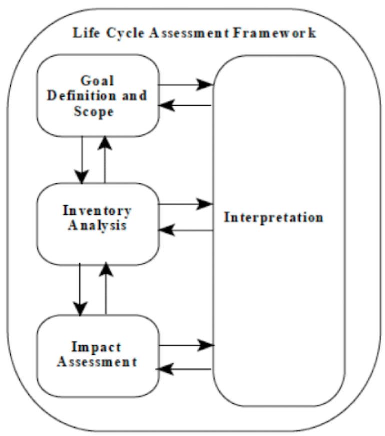

Figure 1: Phases of an LCA (Rajagopal, 2022)

The functional unit for this comparative life cycle assessment is **per minute** of scene. To quantify the critical input and outputs of the process involved in virtual production and physical production, we focus on the sectors, transportation, energy, computing, and materials, after reviewing previous projects for the Sustainable Production Alliance as well consultation with the clients. Virtual production has the potential to reduce transportation, energy and material related emission from physical production which requires air or road transport, on location generators and extensive use of material for set builds. It is also possible that Computing power might increase and there is a need to quantify this to be able to truly understand the difference in the environmental impact between the two types of production. The scope of the project includes processes which are relevant to a comparison and processes which are common to both types of production are not considered. The impact is assessed using carbon dioxide as the performance metric because it is an important metric with available data. The data comes from industry professionals, environmental datasets and estimates from scientific literature (refer to Appendix A).

Sensitivity Analysis

To tackle uncertainty introduced into our analysis from assumptions made due to a lack of data, we perform a sensitivity analysis of six input variables to better understand how the changes in these inputs would affect the result or output of our model and our overall model. The variables are chosen on the basis of their contribution to overall emissions, their source uncertainty, and the likelihood of the variable to change over time as, for example, the technology improves.

The first variable chosen for the sensitivity analysis is the percentage of materials in Scenario 3 that are reused. According to a set designer, approximately 75% of the materials in Scenario 3 would have been obtained secondhand from a prop warehouse. In the model, this is accounted for by subtracting 75% of total materials-related emissions to represent that 75% of the props are not generating “new” emissions. However, this is an oversimplification of LCA calculations, which divides the emissions of each prop by their expected lifetime or number of uses. The team was unable to obtain specific data regarding prop lifetime or expected usage. Given that materials reused from a props shed should still have emissions associated with them, the sensitivity analysis focuses on lower percentages of materials recycled.

The next variable is the percentage of energy added to account for the energy usage of cameras and food. Given the lack of data on cameras and food in on location shoots, 30% of total energy-related emissions are added to account for the energy consumption of cameras and food catering equipment. 30% is likely an overestimate, so the sensitivity analysis tests 10%, 20% and 40%.

A sensitivity analysis is also conducted on the number of PC computers needed in a VP set up. According to an industry webpage, 7 computers are used in the VP set up for Scenario 3. Because no data was obtained about the number of computers for the remaining scenarios, the same number of computers were assumed for Scenarios 1 and 2. However, it is likely that there is variation in the number of computers for different scenarios based on the complexity of the scene and background. Additionally, the calculation for computers does not account for running the energy-intensive game engine system in VP productions. Thus, the sensitivity analysis looks at how the delta emissions/minute values change for computers greater than 7. An industry professional we spoke with mentioned that their studio used approximately 30 computers running at half capacity. However, this value varies greatly between production companies and the exact emissions for each were not able to be quantified.

Two sensitivity analyses are conducted for estimation of it taking 25 hours to hypothetically shoot Scenario 2 conventionally. The first examines the assumption that it takes 5 hours each day for 5 days to shoot Scenario 2 conventionally, on location, by changing the number of hours of conventional shoot. The second also changes the number of hours of conventional shoot, but replaces diesel generators to R99 generators to see how delta emissions per minute would change if a production were to elect a cheaper fuel option.

Lastly, a sensitivity analysis is performed for the CO_2 emission rate of an HVAC system, because the emissions generated from the industrial-size HVAC systems in the studios were scaled from the emissions of a 1.4 ton residential AC unit. Given that the emissions from HVAC may not increase at a 1 to 1 ratio with tonnage, the analysis focuses on how increasing the emission rate for the HVAC system would affect delta emissions per minute for all three scenarios.

Results

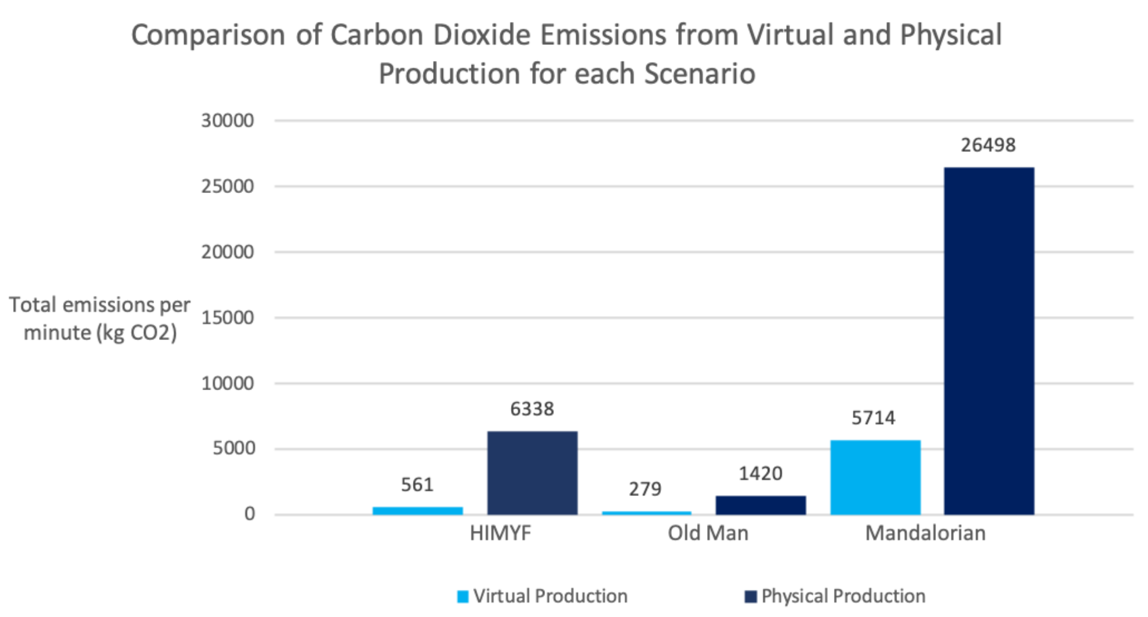

Figure 2: The total emissions per minute for each scenario, shot in virtual production and physical production

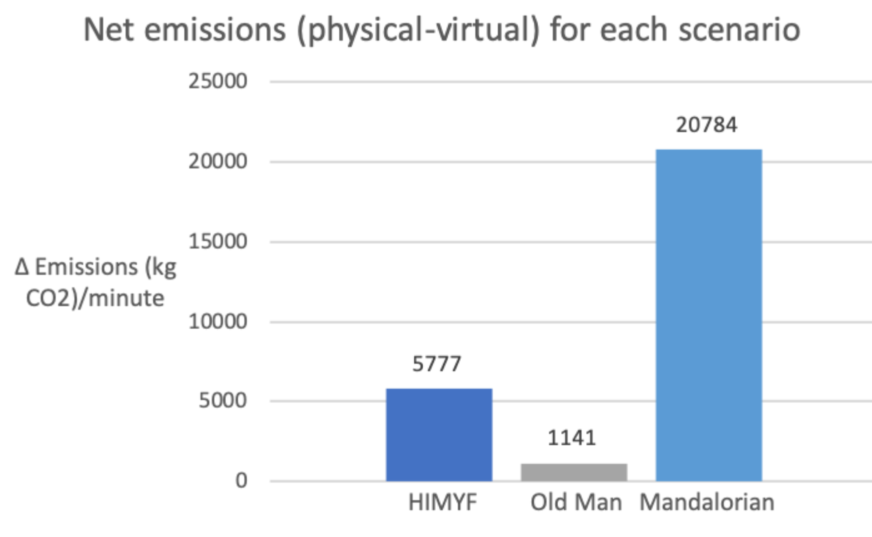

Figure 3: The net emission obtained by subtracting the emission from shooting scenes virtually from the emission of shooting them physically

