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Analyzing the Impact of Technological Improvements on the Performance of Delivery Drones

Miguel Figliozzi*

Portland State University, P.O. Box 751 CEE, Portland, OR 97207-0751, USA

Abstract

Though many studies have proposed many types of models for drones, there is a lack of understanding of the current and future limits of drone technologies for deliveries. This research fills this gap by using first principles and optimization to understand future capabilities of drones that can perform vertical takeoff and landing (VTOL). Range and optimal battery and payload formulas are derived and insights are discussed. The results show that substantial range and payload gains could be expected in the near future as a result of improvements in battery technology and drone design. The analysis also indicates that hybrid designs are likely to have a higher impact in rural areas, where major gains in range and payload are expected. The regulatory framework is also going to have a significant role in the real-world performance of delivery drones.

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Keywords: drone; deliveries; technology; range; payload;constraints; optimization

1. Introduction

Nomenclature

θ	forward flight efficiency
η	electromechanical efficiency
λ	value of the multiplier for the lagrangian mass constraint
E	battery energy density
g	constant of gravity
m	drone take-off mass

* Corresponding author. Tel.: +1-503-725-2836.
E-mail address: figliozzi@pdx.edu

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M	maximum amount of mass that can be allocated to the sum of payload and battery
m_b	drone battery mass
m_e	drone empty (tare) mass
m_p	drone payload mass
m'	equivalent mass
R	drone range
W	drone work, product of payload weight by distance

Many studies have documented challenges at the last mile for deliveries and for the first mile for pickups or returns. This research applies to drones that have the ability to perform vertical takeoff and landing (VTOL), as opposed to drones, typically fixed-wing UAVs, that are classified as horizontal take-off and landing (HTOL) aircrafts. The VTOL property is key to facilitate drone adoption in both rural and urban areas due the increased accessibility and lack of specialized landing and take-off equipment and installations. However, VTOL does not mean exclusively rotary wing drones like the one shown in Figure 1 (left). There are hybrid UAVs as shown in Figure 1 (right) with fixed-wing designs and capable of VTOL because they have propellers mainly for the purpose of hovering and propellers for forward movement. For hybrid drones the space required for take-off varies with the size of drone and the technology used, it can be as low as four square metres for a small drone like the WintraOne.

Another important element in defining the scope of the research and findings are drone size and weight. Regulatory agencies have set clear limits for the operation of UAVs. In the USA, for example, the Federal Aviation Administration has set a 25 kg take-off limit for UAVs allowed to fly in class "G" uncontrolled airspace up to 400 ft or 122 m (FAA, 2020). The drone shown in Figure 1 (left) is a rotary wing drone (no fixed wings) which largely exceeds the 25 kg limit whereas the drone shown in Figure 1 (right) is within the scope of this research because its take-off weight is under 25 kg and within the current regulatory limits.

There is research that tackles this complex problem of efficient drone sizing and optimization (Delbecq et al., 2020; Dündar, Bilici and Ünler, 2020) but the focus of these types of research has been on the specification of components such as rotors, engines, or batteries. There have been reviews of drone multicopters energy consumption (Zhang et al., 2021) and life-cycle analysis of drone emissions (Figliozzi, 2017) but to the best of the author's knowledge there is no published or unpublished research addressing the impact of technological improvements on drone range.



Figure 1. (a) multicopter VTOL; (b) hybrid VTOL

2. SCENARIOS

Two types of technological changes are analysed in this research: a) the impact of battery technology improvements, and b) the impact of changes in drone structure and engine design that results in a decrease of drone empty mass or tare. In addition, formulas for range and drone mass distributions are derived for different scenarios: one-way delivery and round-trip delivery, i.e. two-way delivery with empty return and for two types of drones: multicopter and hybrid, as described above.

The initial mass distribution of the drones is a key parameter (Figliozzi, 2023). A report analysing the specifications of multicopters found m_b/m ratios ranging between 0.22 and 0.33 and maximum m_p/m ratios ranging between 0.25 and 0.30 (Figliozzi, 2018) which implies values of m_e/m ratios ranging from 0.42 and 0.47. The base case for drone take-off mass is 20 kg with a mass distribution that prioritizes durability and maneuverability with the following values for the following ratios for battery, payload, and empty masses: 0.30, 0.25, and 0.45 (6, 5, and 9 kgs respectively for battery, payload, and tare). Reductions in drone tare are considered in a final scenario.

