



The Environmental Life Cycle Costs (ELCC) of Urban Air Mobility (UAM) as an input for sustainable urban mobility

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ABSTRACT

The growth of shared mobility has recently challenged the way mobility has traditionally been conceived. In this perspective, this study investigates the Environmental Life Cycle Costs of Urban Air Mobility (UAM) services to evaluate their potential integration with other transport systems, in the three-time horizons (2025, 2030, 2035). The key area of research was focused on the determination of the cost components of UAM required to calculate the unit costs of UAM transportation. To this end, unitary data and the method from a 2017 EC DG MOVE's report on urban accessibility have been adopted. The analysis confirms that most of the cost is related to the aircraft energy consumption during flight, while the rest is used by ground infrastructure. Moreover, the energy cost is strongly correlated with the distance travelled and the size of the aircraft. The longer the flight and the bigger the aircraft, the higher is the energy cost. Complex cost analysis should be able to support decision-makers in the definition of Sustainable Urban Mobility and their principles of integration, participation, monitoring and evaluation. However, it will be necessary to be able to draw on more consolidated and widespread data over time for the creation of Urban plans for Sustainable Mobility.

1. Introduction

The environmental impact of the transport sector has become a priority for policies and decision-makers. Mobility-related activities consume one-third of global energy demand and are the source of one-sixth of global Greenhouse Gas emissions (GHG) (D'Adamo et al., 2020). The debate on sustainable mobility in cities has been growing more and more, as the transport sector is an area that most influences sustainability and quality of life in urban areas (Arbolino et al., 2017; Foltýnová et al., 2020). In this context, Urban Air Mobility (UAM) has increasingly emerged as a potential development of urban sustainable transport services (Cho and Kim, 2022; Straubinger et al., 2020; Tojal et al., 2021). According to European Environment Agency (2021), "Urban Air Mobility is a new air transportation system for passengers and cargo inland around densely populated and built environments, made possible by electrical vertical take-off and landing aircraft (eVTOL) equipped with new technologies such as enhanced battery technologies and electric propulsion". Literature highlights that

traditional fuels play a major role in generating global climate change (Falcone et al., 2019). One of the urban zero emission solutions, next to cargo bikes and inland water freight, is a system of unmanned freight drones. However, it is well explained in the Sustainable and Smart Mobility Strategy (2020), the Commission fully supports the deployment of drones and unmanned aircraft and will further develop the relevant rules, including on the U-space, to make it fit for enhancing safe and sustainable mobility, adopting 'Drone Strategy 2.0'. Multimodal logistics must be a part of this transformation (see Table 1–4 and 6–8, Figs. 1–4).

Additionally, researchers have demonstrated the environmental benefit of the introduction of electrified UAM services in the urban areas by calculating the CO₂ emissions (Afonso et al., 2021; Mudumba et al., 2021). From a policymaker, multiple aspects will have to be considered. From the definition of the real sustainability of these services, and thus also the assessment of Environmental Life Cycle Cost (ELCC), to safety aspects. The UAM ecosystem is growing rapidly as players from diverse industries become involved and new companies emerge on the hunt for new revenue opportunities in the future urban mobility landscape

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Nomenclature		EE	Energy Efficiency
AVM	Automatic Vehicle Monitoring	ELCC + E	Environmental Life Cycle Costing + Energy effectiveness
BEV	Battery Electric Vehicles	ELCC	Environmental Life Cycle Costing
Cd	End of life costs	eVTOL	Electrical Vertical Take-Off and Landing aircraft
Ce	Energy costs	EU	European Union
Cenv	Environmental costs	GFRC	Glass Fiber Reinforced Concrete
CFRC	Carbon-Fiber-Reinforced Carbon	GHG	Greenhouse Gas emissions
Cic	Investment costs	ICAO	International Civil Aviation Organization
CNG	Compressed Natural Gas	ICEV	Internal combustion engine vehicle
Co	Operational Costs	LCC	Life Cycle Cost
ConOps	Concept of Operations	MTOW	Maximum Take Off Weight
Cs	Delay and deadhead costs	UAM	Urban Air Mobility
dB	decibels	UAS	Unmanned Aircraft System
DG MOVE	The European Commission department, responsible for EU policy on mobility and transport	UAV	Unmanned Aerial Vehicles
EASA	European Union Aviation Safety Agency	UTM	Unified Threat Management
		WTT	Well-to-Tank
		WTW	Well-to-Wheels

(Airbus, 2018). The role of infrastructure providers and operators, real estate companies, transport hub operators and retailers in building the foundation of the future UAM landscape, is great. Re-planning urban areas, re-purposing current buildings, or constructing UAM infrastructure from scratch (e.g., vertiports. eVTOL parking or charging hubs), are crucial for the future of urban mobility. This is not just limited to the

development of physical infrastructure, digital infrastructure (e.g., sensors. 5G or smart grids), indeed, it is also essential to the deployment of UAM solutions and would need to be further developed, deployed and reinforced for the technology to realise its full potential in the coming years (Swedavia AB, 2021). Nowadays, UAM is being addressed in many projects throughout the world, and the ELCC is becoming a very relevant

Table 1
Key parameters and assumptions for the UAM forecast scenario.