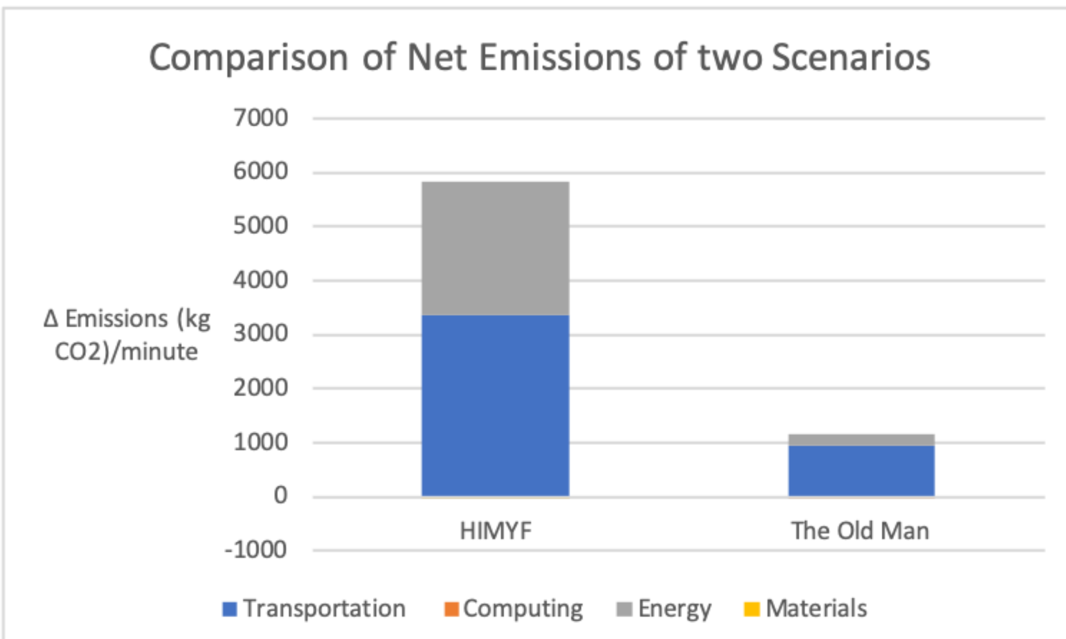

Figure 4: The net emission obtained by subtracting the emission from shooting scenes virtually from the emission of shooting them physically with a sector specific breakdowns for comparison between two scenarios

In Scenario 1, VP produces 561 kg CO_2/min while the conventional, on-location method produces 6,338 kg CO_2/min (Figure 1). VP produces only 9% of the emissions that a conventional shoot of the same scene across the country generates. In Scenario 2, VP produces 279 kg CO_2/min while the conventional, on-location method produces 1,420 kg CO_2/min. VP produces 19.6% of the emissions that a conventional shoot of the same scene produces Finally, in Scenario 3, VP produces 5,714 kg CO_2/min while the conventional, on-location method produces 26,498 kg CO_2/min. VP produces only 22% the emissions that the conventional shoot of the same scene with a constructed set produces.

The difference in emissions between VP and conventional per minute per scene is 5777 kg CO_2/min for Scenario 1, 1141 kg CO_2/min for Scenario 2, and 20783.5 kg CO_2/min for Scenario 3 (Figure 2).

Transportation

Our results indicate that shooting conventionally yields greater transportation-related CO_2 emissions for both Scenarios 1 and 2. While transportation is a component of Scenario 3, transportation emissions are not calculated as both a conventional shoot or a shoot using VP would take place at a soundstage. As our transportation calculations do not account for the transport of sets and materials, there would be no significant comparative difference in the types of vehicles and mileage driven in Scenario 3.

Shooting Scenario 1 conventionally yields 52 times more transportation-related CO_2 emissions per minute of scene than shooting it using VP. A conventional shoot generates 66 kg CO_2/min, whereas shooting it on the volume generates 3,432 kg CO_2/min. The largest contributor to this difference is the air travel required in a conventional shoot. Emissions from airplanes (7,887 kg CO_2) account for approximately 97% of the total transportation emissions (8,168 kg CO_2) in a conventional shoot of Scenario 1.

The transportation emissions benefits of shooting on VP is less dramatic for Scenario 2, which does not require air travel in either the conventional or VP shoot. Shooting Scenario 2 conventionally generates 1,026 kg of transportation-related CO_2 emissions per minute of scene and shooting it using VP generates 77 kg of transportation-related CO_2 emissions per minute of scene, giving a factor of approximately 13. The most significant contributor to this difference is the 30 gasoline passenger cars and 10 gasoline trucks required in a conventional shoot of Scenario 2. Gasoline passenger car and gasoline truck emissions total to 3,603 kg CO_2 (2,474 kg CO_2 and 1,129 kg CO_2 from gasoline passenger cars and gasoline trucks, respectively), which accounts for 59% of the total transportation emissions (6,156 kg CO_2) in a conventional shoot for Scenario 2. Shooting Scenario 2 using VP does not require either gasoline passenger cars nor gasoline trucks, and the only transportation-related emissions come from the 2 gasoline SUVs that are needed to shoot the background and 5 large diesel trucks for trailers at the soundstage.

Computing

When comparing the life cycles of conventional and virtual production, computing is one of the only sectors where the carbon emissions on the virtual production side will be higher than those on the conventional. Because we estimate that the same number of computers are used to run the LED walls in each scenario, the only variance in emissions between scenarios comes from the different shoot lengths. For Scenario 1, assuming 7 PC computers were running for 12 hours, virtual production generates 8,584 gCO_2/min more emissions than conventional production. Similarly, for Scenario 2, with the same number of computers running for 24 hours, virtual production generates 6810 gCO_2/min more emissions than conventional production. Finally, for Scenario 3, 7 PCs running for 36 hours generates 11,308 gCO_2/min during virtual production.

Energy

The sources of carbon emissions are largely different between in-studio (VP production of all scenarios and conventional filming of Scenario 3) and on location (conventional filming of Scenario 1 and 2). First, HVAC was only accounted for in-studio. HVAC emissions on-location were accounted for in generator emissions. For VP for Scenario 1, HVAC had significant emissions at 77,386 g CO_2/min (18% of Scenario 1 VP energy emissions) and for Scenario 2, HVAC had similarly significant emissions at 61393 g CO_2/min (32% of Scenario 2 VP energy emissions). The conventional filming of Scenario 3 had more emissions (302,056 g CO_2/min, 96% of Scenario 3 conventional energy emissions) for HVAC than VP (226,542 g CO_2/min, 13% of Scenario 3 VP energy emissions) because the HVAC was used for longer in conventional.

Next, the impact of trailers stems solely from their beginning and end-of-life stages due to their use stages accounted for by generators and their grid power emissions. This led to a very small emissions result, as a trailer's modern lifetime is 55 years. Scenario 1 for VP was shot at the studio and had 4 trailers total, while conventional had 8 trailers due to it being on location. Scenario 2 for VP had 2 trailers total, while conventional had 5 total. Scenario 3 had the same amount of trailers for VP and conventional, as they were both filmed on the lot and thus extra trailers were not needed.

Next, LED panel emissions were only present in VP. The emissions per minute for LED panels were lowest in Scenario 2 (132,584 g CO_2/min), higher in Scenario 1 (363,699 g CO_2/min), and highest in Scenario 3 (1,547,445 g CO_2/min). Scenario 2 LED panel emissions were 68% of the total VP energy emissions for Scenario 2. Scenario 1 LED panel emissions were 82% of the total VP energy emissions for Scenario 1. Scenario 3 LED panel emissions were 87% of the total VP energy emissions for Scenario 3.

Generator emissions were only present on location, which was the case for conventional filming of Scenarios 1 and 2. Generator emissions were lower per minute in Scenario 2 at 301,585 g CO_2/min, than Scenario 1 which had 2,232,052 g CO_2/min. This large discrepancy is due to the use of diesel out of state and renewable diesel in California. Scenario 2 generator emissions were 77% of the total conventional energy emissions for Scenario 2. Scenario 1 generator emissions were 77% of the total conventional energy emissions for Scenario 1. Scenario 3 had 0 generator emissions due to both VP and conventional taking place on a studio lot where grid power is used instead of generators.

The use of traditional lighting used in conjunction with the Volume in VP was accounted for in all three scenarios with the addition of 1 BP2 LED panel to the count of LED panels for each scenario. In the conventional filming of Scenario 3, lighting produced 301,585 g CO_2/min, accounting for 4% of conventional energy emissions for Scenario 3.

Camera emissions were accounted for only on location, due to the negligible and fairly incalculable nature of their grid and lifetime emissions. On-location camera use was calculated within the addition of an extra 30% of conventional energy emissions for Scenario 1 and Scenario 2. The extra 30% was also attributed to food trucks and catering.

Materials

Given the difference between the scenarios analyzed, material usage varied widely from being a negligible factor when comparing virtual production and conventional shooting, to being among the largest contributors of CO_2 emissions.

Scenario 1 has a moderate discrepancy of emissions between conventional shooting and virtual production, with virtual production requiring more material usage. The conventional approach requires no extra material, while the virtual production filming requires material used to construct a portion of a bridge. The expected emissions generated by the construction of the bridge segment total 103 kilograms of CO_2 (44 kg per minute of film).

Scenario 2 has no difference in material usage between virtual production and conventional filming methods.

Scenario 3 has the largest difference of material usage between virtual production and conventional filming, with material use for the conventional method accounting for 141,910 kilograms of CO_2 emissions (26,183) kg per minute of film. The virtual production material usage accounted for 21,287 kilograms of CO_2 emissions (3,928 kg per minute of film), which was 15% of that for the conventional approach.