Batteries have shown an impressive rate of progress in the last few decades, both in terms of cost and energy density, and these trends are expected to continue (Ziegler and Trancik, 2021). Battery densities of 200 Wh/kg are now normal and it is expected that energy densities can double in the next twenty years if the current rate of progress continues. According to the US Department of Energy (US DOE, 2020) battery pack costs declined from $1000/kWh in 2008 to $185/kWh in 2019. More funding and R&D are expected to enable new battery types with a production cost of less than $60/kWh and specific energy of 500 Wh/kg by 2030. The DOE is planning for a $80/kWh manufactured cost for a battery pack by 2030 for a 300-mile range electric vehicle. Other references provide similar estimates, suggesting nominal cell level specific energies for rechargeable batteries of 489 Wh/kg by 2030, 638 Wh/kg by 2040, and 764 Wh/kg by 2050 (Tiede, O'Meara and Jansen, 2022). The battery scenarios included in this research assume densities of 200 Wh/kg (720 kJ/kg) as a current baseline and future densities of 350 Wh/kg (1260 kJ/kg) and 500 Wh/kg (1800 kJ/kg) for years 2030 and 2040, respectively.

Regarding types of deliveries, the one-way system (OWS) considers that drones have limited flight range with respect to the service area and require recharging stations for extending coverage to a wider area (Hong, Kuby and Murray, 2018), in this system the drone may travel with its load over the whole distance that needs to be covered. The round trip, or two-way system (TWS), assumes that stations are located within the range of customers' demand and then the drone travels to a destination, drops its load and then returns empty to the launching location where a new package could be loaded (Chauhan, Unnikrishnan and Figliozzi, 2019). The parameters for multicopter and hybrid drone designs and efficiencies were adapted from the drone design literature (Hwang, Cha and Jung, 2018; Dündar, Bilici and Ünler, 2020; Oh et al., 2020).

3. METHODOLOGY

The trade-offs among payload, battery, and range of electric drones are analyzed deriving formulas based on first principles and extending the work of Hepperle (2012). The objective function is range maximization and useful work (payload multiplied by range). Novel optimal formulas for battery and payload mass are obtained solving the Lagrangian of the optimization problem. There is also an analytical solution for the shadow price of the mass (drone size) constraint. The objective functions and the decision variables (battery, payload, and tare) are a function of battery energy density as well as type of drone and delivery.

3.1. Range

Range (R) is positively affected by improvements in battery energy density as well as flight and mechanical efficiency. The formula for electric aircraft is simpler than the formula for aircraft with internal combustion engines because the weight of the battery does not change during flight. The relationship between drone mass distribution and range is clear and well established. A drone total take-off mass m can be broken down into three components: payload, battery, and tare or empty mass, where their sum is the total takeoff mass of the drone. In mathematical notation this can be expressed as $m_p + m_b + m_e = m$ where the subindices refer to payload, battery, and empty mass respectively. These mass components have a key role in determining drone range (Hepperle, 2012), the range R of an electric aircraft in steady state forward flight is:

$$R = \frac{E\, m_b\, \eta\, \theta}{g\,(m_p + m_b + m_e)} = \frac{E\, m_b\, \eta\, \theta}{g m} \tag{1}$$

where the term g is the acceleration of gravity, E the energy density of the battery, and the parameters θ and η are the forward flight and electromechanical efficiencies, respectively. Range increases when the battery mass increases and the range increase is significantly larger if the increase in m_b is at the expense of $m_p + m_e$, i.e., keeping total takeoff mass m constant. In equation (1) the range is typically expressed in kilometres, masses in kilograms, E in Joules per kilogram and the parameters θ and η are dimensionless.

3.2. Delivery Work

The second performance measure is defined as useful or delivery work, W. In freight transport and last-mile deliveries, range is important, but the amount of payload is as or even more important. By multiplying range and payload a measure of useful work W can be obtained, after algebraic simplification the following expression is obtained:

$$W = \frac{E\ \eta\ \theta\ m_b m_p}{m_e + m_b + m_p} = \frac{E\ \eta\ \theta\ m_b m_p}{m} \tag{2}$$

3.3. Optimal Values

The optimal values of the performance measures are obtained solving the Lagrangian for each performance measure (range or delivery work) with the mass constraint $m_e + m_b + m_p \leq m = m_e + M$. In this expression M, $M \geq m_b + m_p$, is the maximum amount of mass that can be jointly allocated for payload and battery. The Lagrange multiplier method is used because it provides analytical solutions but in addition the λ multiplier associated with the mass constraints provides the rate of the change in the optimized function with respect to the change of the parameter M.