<u>Union, 2021 1</u>	<u>Union, 2021 2</u>	<u>Union, 2021 3</u>	<u>Union, 2021 4</u>	<u>Union, 2021 5</u>	<u>Union, 2021 6</u>
<u>Direct last-mile delivery</u>	<u>Point-to-point public services</u>	<u>Advanced last mile delivery</u>	<u>Point-to-everywhere public services</u>	<u>Direct medical transport of people</u>	<u>Automatic personal aerial transportation</u>
Drones will conduct delivery flights up to 20 km. Others parameters and assumptions:	Drones will perform delivery flights up to 30 km. Others parameters and assumptions:	Drones will perform multiple delivery flights up to 50 km. Others parameters and assumptions:	Drones will perform delivery flights up to 80 km. Others parameters and assumptions:	Drones will perform medical passenger flights up to 200 km. Others parameters and assumptions:	Drones will perform passenger flights up to 80 km. Others parameters and assumptions:
<u>Aircraft parameters</u>	<u>Aircraft parameters</u>	<u>Aircraft parameters</u>	<u>Aircraft parameters</u>	<u>Aircraft parameters</u>	<u>Aircraft parameters</u>
Configuration: Multirotor VTOL	Configuration: Multirotor VTOL	Configuration: Decoupled propulsion VTOL	Configuration: Decoupled propulsion VTOL	Configuration: Decoupled propulsion VTOL	Configuration: Decoupled propulsion VTOL
Number of aircraft: 40	Number of aircraft: 50	Number of aircraft: 5	Number of aircraft: 8	Number of aircraft: 5	Number of aircraft: 4
Cost of purchase: 15 k euro	Cost of purchase: 15 k euro	Cost of purchase: 300 k euro	Cost of purchase: 100 k euro	Cost of purchase: 1 M euro	Cost of purchase: 1.5 M euro
Vehicle life: 10 years	Vehicle life: 10 years	Vehicle life: 13 years	Vehicle life: 10 years	Vehicle life: 20 years	Vehicle life: 20 years
Vehicle Gross Weight: 25 kg	Vehicle Gross Weight: 25 kg	Vehicle Gross Weight: 1000 kg	Vehicle Gross Weight: 235 kg	Vehicle Gross Weight: 1000 kg	Vehicle Gross Weight: 2400 kg
Payload: 5 kg	Payload: 5 kg	Payload: 150 kg	Payload: 35 kg	Pax capacity/Payload: 1/150 kg	Pax capacity/Payload: 4/360 kg
Battery specific energy: 250	Battery specific energy: 250	Battery specific energy: 250 Wh/kg	Battery specific energy: 250 Wh/kg	Battery specific energy: 2500 Wh/kg	Battery specific energy: 2500 Wh/kg
Propulsion: electric	Propulsion: electric	Propulsion: electric	Propulsion: electric	Propulsion: electric	Propulsion: electric
<u>Trip parameters</u>	<u>Trip parameters</u>	<u>Trip parameters</u>	<u>Trip parameters</u>	<u>Trip parameters</u>	<u>Trip parameters</u>
UAM climbing speed: 2.5 m/s	UAM climbing speed: 2.5 m/s	UAM climbing speed: 2 m/s	UAM climbing speed: 2 m/s	UAM climbing speed: 2 m/s	UAM climbing speed: 2 m/s
UAM cruise speed: 13 m/s	UAM cruise speed: 13 m/s	UAM cruise speed: 25 m/s	UAM cruise speed: 25 m/s	UAM cruise speed: 50 m/s	UAM cruise speed: 50 m/s
UAM cruising altitude: 120 m	UAM cruising altitude: 120 m	UAM cruising altitude: 300 m	UAM cruising altitude: 300 m	UAM cruising altitude: 600 m	UAM cruising altitude: 600 m
<u>Operational parameters</u>	<u>Operational parameters</u>	<u>Operational parameters</u>	<u>Operational parameters</u>	<u>Operational parameters</u>	<u>Operational parameters</u>
Number of operations: 1000/year	Number of operations: 1000/year	Number of operations: 1000/year	Number of operations: 1000/year	Load factor: 1	Load factor: 1.3
Number of onboard pilots: 0	Number of onboard pilots: 0	Number of onboard pilots: 0	Number of onboard pilots: 0	Number of operations: 1000/year	Number of operations: 1000/year
Number of remote pilots: 3/day	Number of remote pilots: 3/day	Number of remote pilots: 3/day	Number of remote pilots: 3/day	Number of onboard pilots: 0	Number of onboard pilots: 0
<u>Infrastructure parameters</u>	<u>Infrastructure parameters</u>	<u>Infrastructure parameters</u>	<u>Infrastructure parameters</u>	<u>Infrastructure parameters</u>	<u>Infrastructure parameters</u>
Number of landing pads: 20	Number of landing pads: 25	Number of landing pads: 8	Number of landing pads: 12	Number of remote pilots: 10/day	Number of remote pilots: 3/day
Cost of landing pad: 150 k euro	Cost of landing pad: 150 k euro	Cost of landing pad: 700 k euro	Cost of landing pad: 300 k euro	Number of landing pads: 12	Number of vertiports: 6
				Cost of vertiport: 400 k euro	Cost of vertiport: 1 M euro

Table 2
Overview of cost types.

Cic – investment costs	Aircraft cost Vertiport building/modernization/conversion costs Software costs (passenger service system, UTM/ATM interface software, ...) Certification costs												
Ce – energy costs	Aircraft flight energy consumption cost Energy consumption by landing pad/vertiport infrastructure												
Co – operational costs	<table border="0"> <tr> <td>Direct Operational costs</td> <td>Indirect Operational Costs</td> </tr> <tr> <td>Cost of flight (crew salaries, trainings benefits, insurance), operational oils/lubricants, airframe insurance)</td> <td>Cost of passenger services (cost of passenger insurance + passenger handling + passenger baggage handling + sales and reservations + security + miscellaneous passenger costs)</td> </tr> <tr> <td>Cost of depreciation (airframe, engines, propellers, avionics systems, spare parts, engine parts)</td> <td>Cost of maintaining and depreciation of ground equipment and facilities</td> </tr> <tr> <td>Maintenance costs (labour cost of airframe and systems + labour cost of engines + the airframe and system (other than the engines) maintenance material cost + the engine (s) maintenance material cost)</td> <td>Cost of aeroplane and traffic servicing, control and freight (cost of airplane service + cost of airplane control (ground manoeuvres) + cost associated with handling freight)</td> </tr> <tr> <td>Cost of financing</td> <td>Cost of general administrative expenses (cost of requirements for administrative and accounting personnel and for their facilities commissions to travel agencies + cost requirements for corporate staffers and their facilities)</td> </tr> <tr> <td>The cost of fees associated with flight and non-operational time (landing fees, navigation fees, hangar and tie-down fees, ramp fees, after Hours Fee, flight permit fee, recharging/refuelling fee + registry taxes + property tax + annual use tax (lease only)</td> <td>Cost for promotion, sales and entertainment (commissions to travel agencies + publicity and advertising campaigns + entertainment)</td> </tr> </table>	Direct Operational costs	Indirect Operational Costs	Cost of flight (crew salaries, trainings benefits, insurance), operational oils/lubricants, airframe insurance)	Cost of passenger services (cost of passenger insurance + passenger handling + passenger baggage handling + sales and reservations + security + miscellaneous passenger costs)	Cost of depreciation (airframe, engines, propellers, avionics systems, spare parts, engine parts)	Cost of maintaining and depreciation of ground equipment and facilities	Maintenance costs (labour cost of airframe and systems + labour cost of engines + the airframe and system (other than the engines) maintenance material cost + the engine (s) maintenance material cost)	Cost of aeroplane and traffic servicing, control and freight (cost of airplane service + cost of airplane control (ground manoeuvres) + cost associated with handling freight)	Cost of financing	Cost of general administrative expenses (cost of requirements for administrative and accounting personnel and for their facilities commissions to travel agencies + cost requirements for corporate staffers and their facilities)	The cost of fees associated with flight and non-operational time (landing fees, navigation fees, hangar and tie-down fees, ramp fees, after Hours Fee, flight permit fee, recharging/refuelling fee + registry taxes + property tax + annual use tax (lease only)	Cost for promotion, sales and entertainment (commissions to travel agencies + publicity and advertising campaigns + entertainment)
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Cost of financing	Cost of general administrative expenses (cost of requirements for administrative and accounting personnel and for their facilities commissions to travel agencies + cost requirements for corporate staffers and their facilities)												
The cost of fees associated with flight and non-operational time (landing fees, navigation fees, hangar and tie-down fees, ramp fees, after Hours Fee, flight permit fee, recharging/refuelling fee + registry taxes + property tax + annual use tax (lease only)	Cost for promotion, sales and entertainment (commissions to travel agencies + publicity and advertising campaigns + entertainment)												
Cs – Delay and deadhead costs	delays of passenger flights UAS repositioning flights												
Cenv – environmental costs	CO2 emission fee during flight (kWh CO2 equivalent) Noise pollution costs												
Cd - End - of - life costs	Recycling costs Incineration costs Landfill costs												