Discussion

Our research has significant insights into the environmental impact of virtual production (VP) as an alternative shooting method in the film industry. Based on an industry-wide consensus, VP involves shooting approximately 30% more material within the same amount of time compared to conventional shooting methods, which can serve as an incentive to production studios. This indicates that the 12 hours of VP shoot in Scenario 1 captures 30% more material than the conventional shoot did. Thus, a comparison of a conventional and VP shoot of Scenario

1 may not be considering the same quality of scene. To normalize the delta emissions values by the same amount of material shot, alternative numbers were calculated by dividing the 12 hours, which encompasses 30% more material, by 1.3 to get 9.2 hours. The same method was used to calculate new VP shoot hours for Scenario 2. In Scenario 2, 24 hours of VP shoot would cover 30% more material than the conventional shoot. To get equal amounts of material, the VP shoot would take 18.5 hours. Scenario 3 did not require this adjustment as the calculated shooting times (36 and 48 hours for VP and conventional, respectively) already accounted for the increased material capture in VP.

There also is a potential rebound effect that can influence calculations; as VP enables faster shooting, it can potentially lead to higher-quality material being captured compared to conventional shooting footage. This indicates whether the quality of scenes should be taken into account when calculating emissions. If the quality of scenes captured in VP is consistently higher than in conventional shooting,potentially leading to different emission comparisons. Additionally many of the values discussed, especially those of conventional shooting, are hypothetical in nature as different producers have their own unique styles for shooting and production preferences, which can result in different lengths of time when capturing the same scene. The amount of hours needed for conventional shooting are estimates from industry professionals who were consulted, so it's important to keep in mind that those numbers may not be universally applicable.

In terms of the delta emissions value, which is the difference between total emissions from conventional shooting and virtual production, Scenario 1 and Scenario 2 show contrasting results despite being filmed with similar materials under comparable conditions. The smaller delta emissions value in Scenario 1 can be attributed to the difference in fuel sources used for the generators. For shooting at an out-of-state location, Scenario 1 would rely on diesel fuel, which leads to higher emissions compared to Scenario 2 in California, where R99 fuel was used. Moreover, the transportation sector plays a significant role, as the additional out-of-state travel in Scenario 1 contributes to extra emissions. For Scenario 3 there is a significant difference in emissions, but this is largely attributed to the amount of materials used which have their own separate emissions factors.

There are also certain limitations that would indicate inaccurate results, particularly importantly is the lack of available data and accurate reporting of materials used during filming. This project demonstrates the need for more comprehensive and precise reporting to justify the environmental impact of materials in the film industry. The lack of life cycle assessments for materials within different sectors further lessens understanding of their environmental implications. Making it more essential to continue making this data more available and up-to-date to provide studios with accurate models and representations of their environmental impact. Moving forward there should be a focus on updating the life cycle data for materials not included in this study, as well as incorporating pre- and post-production phases to obtain a comprehensive understanding of the overall environmental impact of film production.

Transportation

This research shows that the benefits of virtual production are more apparent when there is air travel involved in the shoot. This was the case in Scenario 1 where using virtual production reduced carbon emissions. Thus, this data can be useful to make the case for using virtual production in lieu of flying to a location when production is planning shoots. The benefits are less prevalent when the shoot involves driving or travel by road, which was the case in Scenario 2. It is also important to note that transportation emissions were not calculated for Scenario 3 because the use case was to understand the impact of a complicated set build. Thus, transportation was not a variable important for the comparison because the emissions would nullify each other in a comparison.

Computing

Computing is an interesting sector to look at when considering the benefits of virtual production over conventional production. Calculations to determine the emissions of gCO_2 for PC computers relies on the computing power in kWh that is required to run the graphics used for the LED walls. As computing is a variable that is only considered on the virtual production side, any improvements in the efficiency of computing power has the potential to improve the benefits of virtual production over conventional production. This means that our team's overall results are likely to become more and more conservative over time as technology improves.

Energy

This research sheds light on the significant role of energy consumption that is required in production, either VP or conventional shooting methods. HVAC power consumption is a large contributor to energy consumption and CO_2 emissions, particularly in relation to mitigating the heat generated by the LED panels and cooling the large studios. Therefore, addressing the energy efficiency and carbon emissions of HVAC systems should be a priority across various industries. Additionally, the implications of this research highlight the need for increased investment in energy-efficient and carbon-neutral HVAC systems, considering their prolonged usage during production shoots. Therefore, it would be beneficial to conduct further life cycle assessments on HVAC systems, specifically focusing on their efficiency during long shoot periods.

Due to the use of modern and more efficient production trails, the contribution to CO_2 emissions are relatively small and the trailer's contribution remains relatively similar between virtual and conventional production. VP offers an advantage in terms of reduced emissions compared to conventional production, as the majority of the production takes place in the studio rather than on location so less trailers are necessary. On-location production often requires additional generators and trailers, leading to increased energy consumption and emissions.

Therefore to have the most positive impact on reducing emissions, reducing the amount of trailers running on diesel is vital.

Focusing specifically on LED panels, emissions are only present in VP scenarios as LED panels are what makes up the VP wall, and aren't included for the conventional shoots. The size of the LED panel volume varies significantly and can be associated with a genre of the production to which would continue to affect the quantity of emissions from LED panel energy consumption. The emissions were lowest in Scenario 2, followed by Scenario 1, and highest in Scenario 3, as the amount of LED panels required to film the individual scenes varied depending on the complexity of background displayed on the size of the volume wall. This discrepancy suggests that different scenarios have distinct energy requirements and associated emissions. Also, due to the lack of available LCAs on LED panels it is essential that more LCAs be conducted specific to this technology. This information can guide industry stakeholders in making informed decisions regarding LED panel usage, including potential improvements in design, manufacturing processes, and end-of-life management.

For generators used for trailers and general on-location power needs, a notable difference in emissions emerged between Scenario 1 and Scenario 2, which can be attributed to the type of fuel used. Scenario 1 utilized diesel generators to film conventionally at an out-of-state location, whereas Scenario 2 employed R99 generators in California. Despite Scenario 1 generators running for approximately half the duration of Scenario 2 generators (14 hours vs. 25 hours), the emissions in Scene 1 were 2.93 times higher. This contrast is due to the significant difference in emissions factors between R99 and diesel fuels that have been established by extensive life cycle analysis. These findings indicate the large potential impact of switching to R99 generators in reducing overall emissions. Additionally, providing the percentage of CO_2 emissions contributed by generators in Scenario 1 compared to their proportion in Scenario 2 would offer further insight into the relative significance of generators in each scenario. It is important to note that in Scenario 3, generators were not used, as the production relied solely on the grid available at the studio lots and as indicated in the lower energy emission values. This demonstrates the potential for emissions reduction by leveraging grid electricity and minimizing the reliance on generators. It can also help strongly advocate for a widespread transition to R99 generators targeted towards production studios in charge of shooting these different scenes. The comparison between Scenario 1 and Scenario 2 clearly demonstrates this potential for substantial emissions reductions by replacing diesel generators with R99 generators. Implementing this switch across the board in the industry could result in a significant overall decrease in carbon emissions.

By addressing these areas and encouraging collaboration among industry stakeholders, we can drive innovation and advancements in HVAC systems, LED panel technology, generator design, cameras, and lighting. Ultimately, these efforts will contribute to more energy-efficient and sustainable production practices in the entertainment industry.

Materials

Material use across the scenarios was highly variable, and our research indicates that across the filmmaking industry, material usage for scenes is highly specific to the scene in question. Scenario 1 requires materials for set-building on the virtual production side but not on the conventional side. In this scenario, the benefits of virtual production in other sectors vastly outweighs the environmental cost of requiring material use for virtual production. Scenario 2 does not require any change in material use between virtual production and conventional shooting as is the case with many outdoor or car scenes.

Scenario 3 sees the highest use of materials out of all scenarios, and material use is the largest factor in the difference of emissions between virtual production and conventional shooting. Scenario 3 requires extensive set building across a large area as well as a large amount of props spread within the space. The calculations estimated the materials used and amounts of those materials based on all available data. Due to the reuse of props and prevalence of prop warehouses studios can utilize, 75% of the total material emissions on the conventional side were subtracted to account for reuse. For the virtual production material usage of Scenario 3, we estimate that 15% of the non-reused materials used on the conventional side would be required.

Overall, material usage is only reduced by virtual production in Scenario 3; however, that reduction is the largest reduction of a sector's emissions across all three scenarios. Furthermore, while Scenario 1 requires more material usage on the virtual production side, virtual production still reduces emissions for the scene overall. Based on these results, material use is an important factor to look into when considering virtual production. While the relevance and impact of material usage may be highly dependent on the scene, it can be a hugely significant consideration for scenes that do have high material use.

Sensitivity Analysis

Various sensitivity analyses were conducted in order to determine how our emissions values would change in the case of uncertainty, in this case largely due to lack of available data and assumptions. Because a sensitivity analysis shows how our results will change if we were to change our assumptions, it can be used to help inform decision makers of the critical parameters which have the largest impact on our results. By altering the percent change in a given factor, we are interested in analyzing the change in emissions, also referred to as delta, per minute of scene which is our functional unit.

Table 1: Sensitivity analysis table for the percentage of materials recycled

% of materials recycled	Δ Emissions/minute of scene (kg CO2/min) for Scenario 3
45%	47,490
55%	38,588
65%	29,686
75%	**20,784**
85%	11,881

Table 1 shows a sensitivity analysis which was conducted on the percentage of materials recycled in Scenario 3, the Mandalorian. Changing the percentage of materials recycled dramatically changed the delta CO_2 emissions per minute of scene, which is reasonable given that Scenario 3 is a particularly materials-intensive scene. Lowering the percentage by 20% to 55% materials recycled nearly doubled the delta CO_2 emissions per minute of scene from 20,784 kg CO_2/min to 38,588 kg CO_2/min, resulting in a 85.7% change in favor of VP. Therefore it can be concluded that increasing the percentage of reuse for materials can drastically reduce carbon emissions for a production.