Table 1. Optimal one-way values for battery and payload mass.

Performance Measures (PMs) $f(m_b, m_p)$	**Optimal Values**	**Lambda (λ)**	**λ Units**
Range (R)	$m_p = 0$ $m_b = M$	$\frac{E\ \eta\ \theta\ (m_e + m_p)}{g\ m^2}$	$\left[\frac{m}{kg}\right]$
Delivery Work (W)	$m_p = \frac{M}{2}$ $m_p = \frac{M}{2}$	$\frac{E\ \eta\ \theta\ M\ (2m_e + m_b + m_p)}{4g\ m^2}$	$\left[\frac{J}{kg}\right]$

In Table 1 the optimal values for range for one-way deliveries are simple: allocate as much mass as possible to the battery and reduce payload to zero. To maximize delivery work it is optimal to allocate the same amount of mass to the battery and the payload. Table 2 shows that the optimal battery/payload allocation has not changed but there were changes to the battery/payload allocation that maximized delivery work. It can be formally proved that for positive values, payload mass is always greater than battery mass if the objective is to maximize delivery work.

In Table 2, an "equivalent mass" m' is used to simplify the equations and is a function of the battery-payload total mass constraint M, where the formula for $m' = \sqrt{M^2 + 3Mm_e + 2m_e^2}$ has mass [kg] units and depends on the mass distribution of the drone. Only results for two-way deliveries are discussed henceforward.

Table 2. Optimal two-way optimal values for battery and payload mass

Performance Measures (PMs) $f(m_b, m_p)$	**Optimal Values**	**Lambda (λ)**	**λ Units**
Range (R)	$m_p = 0$ $m_b = M$	$\frac{E\,\eta\,\theta\,(m_e + m_p)}{g\,m^2}$	$\left[\frac{m}{kg}\right]$
Delivery Work (W)	$m_p = 2m - \sqrt{2}\,m'$ $m_b = \sqrt{2}m' - m - m_e$	$E\,\eta\,\theta\,M\,\frac{3\,m' - 2\sqrt{2}\,M - 3\sqrt{2}\,m_e}{g\,(m')^2}$	$\left[\frac{J}{kg}\right]$

4. RESULTS

For two-way deliveries, the first set of results highlights the impact of battery mass and battery technology on drone range, see Figure 2 using the formulas presented in Table 2. Assuming a constant payload and tare 5 kg and 9 kg, respectively, but with a changing battery mass on the x axis. Six curves show the impact of drone type, where MC stands for 'multicopter' and Hy for 'hybrid' combined with three different battery energy densities.

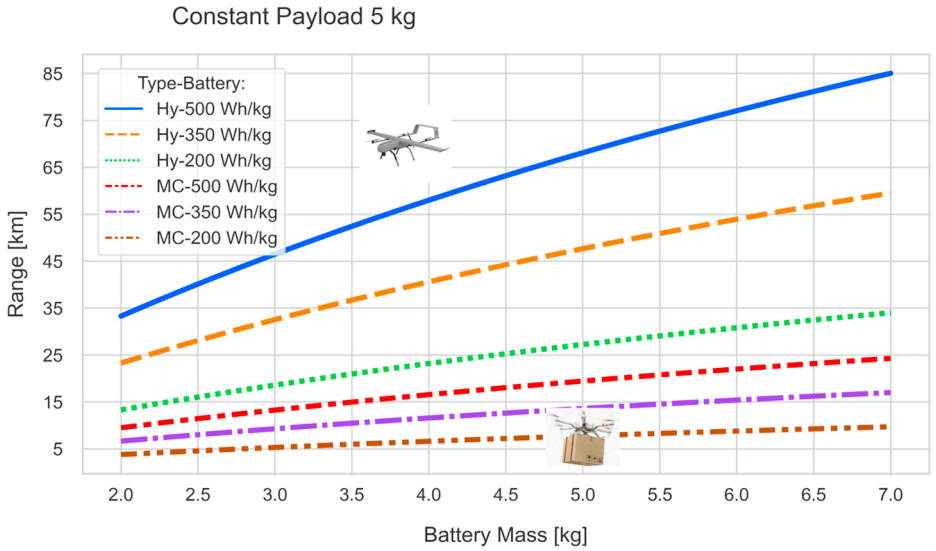


Figure 2. Range as a function of Drone Type and Battery Energy Density (Payload 5kg)