tool more influencing policy maker. Nevertheless, literature pays little attention to the relevance of the ELCC as a tool to support the decision adoption process of environmentally friendly innovations, like UAM. The UAM operations considered in this article are those established within the ASSURED-UAM project financed by the Hope et al., 2021 Programme, and are placed within the forecast scenarios in relation to the 2025, 2030, and 2035 time horizons for both passenger and freight transport. As the pace of future deployment of UAM operations is not yet known, the scenario presented below describes the early stage of UAM services in terms of infrastructure, aircraft technology, deployment, operations, energy efficiency and environmental footprint that play a crucial role in the UAM market. The study does not give defined or closed solutions to the issue of integration between UAM and other transport systems, but provides elements related to the Environmental Life Cycle Cost for Urban Air Mobility, to guide research in terms of sustainability in this area. The study focuses on the cost-effectiveness

Table 3
Investment costs per case study.

INVESTMENT COSTS						
USE CASES	Aircraft		Landing pads		Total cost	
	Lifetime	N.	Cost/unit	N.		
Union, 2021 (1) Direct last mile delivery	10	40	15 k EUR	20	150 k EUR	3,6 M EUR
Union, 2021 (2) Point to Point public services	10	50	15 k EUR	25	150 k EUR	4,5 M EUR
Union, 2021 (3) Advanced last mile delivery	13	5	300 k EUR	8	700 k EUR	7,1 M EUR
Union, 2021 (4) Point-to-everywhere public services	13	8	100 k EUR	12	300 k EUR	4,4 M EUR
Union, 2021 (5) Direct medical transport of people	20	5	1 M EUR	12	400 k EUR	9,8 M EUR
Union, 2021 (6) Automatic personal aerial transportation	20	4	1,5 M EUR	6	1 M EUR	12 M EUR

Table 4
Reference recycling cost of materials.

Aluminium	Steel	Titanium	Copper	CFRC	GFRC	Polymers
0.87 EUR/kg ^a	0.17 EUR/kg ^b	7.00 EUR/kg ^c	1.40 EUR/kg ^d	4.17 EUR/kg ^e	0.33 EUR/kg ^f	0.33 EUR/kg ^g

- ^a Soo et al., 2019.
- ^b <http://recyclletucson.com/cost-recycle-metal/>.
- ^c <https://www.jefferies.com/CMSFiles/Jefferies.com/files/Insights/BasicMaterials.pdf>.
- ^d Zeng et al. (2018).
- ^e Meng et al. (2018).
- ^f Cousins et al. (2019).
- ^g Genc et al. (2019).

Table 6
WTT factors for selected sources of energy (MJ/MJ) (Biedka et al., 2017).

Petrol	Diesel	LPG	CNG	Electric
0.1842	0.2042	0.1184	0.1653	2.2616

criterion that is a key concept for the design of transport services and associated plans, as well as the development of mobility assets, forecasting both expected costs and revenue streams as precisely as possible. Moreover, the environmental footprint will be considered to provide conclusions related to the European Green Deal - Mobilising industry for a clean and circular economy and accelerate the shift to sustainable and smart mobility. Task results will be translated into measurable and comparable indicators that enable cost comparison with other means of transport. Summarily, by observing the Environmental Life Cycle Costs of Urban Air Mobility (UAM) services, this study focuses on the following research questions: is it possible to integrate UAM into a transport system? Second, what are the main factors to conduct research in terms of UAM sustainability? We test these research questions in the three-time horizons: 2025, 2030, 2035.

2. Literature review

The development of aircraft for UAM services as well as complementary systems can be easily observed nowadays. The progress made within the technological area and services with the use of unmanned

aircraft systems has resulted in the intense work of regulatory organisations throughout the world who have been forced to catch up with the advancing new modes of transportation in terms of required standards and regulations (Garrow et al., 2021). Among the many factors affecting the success of UAM, besides the use of technology, there are factors related to the development of an adequate infrastructure for take-off and landing points, maintenance, power supply and communication, services with sound business and operational models, and a regulatory framework to control and govern safety, liability, emissions, and much more (Berger, 2018). Indeed, the continuous development of technical innovations provides the opportunity to create new economic markets and a wealth of new services. However, these innovations sometimes raise concerns, notably in terms of societal, safety, and environmental impacts. This is the case for services related to the operation of Unmanned Aerial Vehicles (UAV), which are emerging rapidly (Kellermann et al., 2020). Nowadays, drones of various types and sizes are used for many purposes, such as precision agriculture, search and rescue missions, aerial photography, shipping and delivery, etc. The use of UAVs in the urban context is different, not least in relation to traffic surveillance and monitoring, as tools for transport managers and engineers and as an integral part of traffic management and control strategies (Papageorgiou et al., 2008). Starting to operate in areas with low population density, drones are now looking for business in urban and suburban areas, in what is UAM (Cetin et al., 2022). The objectives of the procedures to define the mitigation measures are described in an opportune theoretical framework in the literature (Cetin et al., 2022). Although UAVs were firstly introduced for military missions, their use has been recently expanded to civil applications; the last was facilitated by a burst in the UAV industry, which systematically provides smaller and lower cost aircraft (Mahadevan, 2010). Since most UAVs can get up in the air in a matter of minutes thanks to the latest advances in lightweight materials and equipment, they can cover large distances in very short time intervals, while most UAVs use environmentally friendly energy sources (Gupta et al., 2013). Their use and possible integration with other means of transport can be facilitated by the fact that, due to their relatively small size, they can reach places inaccessible for an Automatic Vehicle Monitoring (AVM), e.g., a dense urban area with tall buildings and transport infrastructure (Barmounakis et al., 2016). An interesting precedent in terms of a Life Cycle Assessment study to calculate and compare the life cycle of the gas emission of Battery Electric Vehicles (BEVs) and conventional vehicles with petrol internal combustion engines (ICEVs) under three different time scenarios (2010, 2014 and 2020) was the research (Wu et al., 2018), which shows that by changing the electricity mix, advancing power generation technologies and increasing the scale of cogeneration, the greenhouse gas emission reduction potential of BEVs can be improved.