Table 2: Sensitivity analysis table for the percent added energy to account for cameras and food

Added energy to account for cameras and food	Δ Emissions/minute of scene (kg CO2/min) for Scenario 1	Δ Emissions/minute of scene (kg CO2/min) for Scenario 2
10%	5,330	1,081
20%	5,554	1,111
30%	**5,777**	**1,142**
40%	6,001	1,172

Table 2 shows a sensitivity analysis which was performed on the addition of energy to account for cameras and food. Changing the original 30% estimate to 10% in Scenario 1, resulted in a 7.7% change from 5,777 kg CO_2/min to 5,330 kg CO_2/min, reducing the emissions difference between conventional and virtual productions. Changing the original 30% estimate to 10% in Scenario 2 resulted in a lower percentage change of 5.3%.

Table 3: Sensitivity analysis table for the number of computers

Original number of computers	Percentage Change	New number of computers	Δ Emissions/minute of scene (kg CO2/min) for Scenario 1	Δ Emissions/minute of scene (kg CO2/min) for Scenario 2	Δ Emissions/minute of scene (kg CO2/min) for Scenario 3
7	**0%**	**7**	**5,777**	**1,142**	**20,784**
	100%	14	5,769	1,135	20,772
	200%	21	5,761	1,128	20,761
	300%	28	5,752	1,121	20,750
	400%	35	5,743	1,114	20,738
	500%	42	5,734	1,107	20,727

Table 3 shows a sensitivity analysis on the number of PC computers needed in a VP set up. While increasing the number of computers would lower the apparent benefits of VP, the results show that changing the number of computers had no significant effect on the delta emissions per minute of scene for all three scenarios. For Scenario 1, a 500% change in the number of computers from 7 to 42 computers resulted in a 0.7% change in delta emissions per minute of scene. The same change in computers in Scenario 2 and Scenario 3 yielded a 3.0% change and a 0.3% change, respectively, in delta emissions per minute of scene.

Table 4: Sensitivity analysis table for the number of hours it takes to shoot Scenario 2 conventionally

Original time it takes to shoot Scenario 2 conventionally (hours)	Percentage Change	New time it takes to shoot Scenario 2 conventionally	Δ Emissions/minute of scene (kg CO2/min) for Scenario 2
25	-20%	20	1,063
	-10%	22.5	1,102
	0%	**25**	**1,142**
	10%	27.5	1,181
	20%	30	1,220
	30%	32.5	1,260
	40%	35	1,299

Table 5: Sensitivity analysis table for the number of hours it takes to shoot Scenario 2 conventionally when R99 generators are replaced with diesel generators

Original time it takes to shoot Scenario 2 conventionally (hours)	Percentage Change	New time it takes to shoot Scenario 2 conventionally	Δ Emissions/minute of scene (kg CO2/min) for Scenario 2 when R99 generators are replaced with diesel generators
25	-20%	20	2,632
	-10%	22.5	2,868
	0%	**25**	**3,103**
	10%	27.5	3,339
	20%	30	3,575
	30%	32.5	3,810
	40%	35	4,046

Additionally, two sensitivity analyses were conducted on the time it takes to shoot Scenario 2 conventionally and the time it takes to shoot the scene when R99 generators are replaced with diesel (Table 4 and Table 5, respectively). Changing the time it takes to shoot Scenario 2 conventionally yields greater percentage change in delta emission per minute values when the generators run on diesel. For example, increasing the conventional shoot time by 20% to 30 hours yields a 15.2% change with diesel generators, and a 6.9% change in delta emissions per minute of scene with R99 generators. As the length of shoot time increases, the difference in the amount of change in emissions per minute generated by a shoot with diesel generators and that produced by a shoot with R99 generators increases. For example, a 20 hour conventional shoot of Scenario 2 using diesel generates a delta emission/minute of scene value of 2,632 kg CO_2/min, which is 2.5 times greater than the that for a 20 hour conventional shoot of Scenario 2 using diesel R99 generators (1,063 kg CO_2/min). A 35 hours conventional shoot of Scenario 2 using diesel yields a delta emission/minute value of 4,046 kg CO_2/min, which is 3.1 times greater than when using R99 fuel (1,299 kg CO_2/min).

Table 6: Sensitivity analysis table for the CO_2 emission rate of HVAC systems

Original CO2 emission rate for HVAC system (g CO2/hr*ton)	Percentage Change	New CO2 emission rate for HVAC system (g CO2/hr*ton)	Δ Emissions/minute of scene (kg CO2/min) for Scenario 1	Δ Emissions/minute of scene (kg CO2/min) for Scenario 2	Δ Emissions/minute of scene (kg CO2/min) for Scenario 3
171	**0%**	**170.5**	**5,777**	**1,142**	**20,784**

	50%	255.8	5,739	1,111	20,821
	100%	341.1	5,700	1,080	20,859
	150%	426.3	5,661	1,049	20,897
	200%	511.6	5,623	1,019	20,935
	250%	596.9	5,584	988	20,972

Lastly, a sensitivity analysis was performed for the CO_2 emission rate of an HVAC system. Increasing the CO_2 emission rate for HVAC had the biggest effect on Scenario 2, followed by Scenario 1, and Scenario 3. For Scenario 2, increasing the CO_2 emission rate for HVAC by 200% from 170.5 g CO_2/hr*ton to 511.6 g CO_2/hr*ton yielded a 10.8% decrease in delta emissions per minute of scene. For Scenarios 1 and 2, this same increase yielded a smaller 2.7% decrease and a 0.7% increase, respectively, in delta emissions per minute of scene.

Limitations and Challenges

Given the vast scope, novelty and complexity of this project there were some limitations and challenges we encountered. One of the greatest limitations in our project was working in a data-limited environment. Given how expansive a single production activity is, there is a limitation in obtaining aggregated data within a certain timeframe. To supplement gaps in our data, we used the best available scientific studies and obtained estimates by interviewing industry experts. For better confidence in our values, we conducted sensitivity analyses on values with high uncertainty. Another limiting factor in our analysis was the hypothetical nature of the conventionally shot alternatives for the scenarios. Industry professionals provided estimates as to how these scenarios would be shot without the use of virtual production, however, given the variance in how filmmakers and studios work, our conventional shooting estimates are hypothetically representative of how these scenarios could potentially be shot. As our data uses certain estimates and outdated scientific studies, it is crucial to interpret our findings not as conclusive or comprehensive, but rather as a reflection of the currently available data. Ongoing data refinement, especially as greater research on VP is published, is important to enhance the accuracy and completeness of our results. We intend for the transparency of our formulas and data sources incorporated into our model to allow future researchers to build upon our work, particularly as newer and improved data becomes available pertaining to VP.

Transportation

Due to the limited availability of specific data on prop materials and sets from clients, our team had to rely on estimates from team members themselves and professors who did not have direct involvement in the production of the specific scenarios. Consequently, there exists a considerable level of inherent uncertainty surrounding the quantities and sizes of props and sets. Considering this uncertainty, it was not feasible to accurately calculate emissions associated with the transportation of these props and sets. This is particularly crucial for scenario 3, which involves a substantial set build. Including the calculation of transportation-related emissions for props and sets would have favored VP, because a conventional shoot requires a larger physical construction of sets compared to a virtual production shoot.

Computing

Due to the novelty of the LED volume technology, there was limited data available online regarding the computing power required for VP. One article we found indicated that for Scenario 3, there were four PCs used to run the LED volume wall and an additional three to run the ‘brain bar’ which housed the game engine and VFX display (FX Guide, 2020). The LED wall mentioned in the article, which used the seven total computers, was a 180 degree wall composed of 1,326 individual LED screens. While not all of the scenarios were confirmed to have used a wall of the same dimensions, there was limited data to extrapolate. Unfortunately, industry professionals were not able to provide specific values for the numbers of computers used for each scenario so it was estimated that seven total computers were used for each VP section of each scenario. In reality, there may have been more or less computers used to fully operate the VP of each scenario. Additionally we were unable to account for the computing power used or saved in prep and post production, including the emissions generated from graphically constructing the backdrops on VP. We were also unable to find information regarding the energy requirements for running the game engine for VP. Also, these results do not factor in the additional emissions that would be produced during the pre-production phase while programming the LED screens and preparing the graphics to be used during virtual production. They also do not factor in any emissions on the conventional side that would be produced in post-production for tasks like green screen processing or lighting fixes.

Energy

The bulk of the energy section comes from the LED panels, which are the main component of virtual production. There are no existing LCAs on LED panels specifically, so LED monitors were used as a proxy to obtain data on raw materials and manufacturing. The distribution was calculated based on likely shipping size. The weight of the LED panel frame was calculated by subtracting the weight of the LED panel display from the overall weight, and scaled all our calculations to size. Unfortunately, this method was rather time consuming and not very exact. An average ratio of 1.75:1 was assumed for BP2:CB5 across all VP stage sizes when no other data was available, since the data for exact number of each type for each stage was unavailable. However, this ratio is likely not the same for each stage type.