Batteries are expensive and with a short life. It is clear that as battery density improves it will be possible to reduce battery size and mass but still keep or even increase the range of the drone. There is a clear advantage in using hybrid drones given that the benefits of adding battery mass are more pronounced for hybrid drones with a high energy density battery. This effect is also observed in the values of lambda (λ), for an additional kg of battery there is a gain of 0.9 km, i.e $\lambda = 0.9\ \ [km/kg]$ for a multicopter with a 200 wh/kg battery. But the value of λ increases steadily with E and for hybrids. In the case of a hybrid with E = 500 wh/kg the value of $\lambda = 7.87\ \ [km/kg]$. In this section it is assumed that the forward flight efficiency is 1 and 3.5 for multicopter and hybrid drones respectively. The electromechanical efficiency is equal to 0.7 in all cases.

The results show that the efficiency of hybrid drones is an order of magnitude larger in terms of range. Though even with VTOL capabilities, hybrid drones have some limitations in urban areas. They require more space for maneuvering and are not able to navigate easily in dense urban environments. However, in rural areas with less obstacles hybrid drones have an advantage. As such, it may be reasonable to suggest that in rural areas regulatory drone mass limits could be relaxed for hybrid drones if there is a lower potential for crashes and damage.

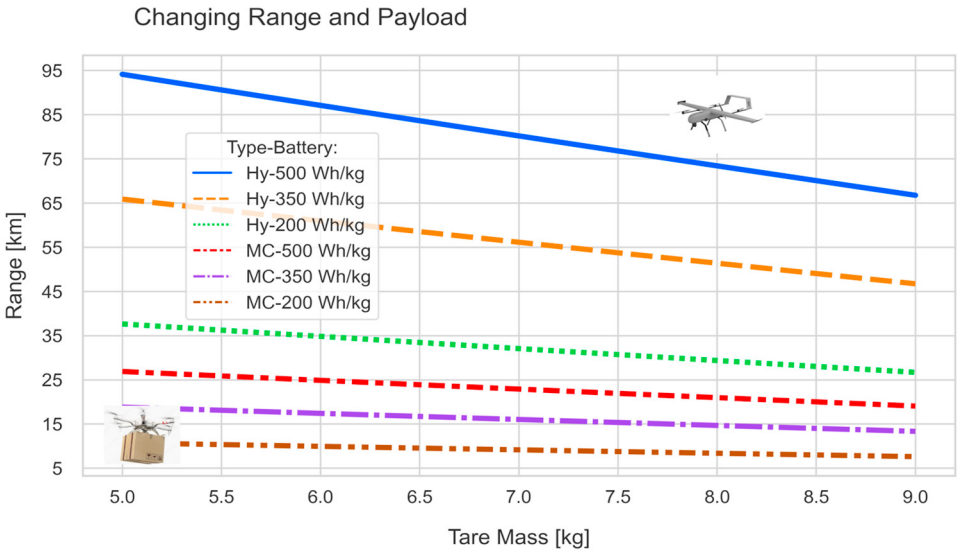


Figure 3. Range as a function of Tare, Drone Type, and Battery Energy Density

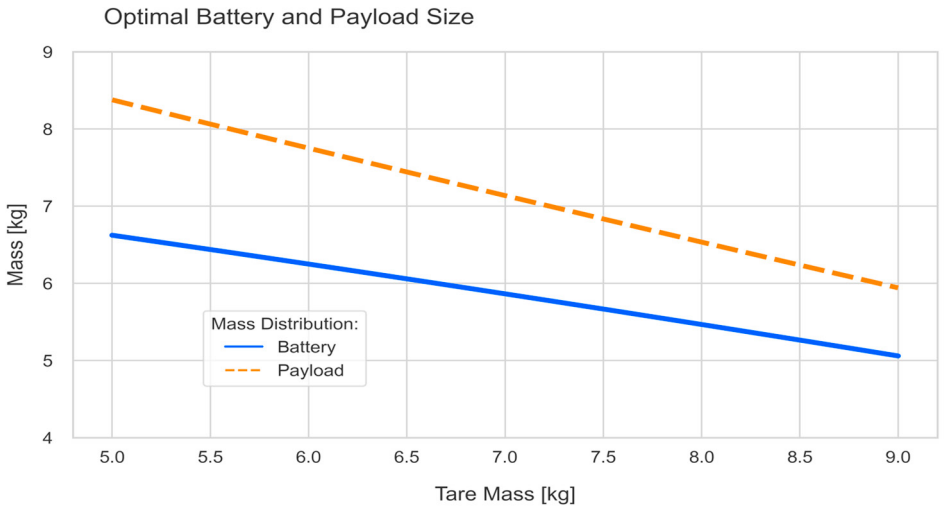


Figure 4. Optimal Battery and Payload as a function of Tare

The results presented in Figures 3 and 4 correspond to the same scenario using formulas presented in Table 2 for Range and Work respectively. In Figure 3 the plots show the impact of reductions in tare mass on drone range. Assuming a constant drone mass of 20 kg, range on the y axis and tare on the x axis. Unlike the previous graph, battery

and payload masses are also changing following the equations shown in Table 2 for delivery work W. Six curves show the impact of drone type, where MC stands for 'multicopter' and Hy for 'hybrid' and there are three different battery energy densities.

New additive manufacturing technologies and different types of 3D modelling and printing have great potential to reduce the structural weight of drones. In addition, these technologies can provide more accurate and intricate designs for multicopter components while preserving robustness and lightweight (Ferro et al., 2016).