The role of different costs involved in the industrial process is crucial for transport and mobility efficiency. Indeed, investments and relative costs have a significant influence on technical efficiency levels. The theoretical framework motivating the impact of costs in the transport efficiency is based on the use of a production function, where the different costs could play a significant role in the inefficiency index, measured as the gap between the best result possible in terms of frontier and the current value of production (Sami et al., 2013). In addition to the scientific bibliography, sector studies and European regulatory references were analysed to explore the scientific topics covered. About the Current Aviation CO₂ emission charging/fee (combustion engines), the report of global forecast of UAV Market shows the expected growth to USD 58.4 billion by 2026 (Market sand Markets Research Private Ltd). In line with the Union, 2021 Paris Agreement European Green Deal goal is

Table 7

GWP values for key materials in the aircraft expressed in kg CO₂eq/kg of material and kg CO₂eq/kWh for lithium battery (ICCT, 2018).

Aluminium	Steel	Titanium	Copper	Carbon Fiber	Glass Fiber	Polymers	Lithium battery
19.0	18.0	8.0	8.0	13.0	6.0	6.0	170.5

Table 8

GWP values for different fuel types.

Coal	Natural Gas	Diesel	Petrol
0.82	0.49	0.248	0.237

to be climate neutral by 2050. The 2030 milestone requires reducing greenhouse gas emissions, especially in transport, by 55% compared to the levels of 1990 (DG Climate Action European Commission, 2021). As a part of the legislation package of the European Green Deal, the EU Emission Trading System Directive (DIRECTIVE, 2003/87/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of October 13, 2003) will propose amending the EU's emissions trading system. Transportation is considered as one of the main contributors to CO₂ emissions that contribute to GHG emissions and has posed a serious impact on natural systems (Koiwanit, 2018). The transport policy of the EU aims to establish a sustainable transport sector while meeting future constraints: oil scarcity, growing congestion and the need to cut CO₂ and pollutant emissions to improve air quality, particularly in cities (European Commission, WHITE PAPER Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system, COM/2011/0144 final, 2011).

With the specific topic of the noise, significant reductions in propeller noise can be achieved by increasing the propeller diameter while reducing its rotational speed, thereby reducing its blade tip speed, while maintaining a given level of static thrust. Further significant noise reductions are possible with weight and custom-engineered components (European Union, "Noise pollution in the EU", 2021). As regards environmental protection, the EASA Regulation stresses that drones 'must be designed to minimise noise and emissions as far as possible'. The aircraft need to comply with environmental protection requirements and to be issued with a certificate of airworthiness. When taking measures to address emissions and noise, EASA 'shall prevent significant harmful effects on climate, environment and human health' (European Union Aviation Safety Agency, (EASA)). Some governments have imposed taxes on aviation noise to help finance mitigation measures around airports (Hope et al., 2021). Noise from a drone is only relevant to the extent that it does not exceed ambient (background) noise levels to avoid detection by the objects (human/animals) of interest.

As a new form of pollution, drone noise presents a fresh opportunity to explore the relationship between regulatory and fiscal policies. Regulation is the right answer if noise pollution at any given level is not an acceptable externality. But if drone regulations would still allow some level of harmful noise pollution due to design limitations or lack of regulatory will, taxes might step in.

3. Research method

Considering that the UAM system and the dedicated aircraft are in the beginning phase of development, part of our input originates from a long history of classic aircraft, especially data covering operational aspects of flight. For comparing transport modes in terms of energy efficiency, we adopted unitary data and the method from a 2017 EC DG MOVE's report on urban accessibility (Biedka et al., 2017).

The analysis starts by categorising each mitigation measure in such a way that four different scopes, or categories, are established.

- Regulation and policy, which contains the mitigation that should be part of the regulation made by the policy makers.

- Operational and ConOps, which includes the mitigation measures related to rules and regulations that enable the safe integration of drones with other airspace users.
- Human response and metrics. This category relates to mitigation measures that engage the public.
- Tool and technologies, which include mitigation measures that can be built into or used by drones.

The specific methodological approach for developing the ELCC covers the following subjects.

- Environmental life-cycle costing components and values.
- Energy efficiency of selected aircraft.
- Carbon footprint for selected scenarios.

The key area of research was focused on the determination of the cost components of UAM required to calculate the unit costs of UAM transportation, as these results may be used to compare the UAM with other modes of transport.

As given below in detail, we employed the data from the literature (Biernacki, 2015; Hunkeler et al., 2008) highlighting the cost components of UAM, including environmental aspects. Each cost component is described in detail.

As for the investment costs, the data for those calculations were based on the in-house expertise in helix and aircraft. And then confronted with the findings from Uber Elevate (2016) and McKinsey&Company (2020).

Energy costs were calculated by distinguishing the two sub-categories: aircraft energy consumption and ground infrastructure consumption. Utilising data from literature papers e.g. (Bacchini and Cestino, 2019), (Zhang et al., 2021; Li et al., 2017; Costa et al., 2012) about flight parameters and energy component breakdowns we could transform our assumptions for given use cases into output values of energy costs. In analysing these costs, we must consider the costs of the 1) Aircraft energy consumption and 2) Landing pad/vertiport infrastructure energy consumption cost. Various theories to calculate the energy consumption by aircraft are present. We applied one available by Stolaroff et al. (2018), that includes forces of weight, parasite and induced drag. For hovering rotorcraft, disc actuating theory was employed. Based on the results of the analysis made by Zhang et al. (2021), energy consumption for small rotorcraft (MTOW<25 kg) was calculated. However, larger aircraft with different configurations were analysed in terms of energy consumption (Bacchini and Cestino, 2019). The in-depth analysis allowed for calculation of energy demand for aircraft with MTOW greater than 25 kg. Operating costs were divided into two subcategories: direct and indirect. Direct are related to the activities orientated on flight execution, whereas the indirect to the activities that enable those flights. Required data were acquired from

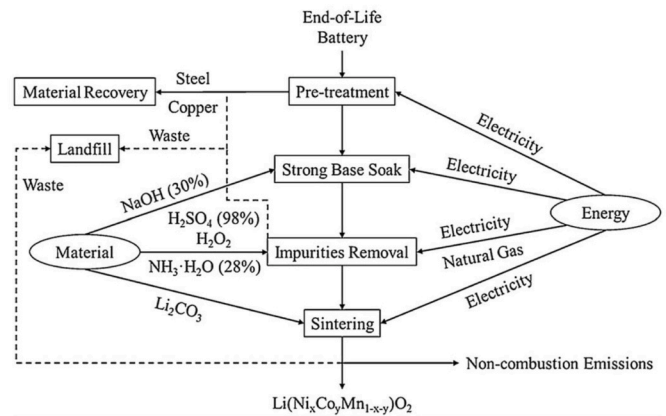


Fig. 2. Nickel Manganese Cobalt (NMC) battery recycling process.