Generators made up a significant portion of the energy sector. The number of generators that would be used for conventional shooting was estimated, and it varies greatly by scenario. For example, in Scene 1, it was assumed that a third generator would be needed for lighting alone, but it is hypothetical. There is also variation in the lifespan, ranging from 10k to 30k hours. This affects the percentage of production emissions that can be attributed to use during these conventional shoots. There was a lack of LCA data regarding HVAC, so estimates were made based on assumptions from other sources that focused on the manufacturing of the HVAC of a basic system and not necessarily used for production studios. There was no confirmation on the HVAC for the smaller volume stage, so this was based on the large stage and making ratios based on square footage. There was also a lack of data regarding the weights of the trailers that were needed to calculate the life cycle assessment calculated by the GREET model. This required making estimates based on available dimensions and similar structured trailers. The assumptions of how many of each trailer was based on the SPA clients who have worked on production and could estimate how many would have theoretically been used based on their previous experiences on other projects.

Quantifying carbon emissions for conventional shooting proved challenging because it is purely hypothetical. This is especially true for cinematic lighting, because the decisions on which products are used are artistic and differ depending on the director of photography. Unfortunately, information on conventional lighting products used in virtual production was not able to be obtained, so it was assumed that the LED panels provided all the necessary lighting. For conventional shooting, guidance was provided from outside sources. Furthermore, there are currently no LCAs for film lighting.

Materials

One of the main challenges for the materials sector of this project, particularly in Scenario 3, was that there was little information available regarding the composition of the props used on the VP set. Additionally, it was difficult to precisely determine what types of materials would have been used to make the props if the scene was constructed conventionally. Only one behind-the-scenes video online was found, which gave some information about the composition of the scene which made it hard to determine the exact dimensions and quantity of each prop (Industrial Light & Magic, 2020). Additionally, in the final scene itself the background was quite blurry, making it hard to determine characteristics of the prop. Because of this, we met with an independent set designer who gave us some insight on how he would have constructed the materials, but overall a lot of it was extrapolation. We also ran into some struggles with finding correct LCAs for each given material and had to utilize what academic literature was available. This meant that for some materials, a different, similar material was considered instead of what it likely would have been constructed from. For example, there was no academic literature available accounting for the emissions of Luan wood which is the film industry standard for wooden prop materials, so a softwood plywood LCA was used instead.

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Appendix

Appendix A: Estimates based on literature, anecdotal evidence from industrial professionals, and environmental data used for our model

General

I. Estimates Based on Literature
    A. Energy
        1. LED monitor EF for a 15" monitor is 104.68 kg CO_2-eq. (Bhaker et. al, 2015) (Andersen et al., 2010).
        2. EF for BP2 raw materials and manufacturing based on LCA of an LED monitor: 0.029472616 kg CO_2-Eq/hour/panel (Bhaker et. al, 2015) (Andersen et al., 2010).
        3. EF for CB5 raw materials and manufacturing based on LCA of an LED monitor: 0.084680079 kg CO_2-Eq/hour/panel (Bhaker et. al, 2015) (Andersen et al., 2010).
        4. The raw materials and manufacturing EF for BP2 LED panel frames is 0.004622709 kg CO_2/BP2 panel/hour (He et al., 2020).
        5. The distribution for BP2 LED panels value based on LCA of LED monitors is 0.000931182 kg CO_2-Eq/hour/panel (Bhaker et. al, 2015) (Andersen et al., 2010).
        6. The production emission total for CB5 LED panel frames is 0.004173578 kg CO_2/CB5panel/hour (He et al., 2020).
        7. The distribution for CB5 LED panels EF value based on LCA of LED monitors is 0.001905711 kg CO_2-Eq/hour/panel Bhaker et. al, 2015) (Andersen et al., 2010).
        8. LED panels are shipped in flight case size boxes from China to the US. (ROE, n.d.).
        9. The ROE BP2 average power consumption is 95 watts. (ROE, n.d.).
        10. The ROE CB5 average power consumption is 250 watts. (ROE, n.d.).
        11. The production emissions for generators is 0.6005074 kg CO_2/gallon (Benton, 2016).

II. Anecdotal Evidence from Industry Professionals
    A. General
        1. The number of hours one normal day of shoot would take would be 12.
    B. Energy
        1. The number of generators used in VP and conventional in-studio shoots is 0.
        2. The LED panel make and models are ROE BP2 and ROE CB5.
        3. The ratio of BP2 to CB5 panels is 1:75:1.
        4. The 10,000 hour lifetime from ROE is in hours, not kWh.
        5. The LED panel watts used average wattage rather than max.
        6. The generator models used are 1400, 1600, and 1800 amps.

7. Generators were operated for 1 hour before and after shooting time.
8. LED panels were not used on location or in conventional studio shoots.
9. The percentage of energy added to the energy emissions total for on location shoots is 30%.

III. Environmental Data

A. General

1. The California average electricity factor for CO_2 is 556.44 lb/MWh or 0.252396394 kg CO_2/kWh. (PEAR)

Scenario 1

I. Estimates Based on Literature

A. Transportation

1. The roundtrip distance is 4950 miles (LAX – JFK, n.d.).
2. Type of aircraft used for the passenger flights is Boeing 767 (https://upgradedpoints.com/travel/best-ways-to-fly-from-los-angeles-lax-to-new-york-jfk/#:~:text=Delta%20Air%20Lines%20flies%20a,that%20of%20an%20international%20flight).
3. An ICEV class 8 day-cab truck is 16,631 lbs (Source: "Class 8 Day-cab Trucks" tab of GREET2_2022). This category of trucks was used to calculate large diesel trucks pulling trailers, because industrial professionals have shared that Ford F550s, a type of day-cab truck, are commonly used to pull trailers (Sunset Studios, n.d.).
4. An ICEV pick-up truck made of conventional materials is 4,491 lbs (Source: "PUT" tab of GREET2_2022). This category of trucks was used to calculate gasoline trucks to account for less heavy-duty trucks used in film productions (Maher, 2015; *Grip trucks*, n.d.).
5. To calculate emissions, the higher heating values (HHV) were used, as opposed to the lower heating values (LHV), because according to the EPA, HHV is typically used in the United States and Canada (EPA, 2016).

B. Energy

1. For a basic HVAC system, for 1.4 tons it releases 5,730 g CO_2 per day, and with the energy consumed has a 33-75% energy for consumption actually used. There is 171 g CO_2 per ton and 171 g CO_2 per hour (Kilgore, 2023).
2. With the CO_2 emission rate being 171 g CO_2, to calculate the emissions for HVAC of that scenario that was filming for 14 hours in VP and conventionally you multiply the emission rate by amount of tons and number of hours to get total emissions.
3. The weights of the trailers determined their lifetime emissions. These weights were assumed based on the dimensions given on the Quixote website and were then plugged into the GREET excel spreadsheet to calculate emissions (Sunset Studios, n.d.).
4. The lifetime of the trailer was given from this literature as an average for modern trailers is 55 years, (Kaiser, 2022).

C. Computing
   1. From an article by FX guide (Seymour, 2020) about the production of Scenario 3, four PCs were used to run the VP wall and were all linked up and running nDisplay. There were three additional PCs used to operate the 'brain bar' area. There was no other available literature, or industry contacts, that could estimate the amount of computers used for this scene for VP, so we used the FX guide values.

II. Anecdotal Evidence from Industrial Professionals
   A. General
      1. It took 2 days to shoot the scene using virtual production.
      2. It would take 14 hours, which is one full shoot day to shoot the scene conventionally on location on the bridge.
      3. It took 2 on location days to shoot the scene for background creation for virtual production.
      4. The number of trailers used while filming that scene was provided by industry professionals. These estimates were given for the number of Double cast trailers for the main actors in the scene, makeup & hair trailers, wardrobe trailer, Office trailers for the production team, and honeywagon bathroom trailers.
   B. Transportation
      1. According to industry professionals, the hotel chosen for cast and crew traveling from Los Angeles would be at a 10 mile round trip distance.
      2. The number of gasoline passenger cars needed for shooting the scene using VP is 1, and it would be used for transporting 2 cameramen shooting background to display on the LED Volume.
      3. The number of large diesel trucks needed for shooting the scene using VP is 6. These trucks are used to pull the trailers for the shoot, which according to industry professionals are 2 double cast trailers, 1 hair and makeup trailer, 1 wardrobe trailer, 1 camera trailer and one grip electric trailer, adding up to a total of 6.
      4. Given that the camera people who shot footage for virtual production were hired locally, there was no air travel involved in shooting this scene using virtual production.
      5. The total number of miles that each gasoline passenger car drives in a VP shoot of the scene is 20 miles.
         a) The roundtrip distance of the hotel to the shoot location was earlier assumed as 10 miles and there are 2 on location days, requiring a distance of 20 miles to be traveled by the passenger car for the VP shoot.
      6. The total number of miles that each large diesel truck drives in a VP shoot of the scene was 28 miles, given that, according to industry professionals each support vehicle would drive 7 miles one way. This would equal a 14 mile round trip on each day of shooting for a total of 28 for 2 days of shooting.