When tare is reduced, the benefits are twofold: on one hand range increases substantially (see Figure 3) and on the other hand payload increases (see Figure 4). The changes in delivery work when the mass constraint is relaxed is estimated by the values of lambda (λ). For a reduction of 1 kg of tare there is a gain of 55.1 kJoules. This increase in delivery work or energy can be translated as being equivalent to moving 1 extra kg of payload for 5.6 kilometres when tare is reduced by 1 kg. It is also important to highlight that as battery production costs drop, the value of adding range and payload will be in the range of $40 per kg of battery which seems a very reasonable value proposition for delivery companies.

The analysis also shows that it is not a good idea to assume that one-way and two-way delivery scenarios have similar results or that changes in the payload/battery mass ratios can be neglected as assumed in previous research efforts (Stolaroff et al., 2018). Optimal battery and payload mass are clearly different, and it may not be reasonable to design drones with high battery masses unless range is the priority.

5. CONCLUSION

Summarizing, it is clear that battery technological improvements regarding energy density and enhancements in drone materials and construction methods are likely to significantly increase the performance of delivery drones, both in terms of payload and range. Compounding the effects of these improvements it is likely that range may be increased 3.5 times in the next 10 or 15 years. In addition, the cost of drones is also likely to drop as batteries become more prevalent and affordable. Furthermore, the cost of extending drone range will be in the range of $40 per 5 kilometres if the current DOE projections hold.

The results of this research indicate that the efficiency of hybrid drones is an order of magnitude larger in terms of range and energy efficiency over the performance of multicopters. However, even with VTOL and capabilities, hybrid drones require more space and are less maneuverable which is likely to restrict their application when used in dense urban areas. Low density rural areas are likely to benefit the most from adopting hybrid drones due to the longer ranges, cheaper batteries, and that the lighter drones can reduce delivery costs. Payloads are likely to increase significantly in rural areas and it may be reasonable to relax drone size restrictions in settings where the likelihood of crashes or major damage is negligible.

Drone deliveries continue to grow. For example, in 2022 Walmart made 6000+ drone deliveries from 36 stores scattered across seven states in the US (Walmart, 2023) and drones will likely become a credible delivery option in many areas. Unlike deliveries using ubiquitous internal combustion commercial trucks, delivery by drone is not a mature industry and keeps evolving rapidly. Large adoption and major R&D investments by public and private stakeholders are likely to result in major improvements in the next decade. In turn, improvements in drone technology, range, and payload are likely to accelerate the growth and adoption of this new technology as well as new investments and infrastructure. Regulation is still a major source of uncertainty, mainly in urban or densely populated areas.