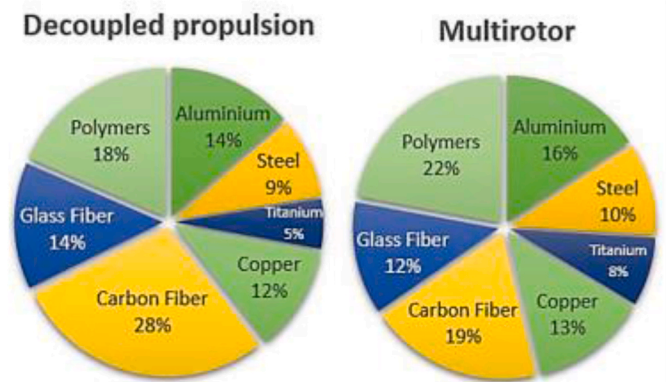


Fig. 3. Material composition in the decoupled propulsion and multirotor VTOLs excluding the lithium battery (Andře and Hajek, 2019)

airlines and then adjusted to the ASSURED-UAM use cases due to the lack of relevant and reliable data for drone operations. Details of operating cost assumptions are given in section 4. Theory and calculation.

The delay costs were assumed on the basis of the data from literature data (Liu et al., 2019a,b), who described the delivery operations of Fedex company. Again, the data is for the calculations are from general aviation but adjusted to our purposes.

Environmental costs were calculated considering the greenhouse gases and noise emission fees for general aviation and requirements and goals determined by the EU commission in relevant directives and standards. A proposal for a directive providing for the harmonization of

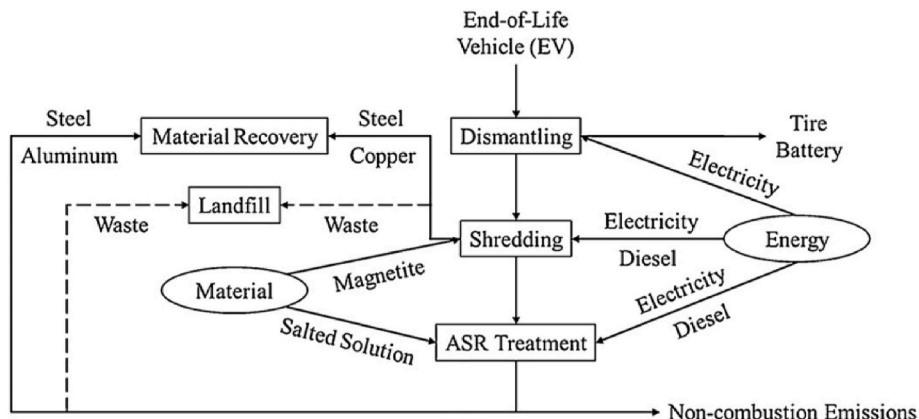


Fig. 1. Electric vehicle recycling process.

methods of assessment of noise exposure and the mutual exchange of information. The proposal could include recommendations on noise mapping and the provision of information on noise exposure to the public. In a second stage, the consideration could be given to the establishment of target values and the obligation to take action to reach the targets (Commission of the European community's future noise policy - European Commission Green Paper COM/96/0540 FINAL).

End of life costs are strongly related to the means of the aircraft disposal, among which are landfilling, incineration and recycling. Because only the recycling process is the most promising in terms of gains both economic and environmental, we calculated the end-of-life costs considering the recycling process. Then, using data from literature about the material composition of VTOLs, the recycling cost of individual materials, we could calculate the total cost of recycling the aircraft.

Energy efficiency as a factor enabling the comparison of different modes of transportation was also the subject of our analysis. We considered our results from the calculation of energy consumption of people transporting drones and then calculated the energy per passenger.

The carbon footprint for all use cases was calculated in relation to the results of energy consumption and end of life costs. This is because the carbon footprint comes from 3 phases of UAM component life: manufacturing, operational and end of life. The detailed approach to the calculations is described in the subsequent section.

3.1. Key parameters and assumptions for the UAM forecast scenario

Three categories appear to play the most significant role in the deployment and management of the aerial operations within urban

areas: aircraft specification, trip parameters and infrastructure. Each of these groups is thoroughly addressed below with the reference to the proposed use cases in three-time horizons. The presented costs of purchase exclude dedicated internal equipment directly related to the mission purpose (e.g., medical devices necessary to be installed aboard in case of patient transport). Analysed use cases, both commercially and public interest driven, should be understood as being in the initial phase of service development (among others in terms of number of operations). The large variety of available solutions, even if in terms of UAV configuration connected with real commercial and social potential of UAS in urban areas, concludes that the presented calculations should be considered only estimation/assessment burdened by certain errors (especially if other than taken assumptions are presumed).

4. Research methodology

The methodological approach was developed in terms of the following.

- Environmental life-cycle costing components and values;
- Energy efficiency for selected aircraft;
- Carbon footprint for selected scenarios;

Life Cycle Cost is an additional analysis to the well known LCA (Life Cycle Assessment) that delivers direct information about the costs at each phase of the product's lifetime. The term environmental LCC means that the analysis covers the costs related to the products or service's impact on the environment. Considering UAM operations, it is obvious that it will impact the environment as every other transport mode and thus it is worth making such an analysis. As there is no sufficient