7. The total number of gasoline SUVs needed for shooting the scene conventionally is 3. According to industry professionals, 3 vans are needed (1 for director and GP, 1 for actors, 1 for miscellaneous).
8. The total number of gasoline passenger cars needed for shooting the scene conventionally are approximated to be 12.
9. The total number of gasoline trucks needed for shooting the scene conventionally is 10.
10. The total number of large diesel trucks needed for shooting the scene conventionally is 9.
11. The total number of passengers flown from LA to an out-of-state filming location for the shoot of the scene in conventional production would have been 10. This includes the director, director of photography, first and second assistant directors and 6 main cast members.
12. The basecamp for a scene would be 5 miles away, making it a 10 mile round trip. Thus the gasoline passenger cars, gasoline SUV's and diesel trucks would travel a total of 10 miles per day in a conventional, on location shoot.

C. Energy

1. For HVAC on location, the system is included in the trailers so any emissions from HVAC will be included in the calculations for trailers and generators.
2. For HVAC in VP, the volume soundstage is 11,000 square feet, so using the ratio from the bigger VP stage of 25,350 square feet with a 200 ton HVAC system, it can be assumed that a HVAC system of 86.7 tons would have been used for a 11,000 square foot stage.
3. HVAC was running the entire time to shoot the scene for 14 hours.
4. The number of ROE BP2 panels used was 701 panels.
5. The number of ROE CB5 panels used was 200 panels.
6. The number of extra LED BP2 panels to account for additional VP LED lighting was 1.
7. The generators used were 3 1400 amp generators.
8. The generators were running for 14 hours.
9. Diesel fuel was used for the generators.
10. The cameras used were the same for VP and conventional.

D. Computing

1. A computing power value of 0.8 kWh per computer was obtained via industry contacts.

E. Materials

1. The dimensions for flooring of a conventional set would be 20 x 30 ft.
2. Four coats of paint would be used for the railings, 3 coats for the white stripe down the center of the flooring.
    a) Flat medium paint was used, which is an acrylic paint.
    b) One coat would be 'primer,' followed by 2 coats of actual paint, and finished with a top coat of 'texture'.
3. Softwood plywood would be used for any props made out of plywood on set.

4. Linoleum would be used for flooring, which is the cheapest and most accessible material.

III. Environmental Data

A. Transportation

1. Values for fuel energy content, well-to-pump emissions, pump-to-wheel emissions, and vehicle cycle emissions were found in GREET1_2022 and GREET2_2022.
2. Values for vehicle fuel efficiency and fuel (emission factor) EF were found in PEAR. When possible, these PEAR values were updated with more recent values using the same source. For instance, PEAR gives the fuel efficiency of vans, pickups, and SUVs as “17.5” mpg using Edition 32 of the Transportation Energy Data Book. Using Edition 40 of the same source, this value was replaced with the updated fuel efficiency of 20.8 mpg.

B. Energy

1. For trailers: the lifetime emission assessment was calculated from GREET and then divided by the average lifetime of a trailer being 55 years or 481,800 hours for each type of trailer (Sunset Studios, n.d.).

C. Computing

1. The only available LCA that could be found for PC computers was out of Australia in 2012 (Sirait et al., 2012).
2. CO_2 emissions rates were taken from PEAR.

D. Materials

1. LCAs were used for paint, softwood plywood and linoleum.
   a) These LCAs (everything except wood) gave emissions values in gCO_2e. To convert between gCO_2e and gCO_2, we used the EEIO industry averages which accounts for the amount of GHG emissions were CO_2. We then multiplied this percentage times our gCO_2e values from the LCA.
   b) For paint, the % of total GHG which is CO_2 is 99.4% so we assumed there was a 1:1 ratio between CO_2 and CO_2e.

Scenario 2

I. Estimates Based on Literature

A. Transportation

1. An ICEV class 8 day-cab truck is 16,631 lbs (Source: “Class 8 Day-cab Trucks” tab of GREET2_2022). This category of trucks was used to calculate large diesel trucks pulling trailers, because industrial professionals have shared that Ford F550s, a type of day-cab truck, are commonly used to pull trailers (Kilgore, 2023).
2. An ICEV pick-up truck made of conventional materials is 4,491 lbs (Source: “PUT” tab of GREET2_2022). This category of trucks was used to calculate gasoline trucks to account for less heavy-duty trucks used in film productions (Maher, 2015; *Grip trucks*, n.d.).

3. To calculate emissions, the higher heating values (HHV) were used, as opposed to the lower heating values (LHV), because according to the EPA, HHV is typically used in the United States and Canada (EPA, 2016).

B. Energy

1. For a basic HVAC system, for 1.4 tons it releases 5,730 g CO_2 per day, and with the energy consumed has a 33-75% energy for consumption actually used (Kilgore, 2023). There is 171 g CO_2 per ton and 171 g CO_2 per hour.
2. With the CO_2 emission rate being 171 g CO_2, to calculate the emissions for HVAC of that scenario that was filming for 14 hours in VP and conventionally you multiply the emission rate by amount of tons and number of hours to get total emissions.
3. The weights of the trailers determined their lifetime emissions. These weights were assumed based on the dimensions given on the Quixote website and were then plugged into the GREET excel spreadsheet to calculate emissions (Sunset Studios, n.d.).
4. The lifetime of the trailer was given from this literature as an average for modern trailers of 55 years (Kaiser, 2022).

C. Computing

1. From an article by FX guide (Seymour, 2020) on the production of Scenario 3, four PCs were used to run the VP wall and were all linked up and running nDisplay. There were three additional PCs used to operate the 'brain bar' area. There was no other available literature, or industry contacts, that could estimate the amount of computers used for this scene for VP so we went with the FX guide values.

II. Anecdotal Evidence from Industry Professionals

A. General

1. A 10-minute scene for Scenario 2 is equivalent to 15 pages of script.
2. To shoot this 10-minute sequence conventionally, actors and crew would have to drive approximately 50 miles from Los Angeles.
3. Shooting this 10-minute sequence using stagecraft technology would take 2 days.
4. Shooting this 10-minute sequence conventionally on location would take 5 days.
5. When shooting on location, there is a 3 hour window to shoot sunset. While golden hour lasts for a single hour, color correction in post production allows for a wider window of 3 hours.
6. HVAC would be running the entire time to shoot the scene for 14 hours. The number of trailers used while filming that scene was given by industry professionals. These estimates were given for the number of Double cast trailers for the main actors in the scene, makeup & hair trailers, wardrobe trailer, Office trailers for the production team, and honeywagon bathroom trailers.

B. Transportation

1. 30 gasoline passenger cars are needed for shooting a 10-minute sunset sequence conventionally on location. Each gasoline passenger car drives a total average of 200 miles.
    a) Total miles each gasoline passenger car drives = (50 miles from LA) + [5 days of shoot(10 miles/day from hotel to shoot location + 10 miles/day from shoot location to hotel)] + (50 miles to LA) = **200 miles**
2. 15 hybrid passenger cars are needed for shooting a 10-minute sunset sequence conventionally on location. Each hybrid passenger car drives a total average of 200 miles.
    a) Total miles each hybrid passenger car drives = (50 miles from LA) + [5 days of shoot(10 miles/day from hotel to shoot location + 10 miles/day from shoot location to hotel)] + (50 miles to LA) = **200 miles**
3. 5 electric passenger cars are needed for shooting a 10-minute sunset sequence conventionally on location. Each electric passenger car drives a total average of 200 miles.
    a) Total miles each electric passenger car drives = (50 miles from LA) + [5 days of shoot(10 miles/day from hotel to shoot location + 10 miles/day from shoot location to hotel)] + (50 miles to LA) = **200 miles**
4. 10 gasoline trucks are needed for shooting a 10-minute sunset sequence conventionally on location. Each gasoline truck drives a total average of 200 miles.
    a) Total miles each gasoline truck drives = (50 miles from LA) + [5 days of shoot(10 miles/day from hotel to shoot location + 10 miles/day from shoot location to hotel)] + (50 miles to LA) = **200 miles**
5. 5 large diesel trucks are needed for shooting a 10-minute sunset sequence conventionally on location. The main distinction between gasoline trucks and the large diesel trucks is that the large diesel trucks are used to pull trailers. Each large diesel truck pulls 1 trailer. The trailers needed include 1 double cast trailer, 1 hair and makeup trailer, 1 wardrobe trailer, 1 camera trailer, and 1 grip electric trailer. Each large diesel truck drives a total average of 100 miles. Given that the location has ample parking to set up a permanent basecamp, the trailers would not need to be moved every day. Once they are driven to the on-location site, they remain parked for the duration of the shoot, and are driven back.
    a) Total miles each large diesel truck drives = (50 miles from LA to base camp) + (50 miles from basecamp to LA) = **100 miles**
6. 4 gasoline SUVs are needed for shooting a 10-minute sunset sequence conventionally on location. No distinction is made between the SUV that the lead actors drive and the 3 SUVs with the extras, because an industry professional said that the extra SUVs would drive the same amount of miles as the main SUV, even if they are not visible throughout the entire 10-minute scene. Each SUV drives a total average of 300 miles.
    a) Total miles each SUV drives = (50 miles from LA) + [10 takes(20 miles/take)] + (50 miles to LA) = **300 miles**