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References

Chauhan, D., Unnikrishnan, A., Figliozzi, M., 2019. Maximum coverage capacitated facility location problem with range constrained drones. Transp. Res. Part C Emerg. Technol. 99, 1–18. https://doi.org/10.1016/j.trc.2018.12.001

Delbecq, S., Budinger, M., Ochotorena, A., Reysset, A., Defay, F., 2020. Efficient sizing and optimization of multirotor drones based on scaling laws and similarity models. Aerosp. Sci. Technol. 102, 105873. https://doi.org/10.1016/j.ast.2020.105873

Dündar, Ö., Bilici, M., Ünler, T., 2020. Design and performance analyses of a fixed wing battery VTOL UAV. Eng. Sci. Technol. Int. J. 23, 1182–1193. https://doi.org/10.1016/j.jestch.2020.02.002

FAA, 2020. Small Unmanned Aircraft Systems (UAS) Regulations (Part 107) | Federal Aviation Administration [WWW Document]. URL https://www.faa.gov/newsroom/small-unmanned-aircraft-systems-uas-regulations-part-107 (accessed 9.15.22).

Ferro, C., Grassi, R., Seclì, C., Maggiore, P., 2016. Additive Manufacturing Offers New Opportunities in UAV Research. Procedia CIRP 41, 1004–1010. https://doi.org/10.1016/j.procir.2015.12.104

Figliozzi, M.A., 2017. Lifecycle modeling and assessment of unmanned aerial vehicles (Drones) CO 2 e emissions. Transp. Res. Part Transp. Environ. 57, 251–261. https://doi.org/10.1016/j.trd.2017.09.011

Figliozzi, M., 2018. Modeling the Sustainability of Small Unmanned Aerial Vehicles Technologies: Final Report. Civ. Environ. Eng. Fac. Publ., FMRI Reports.

Figliozzi, M.A. (2023) 'Multicopter drone mass distribution impacts on viability, performance, and sustainability', Transportation Research Part D: Transport and Environment, 121, p.103830

Hepperle, M., 2012. Electric Flight - Potential and Limitations, in: Energy Efficient Technologies and Concepts of Operation.

Hong, I., Kuby, M., Murray, A.T., 2018. A range-restricted recharging station coverage model for drone delivery service planning. Transp. Res. Part C Emerg. Technol. 90, 198–212. https://doi.org/10.1016/j.trc.2018.02.017

Hwang, M., Cha, H.-R., Jung, S.Y., 2018. Practical Endurance Estimation for Minimizing Energy Consumption of Multirotor Unmanned Aerial Vehicles. Energies 11, 2221. https://doi.org/10.3390/en11092221

Oh, S., Kim, M., Kim, H., Lim, D., Yee, K., Kim, D., 2020. The Solution Development for Performance Analysis and Optimal Design of Multicopter-type Small Drones, in: 2020 International Conference on Unmanned Aircraft Systems (ICUAS). Presented at the 2020 International Conference on Unmanned Aircraft Systems (ICUAS), IEEE, Athens, Greece, pp. 975–982. https://doi.org/10.1109/ICUAS48674.2020.9213985

Stolaroff, J.K., Samaras, C., O'Neill, E.R., Lubers, A., Mitchell, A.S., Ceperley, D., 2018. Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery. Nat. Commun. 9, 409. https://doi.org/10.1038/s41467-017-02411-5

Tiede, B., O'Meara, C., Jansen, R., 2022. Battery Key Performance Projections based on Historical Trends and Chemistries, in: 2022 IEEE Transportation Electrification Conference & Expo (ITEC). Presented at the 2022 IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium (ITEC+EATS), IEEE, Anaheim, CA, USA, pp. 754–759. https://doi.org/10.1109/ITEC53557.2022.9814008

US DOE, 2020. Energy Storage Grand Challenge [WWW Document]. Energy.gov. URL https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge (accessed 1.29.23).

Walmart, 2023. Walmart Drone Delivery by the Numbers [WWW Document]. Corp. - US. URL https://corporate.walmart.com/newsroom/2023/01/05/walmart-drone-delivery-by-the-numbers (accessed 1.23.23).

Zhang, J., Campbell, J.F., Sweeney II, D.C., Hupman, A.C., 2021. Energy consumption models for delivery drones: A comparison and assessment. Transp. Res. Part Transp. Environ. 90, 102668. https://doi.org/10.1016/j.trd.2020.102668

Ziegler, M.S., Trancik, J.E., 2021. Re-examining rates of lithium-ion battery technology improvement and cost decline. Energy Environ. Sci. 14, 1635–1651. https://doi.org/10.1039/D0EE02681F