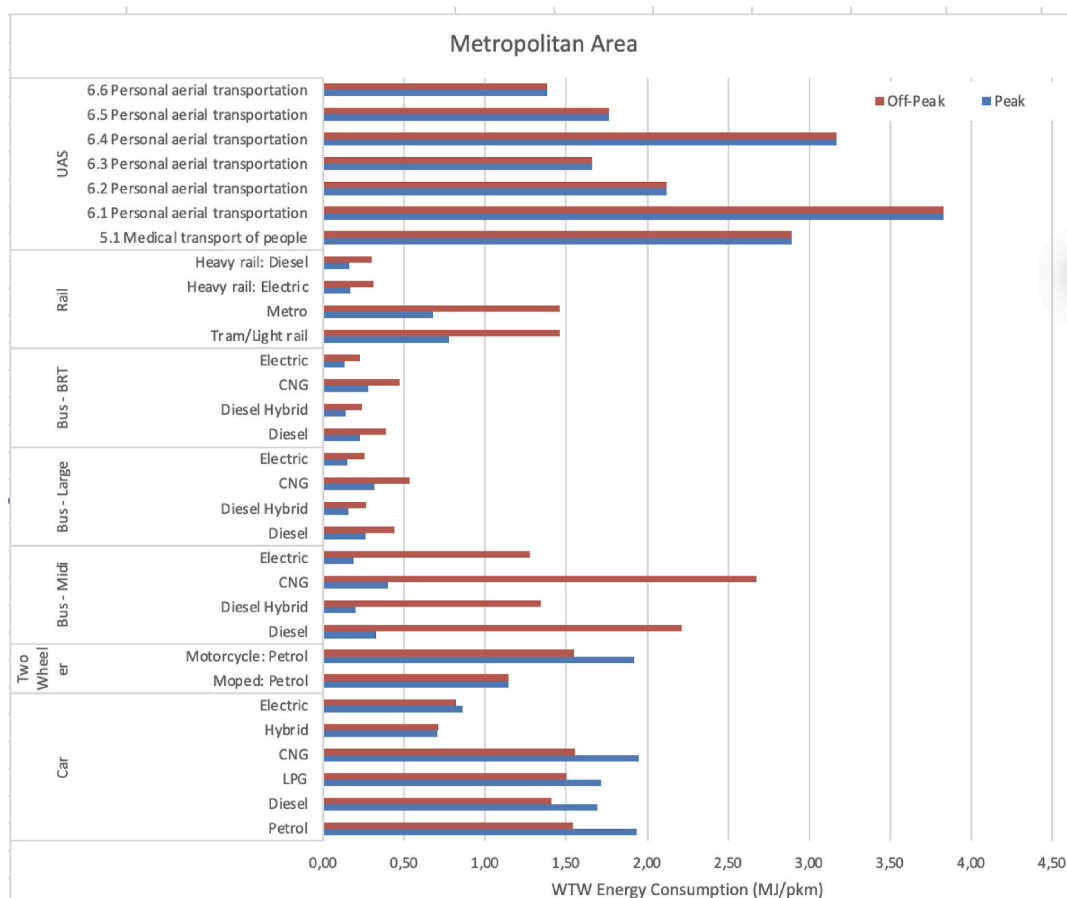


Fig. 4. Energy efficiency comparison of ground and aerial modes of transport in metropolitan area (Biedka et al., 2017).

information about UAM flights to make robust analyses, data from classic aviation (helicopters, airplanes, airports, helipads, etc.) will serve as an input in many costs' calculation.

To analyse the total cost of the UAM operation, the individual components need to be identified. The most suitable for UAM operation cost breakdown structure is given (Biernacki, 2015; Hunkeler et al., 2008). Some components have been modified to suit best the UAM applications. With the support of literature, we identified adequate components of the Environmental Life Cycle Cost:

$$ELCC = C_{ic} + C_e + C_o + C_s + C_{env} + C_d \quad (1)$$

Each of the component can be broken down into more sub-components, which are typical for a certain product or service.

It is important to mention that some components have a bigger contribution to the total cost calculated while the others are minor or even negligible. In the calculations for specific use case-based scenarios, all of the above-mentioned components are addressed, however, detail level may vary depending on the available data. No specific software has been used to assess ELCC due to the insufficient data to cover the UAM topics. Therefore, in-house calculations were performed on the basis of available publications and in-house expertise. Major assumptions have been made regarding the aircraft, vertiports/landing pads and aerial operations and then used in the calculations. Details of the calculations, results and discussion of the application are explained in the following paragraphs.

5. Calculation, results and discussion

By focusing on the Environmental Life Cycle Costs of Urban Air Mobility (UAM) services, the primary goal of the study is to investigate the potential integration with other transport systems, more than three-time horizons (2025, 2030, 2035). Specifically, this research does not give defined or closed solutions to the issue of integration between UAM and other transport systems, but provides elements related to the Environmental Life Cycle Cost for Urban Air Mobility, to guide research in terms of sustainability in this area.

The results for each component of the Environmental Life Cycle Cost are detailed below.

5.1. Investment costs

For these costs, in addition to those already considered above, the following should also be considered: the investment costs are to be assumed by an operator, the software cost installation for the USSP (U-Space Service Providers) platform may also be included in the calculation, which usually amounts to an approximate cost of 10kEUR.

5.2. Energy costs

1) Aircraft energy demand is strongly dependent on two main factors: aircraft configuration and flight parameters. An aircraft's ability to fly is possible thanks to the rotating propellers that deliver the lifting force or aerodynamic wings that use the pressure difference to generate an elevator. Depending on the source of the lifting force, rotorcraft or aeroplanes can be distinguished. Some theories to calculate the energy consumption by aircraft are present. One of them is the Stolaroff et al. energy model that includes forces of weight, parasite and induced drag. For hovering rotorcraft, disc actuating theory is employed.

Having the ASSURED project considered the three-time scales of 2025, 2030 and 2035, we assume that.

- In both use cases for 2025 horizon, the octocopter with an MTOW of 25 kg is considered. The payload is 5 kg, while the net weight of the vehicle is 7 kg. The remaining weight – 13 kg is covered by the

battery with a specific energy of 250 Wh/kg. The power transfer efficiency, which describes the effectiveness in transferring the energy from batteries up to the motors, is 0.57 while the maximum discharge rate of batteries is 0.8.

- For 2030 horizon use cases, decoupled propulsion systems will be under examination. Developments in the battery technology are also expected. The power transfer efficiency is expected to increase to a value of 0.75, whereas the discharge rate to decrease to 0.7 for safety reasons.
 - 2035 horizon use cases will also be investigated considering the decoupled propulsion system aircraft that have superior efficiency. Batteries with 2500-Wh/kg-specific energy are predicted to emerge in the market. Power transfer efficiency will increase to 0.8, while the discharge rate will remain at 0.7.
- 2) Landing pad/vertiport infrastructure energy consumption cost

According to the literature data, energy consumption by civil airports in reference to the civil aviation industry amounts to only 3%, while the amounts of ground services energy consumption is 2% and the energy consumption of other civil aviation units is no more than 1% (Civil Aviation Administration of China, 2008). To calculate the total cost of landing pad/vertiport infrastructure, the data about the structure of energy consumption of the airport has been utilised as a base input for the further assumptions. The Energy coming from the above shown sources is utilised to power heating equipment, lighting equipment, HVAC equipment, baggage-handling facilities, boarding bridges, public supporting facilities and equipment, etc. (Li et al., 2017). As this information may be reflected to the vertiports, where passenger flow may be similar to that at the airport, some assumptions towards using this data for landing pads can be made. To concentrate first on the vertiports, the information required to calculate the energy consumption is the number of operations, the load factor determining the number of passengers and average energy consumption per passenger. Then, using the information about the energy consumption structure and prices for given energy sources, the cost of energy consumption of the vertiport can be obtained. Knowing that the energy consumption by vertiport is 3% of total aviation sector costs, while the ground services and other civil aviation units amount to another 3% of total costs, the consumption cost of the vertiport infrastructure energy can be calculated.

Realizing that landing pads will not require similar infrastructure as vertiports, it is worth remembering that handling the parcels will require an additional labour of the staff.

Since the energy consumption by vertiport is related strictly to the number of passengers travelling, and that there is no sufficient data about energy cost by cargo terminals, the traffic unit has been employed to reflect the amount of transported cargo and thus the energy cost by cargo landing pads. According to the study (Costa et al., 2012), the traffic unit (tu) is used for assessing airports based on the number of passengers and the amount of freight (1 tu = 1PAX or 100 kg Cargo), knowing the average payload transported and the number of operations, it is possible to determine the PAX equivalent.