7. 0 gasoline passenger cars are needed for shooting a 10-minute sunset sequence using VP.
8. 0 hybrid passenger cars are needed for shooting a 10-minute sunset sequence using VP.
9. 0 electric passenger cars are needed for shooting a 10-minute sunset sequence using VP.
10. 0 gasoline trucks are needed for shooting a 10-minute sunset sequence using VP.
11. 5 large diesel trucks are needed for shooting a 10-minute sunset sequence using VP. The main distinction between gasoline trucks and the large diesel trucks is that the large diesel trucks are used to pull trailers. Each large diesel truck pulls 1 trailer. The trailers needed include 1 double cast trailer, 1 hair and makeup trailer, 1 wardrobe trailer, 1 camera trailer, and 1 grip electric trailer. Each large diesel truck drives a total average of 40 miles.
    a) Total miles that each large diesel truck drives = (20 miles from Burbank to Santa Clarita) + (20 miles from Santa Clarita to Burbank) = **40 miles**
12. 4 gasoline SUVs are needed for shooting a 10-minute sunset sequence using VP. In a simple car scene consisting of only front and overhead shots, everything can be shot using the virtual stage and no on location shoot is necessary. Therefore, each gasoline SUV drives a total of 0 miles.
13. 2 gasoline SUVs are needed for shooting a 10-minute sunset sequence using VP. These SUVs are distinct from the stationary prop SUVs above. These SUVs are used to drive a small crew of approximately 7 people to the Antelope Valley to capture the background. Each gasoline SUV drives a total average of 100 miles.
    a) Total miles that each gasoline SUV drives = (50 miles from LA to base camp) + (50 miles from basecamp to LA) = **100 miles**

C. Energy
1. 0 lights would be used for conventional outdoor shooting during magic hour.
2. For HVAC on location, the system is included in the trailers so any emissions from HVAC will be included in the calculations for trailers and generators.
3. For HVAC in VP, the volume soundstage is 11,000 square feet, so using the ratio from the bigger VP stage of 25,350 square feet with a 200 ton HVAC system, it can be assumed that a HVAC system of 86.7 tons would have been used for a 11,000 square foot stage.
4. The number of ROE BP2 panels used was 301 panels.
5. The number of ROE CB5 panels used was 100 panels.
6. The number of extra LED BP2 panels to account for additional VP LED lighting was 1.
7. The generators used were 2 1400 amp generators and 1 1800 amp generator.
8. The generators were running for 25 hours.
9. R99 fuel was used for the generators.
10. R100 EF was an acceptable substitute for R99 EF.

D. Computing

1. A computing power value of 0.8 kWh per computer was obtained via industry contacts.

III. Environmental Data

A. Transportation

1. Values for fuel energy content, well-to-pump emissions, pump-to-wheel emissions, and vehicle cycle emissions were found in GREET1_2022 and GREET2_2022.
2. Values for vehicle fuel efficiency and fuel (emission factor) EF were found in PEAR. When possible, these PEAR values were updated with more recent values using the same source. For instance, PEAR gives the fuel efficiency of vans, pickups, and SUVs as “17.5” mpg using Edition 32 of the Transportation Energy Data Book. Using Edition 40 of the same source, this value was replaced with the updated fuel efficiency of 20.8 mpg.

B. Energy

1. For trailers: the lifetime emission assessment was calculated from GREET and then divided by the average lifetime of a trailer being 55 years or 481,800 hours for each type of trailer (Sunset Studios, n.d.).

C. Computing

1. The only available LCA we could find for PCs was out of Australia in 2012 (Sirait et al., 2012).
2. CO_2 emissions rates were taken from PEAR.

Scenario 3

I. Estimates Based on Literature

A. General

1. The number of trailers used while filming that scene was given by industry professionals. These estimates were given for the number of double cast trailers for the main actors in the scene, makeup & hair trailers, wardrobe trailer, office trailers for the production team, and honeywagon bathroom trailers.

B. Energy

1. For a basic HVAC system, for 1.4 tons it releases 5,730 g CO_2 per day, and with the energy consumed has a 33-75% energy for consumption actually used (Kilgore, 2023). There is 171 g CO_2 per ton and 171 g CO_2 per hour.
2. The CO_2 emission rate is 171 g CO_2.
3. The weights of the trailers determined their lifetime emissions. These weights were assumed based on the dimensions given on the Quixote website and were then plugged into the GREET excel spreadsheet to calculate emissions (Sunset Studios, n.d.).
4. The lifetime of the trailer was given as an average of 55 years for modern trailers (Kaiser, 2022).
5. The total area of the Volume wall was 11244.1 square feet (FXGuide, n.d.).

C. Computing

1. From an article by FX guide (Seymour, 2020), four PCs were used to run the VP wall and were all linked up and running nDisplay. There were three additional PCs used to operate the 'brain bar' area.
2. According to an online interview with industry professionals, it took 3 days to shoot Scenario 3 on VP (Kadner, 2021).

II. Anecdotal Evidence Based on Industrial Professionals

A. Transportation

1. Given that both conventional and VP shoots of this scenario would take place in Los Angeles, and our calculations are not accounting for the transportation of materials (sets/props), there would be no significant difference in transportation.

B. Energy

1. 0 lights would be used for conventional outdoor shooting during magic hour.
2. For HVAC on location, the system is included in the trailers so any emissions from HVAC will be included in the calculations for trailers and generators.
3. For HVAC in VP, the volume soundstage is 11,000 square feet, so using the ratio from the bigger VP stage of 25,350 square feet with a 200 ton HVAC system, it can be assumed that a HVAC system of 86.7 tons would have been used for a 11,000 square foot stage.
4. Assume HVAC was running the entire time to shoot the scene for 36 hours for VP and 48 hours for conventional.
5. The number of ROE BP2 panels used was 1586 panels.
6. The number of ROE CB5 panels used was 906 panels.
7. The number of extra LED BP2 panels to account for additional VP LED lighting was 1.
8. There were no generators used.

C. Materials

1. 75% of materials used in the construction for a conventional version of Scenario 3 would have been pre-existing and pulled from a prop storage warehouse. This number was corroborated by industry professionals.
2. 15% of materials that would have been used for conventional shooting of this scene would have also been used for physical props in VP. This number was corroborated by industry professionals.
3. Catwalks would be rented.

III. Environmental Data

A. Energy

1. For trailers: the lifetime emission assessment was calculated from GREET and then divided by the average lifetime of a trailer being 55 years or 481,800 hours for each type of trailer (Sunset Studios, n.d.).

B. Computing

1. The only available LCA we could find for PCs was out of Australia in 2012 (Sirait et al., 2012).
2. CO_2 emissions rates were taken from PEAR.

C. Materials

1. LCAs were found for softwood plywood, sheet aluminum, expanded polystyrene, paint, and steel (without slag as a byproduct).
    a) Sheet steel would have likely been used in set construction, but the only available LCA was for thin metal aluminum.
    b) LCAs for sheet aluminum, expanded polystyrene, paint, and steel gave emissions values in gCO_2e, which we had to convert to gCO_2. To do this, we used the EEIO industry averages which document the amount of GHG emissions that can be attributed to CO_2. We then multiplied this percentage by our gCO_2e values from the LCA.
        (1) For computing, the % of total GHG which is CO_2 is 99% so we assumed there was a 1:1 ratio between CO_2 and CO_2e
        (2) For styrofoam, the % of total GHG which is CO_2 is 96.6% so we assumed there was a 1:1 ratio between CO_2 and CO_2e
        (3) For paint, the % of total GHG which is CO_2 is 99.4% so we assumed there was a 1:1 ratio between CO_2 and CO_2e
        (4) For Steel, the % of total GHG which is CO_2 is 99.88% so we assumed there was a 1:1 ratio between CO_2 and CO_2e
        (5) For aluminum, the % of total GHG which is CO_2 is 76.89% so we multiplied the CO_2e value by .7982

Literature Cited

Alternative Fuels Data Center: Biodiesel Vehicle Emissions. (n.d.). Retrieved December 7, 2022, from https://afdc.energy.gov/vehicles/diesels_emissions.html

Aptaker, I. (Writer), Berger, E. (Writer), Fryman, P. (Director). (2022, Jan. 18). Pilot (Season 1, Episode 1) [TV series episode] [Image 1]. In H. Duff & I. Aptaker (Executive Producers), *How I Met Your Father*. Hulu.

Arguelles-Arguelles, A., Amezcua-Allieri, M. A., & Ramírez-Verduzco, L. F. (2021). Life Cycle Assessment of Green Diesel Production by Hydrodeoxygenation of Palm Oil. *Frontiers in Energy Research*, *9*. https://www.frontiersin.org/articles/10.3389/fenrg.2021.690725

Arup and BFI (2020) A Screen New Deal: A Route Map to Sustainable Film Production. London: The British Film Institute. Retrieved February 7, 2023, from https://www.arup.com/perspectives/publications/research/section/a-screen-new-deal-a-route-map-to-sustainable-film-production

Author, N. G. (2013). *Life Cycle Greenhouse Gas Emissions from Electricity Generation* (NREL/FS--6A20-57187, 1338444; p. NREL/FS--6A20-57187, 1338444). https://doi.org/10.2172/1338444

Benton, K. (2016). *A LIFE CYCLE ASSESSMENT OF A DIESEL GENERATOR SET*.