5.3. Operating costs

This category is dedicated to all costs beginning during the operational phase of the UAM services. The main division of this category falls into direct and indirect costs. The first one is associated with the costs of operational activities of UAM services, namely, flights. The second subcategory refers to born costs in conducting the operational activities but are not directly related to flying itself. For sure not all appliances are to specific business cases (e.g., passenger service-related costs with cargo transport).

Among the direct and indirect cost categories, we distinguished the following.

- Cost of flight (pilots and dispatchers)

- UAV depreciation rate assumed at 14% per year;
- Maintenance including periodical major mechanical servicing after 300 h of operations. The mechanical inspection after every 50 h and one airworthiness service per year;
- The cost of fees assumed in relation to current manned aviation sector standards and scaled properly to fit the UAM market;
- Cost of passenger services limited to the loading/unloading the cargo;
- Depreciation rate of ground facilities rate assumed at 1.5% per year;

The cost of aeroplane and traffic servicing control and freight/cost of general administrative/cost for promotion. Sales and entertainment expenses are assumed in relation to current manned aviation sector standards and scaled properly to fit the UAM market.

5.4. Delay and deadhead costs

Delays are very common at civil airports due to multiple reasons, such as bad weather conditions, air incidents including bird strikes, air traffic control restrictions, passenger punctuality, cargo loading problems, and many more. It is expected that such delays may also occur to unmanned operations, especially when the number of aircraft airborne will rise.

Two main categories of delay costs exist: hard and soft costs. The first group relates to the compensation that the airline must pay to the passengers due to the flight delay or to the customers due to the package delivery delay. However, soft costs are the after effect of the delays and refer to the deteriorated image of the company that in the longer term may result in fewer tickets acquisitions or packages received for delivery.

Considering the current European regulations concerning airline delay compensations, it is feasible to calculate the average value of delay cost per passenger that airlines bear every year. Similar regulations and standards exist for cargo flights. Delay costs for passenger flights are way smaller than for the cargo flights.

As for the cargo flights, the delay cost is calculated assuming a cost per package of 1.5 euro, which is around 35% less than the average cost per package transported by aeroplanes. This assumption is based on the fact that by using small aircraft, it is more probable that deliveries will be more punctual. Furthermore, end user claims are expected to be rarer and smaller in value rather than from companies or institutions. The average package weight is assumed to be 5 kg. This is the unit cost – 1.5 euro refers to the total cost, including hard, soft costs, crew, ground handling, etc. Moreover, the unit delay cost relates to the 15 min delay that is an average value calculated in reference to data obtained from Fedex deliveries realised at 98 airports (Liu et al., 2019a,b). On the vertiports and landing pads, the delay time may be reduced, thereby the assumed cost at 1.5 euro may be a good approximation.

Passenger delay costs are calculated in relation to an average passenger cost calculated for 25 examined airports, which amounts to 1 EUR per 8 min average delay (Cardenas et al., 2017). If the delay at the vertiports will happen less often, the cost per passenger is 35% less, which amounts to 0.65 EUR.

5.5. Environmental costs

During airline operations, the trip provider must pay for 18% of the CO₂eq emitted. The emission of carbon dioxide (CO₂) is directly proportional to the fuel burnt, and for aviation kerosene the Emission Index is 3.16 kg of CO₂ per kilogramme of fuel burn (ICAO, 2021). For NO_x and nvPM, the CO₂ emissions are directly related to fuel consumption (DG Climate Action European Commission, 2021).

Decarbonising electricity supply, for instance, by substantially accelerating the deployment of renewable energy sources to achieve a share of almost 70% in generation by 2030 and above 80% by 2050, is critical to achieving this objective (European Environment Agency,

Greenhouse gas emission intensity of electricity generation in Europe. 2021). About the noise pollution costs, EU indicators for noise pollution are 55 dB for day-evening-night (Lden) and 50 dB for night (Lnight).

Different methods of noise measurement are present in open area or inside a closed environment by measuring the noise emitted during the flight with a sound-level meter placed at different distances (5 m, 10 m, and 15 m). In this configuration, a typical tonal component of drone noise was highlighted at the frequency of one-third of an octave at 5000 Hz due to the rotation of the blades (Ciaburro et al., 2020).

Compared to light aircraft, UAVs have advantages due to their ability to provide data at high spatial and temporal resolution at low operational cost and risk (Jones et al., 2006).

The EEA (European Environment Agency) has already contributed to the two first European aviation environmental reports, published in 2016 and 2019. The 2019 edition-mentioned drones and stressed that ‘an in-depth life cycle analysis will be required to assess the environmental impacts of [drones] compared to conventional aircraft (European Environment Agency, 2019). To calculate the costs related to noise emissions, the assumption made by EASA (European Union Aviation Safety Agency, (EASA)) that the noise and emission charges may not exceed 1% of all operating costs has been considered. To indicate what part of the operating costs and, finally, to calculate the value of noise pollution related costs, the data from a couple of European airports (Swedavia, 2021; Aeroporti di Roma, 2021) have been utilised. These suggest to us that the noise charge is around 0.4 EUR per tonne of MTOW of an aircraft.

5.6. End of life costs

There are 3 means of disposing the products: landfilling (negative impact on environment), incineration (negative impact on environment) and recycling. Recycling is the process of utilising the dismantled components or processed materials in new products. In other words, recycling enables the recirculation of materials in the environment, contributing to the positive impact of reducing the carbon footprint. Below there is an approach to the calculations we made to assess the recycling costs of UAVs. The information to assess the recycling cost is the material composition of examined UAVs (André and Hajek, 2019).

To demonstrate how the recycling of retired UAVs may look like, the graph below presenting the recycling process of an electric car is given (Hao et al., 2017).

Even though there is a major difference between the design of electric ground vehicles and aerial vehicle, the materials and mechanical structures are pretty the same, yet some differences in material composition may occur. The first step is the dismantling of the vehicle and then shredding it into small pieces, which can be then separated into groups of individual materials.

Batteries and tyres undergo their own recycling process that requires more than only shredding (Hao et al., 2017). The recycling process includes the recovery of cathode materials such as cobalt and nickel in metal form. Other materials that were recovered were lithium, steel, copper, aluminium, plastic. The recovery rate of precious metals from batteries may reach 90% but the average rate is around 50%.

According to a Study on Reuse and Recycling of Batteries Employed in Electric Vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries, the cost of EV batteries recycling is around 1700–2000 USD per tonne.

Having the information about the materials compositions of UAVs and the recycling cost of the individual material per kilogramme, we could calculate the total recycling cost of the UAV, based on its net weight.

5.7. Energy efficiency of selected aircraft

The term energy efficiency can be expressed in various indicators, but regarding transportation, it is the measure of energy usage by the

vehicle related to the number of passengers transported at a given distance. Therefore, the energy efficiency may be presented as follows:

$$EE = \frac{\text{Energy usage per vehicle kilometer}}{\text{Vehicle capacity} \times \text{load factor}} \left[\frac{\text{MJ}}{\text{pkm}} \right]$$

order to produce the best and most reliable data about the EE of UAVs, the Well-to-Tank (WTT) and Well-to-Wheels (WTW) energy usages must be introduced. The first term refers to the energy consumed to produce and distribute the energy from a given source. The second one, however, translates to the thorough energy usage, beginning from its production until the consumption by the vehicle.