Casamayor, J. L., Su, D., & Ren, Z. (2017). Comparative life cycle assessment of LED lighting products. *Lighting Research & Technology*, *50*, 147715351770859. https://doi.org/10.1177/1477153517708597

Coal's Importance to the World—Society for Mining, Metallurgy & Exploration. (n.d.). Retrieved December 7, 2022, from https://www.smenet.org/What-We-Do/Technical-Briefings/Coal-s-Importance-in-the-US-and-Global-Energy-Supp

Corbett, C. J., & Turco, R. P. (2006). (rep.). *Sustainability in the Motion Picture Industry*. California Integrated Waste Management Board. Retrieved from https://www.ioes.ucla.edu/publication/sustainability-in-the-motion-picture-industry/

Distance from Los Angeles to New York (LAX – JFK). Air Miles Calculator. (n.d.). https://www.airmilescalculator.com/distance/lax-to-jfk/

Eichberger, J. (n.d.). *Comparative Evaluation: Life Cycle Analyses of Electric and Combustion Engine Vehicles*. 63.

Facts & Figures. (n.d.). Retrieved December 7, 2022, from https://www.ladwp.com/ladwp/faces/ladwp/aboutus/a-power/a-p-factandfigures;jsessionid=j1TQjRqdVz6VJnXBGLQdWHcgGlKtyypHyWgKr1hML2PhnyRln4dc!-1329355061?_adf.ctrl-state=205k1ss5f_4&_afrLoop=294239368192528&_afrWindowMode=0&_afrWindowId=null#%40%3F_afrWindowId%3Dnull%26_afrLoop%3D294239368192528%26_afrWindowMode%3D0%26_adf.ctrl-state%3Da8m4sjk55_4

FX Guide. (2020, March 13). *Art of (led wall) virtual production sets, part Two: "how you make one."* fxguide. https://www.fxguide.com/fxfeatured/art-of-led-wall-virtual-production-sets-part-two-how-you-make-one/

gemini. (2022, April 11). Where Does LA Get Its Electricity? | Mike Diamond. *Mike Diamond Services*. https://mikediamondservices.com/blog/los-angeles-electrical-power-supply/

Girardi, P., & Brambilla, P. C. (n.d.). *Electric Cars vs Diesel and Gasoline: A Comparative LCA Ranging from Micro-Car to Family Car*. 12.

Green Production Guide [GPG]. (2021). *Toolkit Tutorial: A how-to guide for tools on the Green Production Guide*. https://www.greenproductionguide.com/?smd_process_download=1&download_id=2758

Green Production Guide [GPG]. (2022). *About Us.* https://www.greenproductionguide.com/about-us/

Grip trucks. Unique Producers Services: Grip & Lighting Rental. (n.d.). http://uniqueproducers.com/grip-trucks/

Hertwich, Edgar & Hammitt, James. (2001). A decision-analytic framework for impact assessment - Part I: LCA and decision analysis. The International Journal of Life Cycle Assessment. 6. 5-12. 10.1007/BF02977588.

Idling Reduction for Personal Vehicles. (n.d.). 2.International Standard ISO 14040 (2006) *Environmental Management—Life Cycle Assessment—Principle and Framework*.

Industrial Light & Magic. (2020, February 20). *The virtual production of the mandalorian season one*. YouTube. https://www.youtube.com/watch?v=gUnxzVOs3rk

Kadner, N. (2021). The Virtual Production Field Guide. *Epic Games*, 2, 1–158. https://cdn2.unrealengine.com/Virtual+Production+Field+Guide+Volume+2+v1.0-5b06b62cbc5f.pdf

Kaiser, M. (2022, December 9). *What Is the Expected Life Of A Manufactured Home?*. The Mobile Home Dealer. https://www.sellmobilehome.com/blog/what-is-the-expected-life-of-a-manufactured-home/

Kilgore, G. (2023, March 28). *How to reduce the carbon footprint of your air conditioner by 100%*. 8 Billion Trees. https://8billiontrees.com/carbon-offsets-credits/how-to-reduce-the-carbon-footprint-of-your-air-conditioner/

Lee, J. W. (2020, September 25). *How 'the mandalorian' creators reduced production footprint through technology*. Variety. Retrieved February 7, 2023, from https://variety.com/2020/tv/news/the-mandalorian-variety-sustainability-series-1234783200/

Life Cycle Assessment Harmonization. (n.d.). Retrieved December 7, 2022, from https://www.nrel.gov/analysis/life-cycle-assessment.html

Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. (n.d.). 4.

Maher, M. (2015, September 2). *Camera Cars & Trailers – The Real Movie Cars*. The Beat: A Blog by PremiumBeat. https://www.premiumbeat.com/blog/camera-cars-trailers-real-movie-cars/

Matthews, H. S., Hendrickson, H., & H. Matthews, D. (2014). https://lcatextbook.com/. Open Access.

Morgil, I., Secken, N., Yucel, A. S., Oskay, O. O., Yavuz, S., & Ural, E. (n.d.). *Developing A Renewable Energy Awareness Scale For Pre-service Chemistry Teachers*. 12.

New Climate Narrative | Green Production Guide. (2020, October 16). *Green Production Guide* |. https://www.greenproductionguide.com/new-climate-narrative/

Nrel-jisea-nicholson-box-plot.jpg (612×479). (n.d.). Retrieved December 7, 2022, from https://www.nrel.gov/analysis/assets/images/nrel-jisea-nicholson-box-plot.jpg

Rahman, S. M. A., Masjuki, H. H., Kalam, M. A., Abedin, M. J., Sanjid, A., & Sayeed, I. (2014). Effect of idling on fuel consumption and emissions of a diesel engine fueled by Jatropha biodiesel blends. *Journal of Cleaner Production*, *69*. https://doi.org/10.1016/j.jclepro.2014.01.048

Rajagopal, D. (2022, January 1). The Framework of LCA [Powerpoint Slides] [Figure 1]. Bruinlearn UCLA.

Robb, D. (2022, April 1). Los Angeles Still Leads In Soundstage Space, But FilmLA Says Growth Is Outpaced By Toronto, UK & New York. *Deadline*. https://deadline.com/2022/04/los-angeles-still-leads-in-soundstage-space-but-filmla-says-growth-is-outpaced-by-toronto-uk-new-york-1234992597/

Seymour, M. (2020, March 9). *Art of (LED Wall) Virtual Production Sets, Part Two: 'How you make one.'* fxguide. https://www.fxguide.com/fxfeatured/art-of-led-wall-virtual-production-sets-part-two-how-you-make-one/

Sirait, M., Biswas, W., & Boswell, B. (2012). Personal Computer Life Cycle Assessment Study: The Case of Western Australia. *Proceedings:10th Global Conference on Sustainable Manufacturing.* https://espace.curtin.edu.au/handle/20.500.11937/5389

Solar Panel Life Cycle Analysis Proves Sustainability. (n.d.). *OYA Renewables*. Retrieved December 7, 2022, from https://oyarenewables.com/resources/solar-panel-life-cycle-analysis-proves-sustainability/

Steinberg, J. E (Writer), Levine, R. (Writer), & Wilkinson, J. (Director). (2022, Jul. 21). VII (Season 1, Episode 7) [TV series episode] [Images 2 & 3]. In J. E. Steinberg (Executive Producer), *The Old Man*. Hulu.

Sunset Studios. (n.d.). *Wardrobe truck – Ford F550*. Quixote. https://quixote.com/portfolio/wardrobe-truck-ford-f550/

Sustainable Production Alliance [SPA]. (2022, May). *SPA Soundstage Facility Survey Key Takeaways*. https://www.greenproductionguide.com/wp-content/uploads/2022/08/SPA-Report_05.25_FINAL_with_infographic.pdf

Sustainable Production Alliance [SPA]. (2021, March). *Close Up: Carbon Emissions of Film and Television Production*. https://www.greenproductionguide.com/wp-content/uploads/2021/04/SPA-Carbon-Emissions-Report.pdf

Systems, V. P. (2020, January 29). *The Benefits of an Idle-Free or Reduced Emissions Worksite*. Volta Power Systems. https://voltapowersystems.com/de/blog/the-benefits-of-an-idle-free-or-reduced-emissions-worksite/

The Mandalorian S01E06 "Chapter 6: The prisoner" [4K]. StarWars Screencaps.com [Image 4]. (2023, April 28). https://starwarsscreencaps.com/4k-the-mandalorian-s01e06-chapter-6-the-prisoner/page/1

U.S. EPA Center for Corporate Climate Leadership. (2016, January). Greenhouse gas inventory guidance - U.S. environmental protection agency. https://www.epa.gov/sites/default/files/2016-03/documents/stationaryemissions_3_2016.pdf

What is Clean Energy? How Does it Work? Why is it so Important? (n.d.). Retrieved December 7, 2022, from https://www.twi-global.com/technical-knowledge/faqs/clean-energy.aspx

What is Renewable Energy? - Definition, Types, Benefits and Challenges. (n.d.). Retrieved December 7, 2022, from https://www.twi-global.com/technical-knowledge/faqs/renewable-energy.aspx

World Energy Council. (2004). *Comparison of energy systems using life cycle assessment: A special report of the World Energy Council*. World Energy Council.