Since the energy can come from either fossil fuels or renewables, the WTT factors indicating what part of the output energy is consumed to produce and distribute it, can differ. Therefore, not only the vehicle energy consumption plays an important role regarding economic aspects, but also the effectiveness of energy production and distribution. Below are the WTT factors for the selected energy sources.

According to the table above, the most efficient in terms of the energy gain is the LPG that requires the least energy at the input. However, energy required to produce electricity is high compared to the fossil fuels, which may be a result of the low efficiency of power plants in Europe that are mostly coal-based and have poor energy network.

As the energy efficiency is related to the energy consumed per passenger, we employed the results of energy consumption for use cases 5 and 6, which concern the transport of people. Then we assumed a load factor of 1.3, WTT factor 2.26 (for electric energy), ground mile equivalent 1.42, as the aerial vehicles' travel distance is less than those on the ground, (Elevate, 2016) and finally calculated the energy efficiency. The obtained results were placed among the data for other modes of transportation (Biedka et al., 2017).

5.8. Carbon footprint

While in the calculation of environmental costs, the financial aspect was considered, the results presented below refer to the after effects that UAM will bring in terms of greenhouse gas emissions.

To analyse the carbon footprint of the UAM services, it is crucial to underline the fact that not only during the operations the carbon emissions are released into the atmosphere but also in the manufacturing and end of life phase. To estimate the carbon footprint during the manufacturing phase, the following assumptions have been made.

- Carbon emissions released during the manufacturing of an aircraft depend on the material composition
- Each material is characterised by a unique Global Warming Potential, expressed in kg CO₂eq/kg of material
- The material composition may differ depending on the aircraft type and propulsion technology

Based on data about the material composition in UAVs presented at the End-of-life cost chapter as well as values of Global Warming Potential (GWP) for materials in the above-mentioned aircraft, it is possible to calculate the carbon footprint from each constituent.

The aircraft in the UAM fleet will use the electric propulsion as the most efficient and tested, the information about the GWP of lithium battery must be estimated. To do so, data from multiple papers have been considered and resulted in the average value for lithium battery GWP.

All these data can allow for calculating the total carbon footprint in relation to the manufacturing of one aircraft. As far as the modification of GWP values in relation to further time horizons are concerned, with the development of new designs, manufacturing technologies, material combinations, the recycling process will respond in a balanced and sustained way. Moreover, with the development of battery technology, the GWP value is assumed to drop in proportion to the growth of battery-

specific energy, remaining at a steady, unchanged drastic level.

However, if the goal is to estimate the carbon footprint referred to one operation, two more factors must be considered.

- Vehicle Life
- Number of aircraft

The harmful emissions in this phase come from two sources: the flight and ground operations at the vertiport/landing pads. To calculate the carbon emissions during the flight, the following factors are considered.

- Flight energy consumption
- Battery charging efficiency – 0.85
- Global Warming Potential (kg CO₂eq/kWh of grid electricity) – dependent on the country

Depending on the flight profile, which is correlated with a given use case and the country, in which the flights occur, the output carbon footprint may vary.

However, the operations occurring on the ground are also a great source of harmful gases. To calculate the magnitude of these emissions, these are the key factors: that must be considered.

- Vertiport/landing pad energy consumption/operation (kWh)
- Energy consumption structure at the vertiports/landing pads
- Global Warming Potential (kg CO₂eq/kWh of fuel)

Purchased thermal energy is considered to come from the electricity since the source of heat is strongly dependent on the electricity mix in a specific country. Therefore, for the sake of the following calculations, this assumption has been made.

Since every country has a different electricity mix in Europe, and considering that the elaborations were developed considering the three cities involved in the ASSURED-UAM project (Metropolis GZM, Porto and Bari), the GWP values may vary. Based on data published on electricity maps (<https://app.electricitymaps.com>), calculated electric energy consumption of aircraft and vertiports, the carbon footprint may be computed by multiplying the energy consumption and GWP values.

Opposite to the general thinking, end of life of the aircraft is not climate neutral. Few means of the aircraft disposal exist after its withdrawal from the service and irrespective of what kind it might be, there is either a major or minor impact on the environment.

Based on the current expertise, these are 3 ways of aircraft disposal.

- Recycling
- Incineration
- Landfill

According to a thorough analysis (André and Hajek, 2019), only the recycling has the benefits related to the environment. According to their findings, the incineration of VTOLs has a negligible impact on carbon emissions compared to the GWP of the manufacturing and operational phase. Furthermore, incineration is not the best option to recover precious materials which are embedded in the UAS systems' components. Moreover, landfill is way more negligible than the incineration as in this method no major benefits or harms are achieved.

According to the "Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production: The 2025 case the life cycle GHG emissions from the production of an EV with NMC battery are about 14.9 t CO₂eq (Hao et al., 2017), whereas production of EV with recycling is only 9.8 t. That is to say, about 34% of the total GHG emissions from EV production can be reduced by recycling.

Having that in mind, if the recycling is chosen as a disposal means of an aircraft, the carbon emission savings are prominent in another manufacturing phase. Therefore, in the calculations below, recycling is

chosen as the method for disposal of EoL UAVs.

5.9. Main findings for each analysed section

5.9.1. Environmental life-cycle cost calculation

Investment costs.

- Operations conducted with use of small drones involve smaller investment costs in relation to bigger representatives due to the initial cost of aircraft and landing pads/vertiports
- The investment costs are strongly dependent on the number of aircraft/landing pads/vertiport purchased – the greater the enterprise, the higher the investment costs
- Besides the use case 5, where the UAM infrastructure is not built but retrofitted, most investment costs amount to infrastructure rather than aircraft purchase

Energy costs.

- The energy cost of the breakdown structure indicates that energy consumption by aircraft in operation is greater than the landing pad energy usage
- With an increasing size of UAV, the contribution of energy costs within the total energy costs expands
- Total energy costs are related to the concept of operation and increase with the magnitude of cargo transported or character of the mission (cargo, passenger)
- The highest base costs among all use cases exhibit passenger UAM operations that result from the greatest energy consumption both during the flight and on the ground
- Among cargo operations, the highest base costs are for UC1 and UC2 due to the relatively short distances travelled and small cargo transported compared to UC3 and UC4

To summarise, in terms of energy for the use of UAS, the larger the size, the higher the consumption, and this imbalance is especially noticeable for passenger transport, both in flight and on the ground. Among cargo operations, the highest base costs are for UC1 and UC2 due to the relatively short distances travelled and small cargo transported compared to UC3 and UC4.

5.9.2. Energy efficiency for selected aircraft

Analysing the above shown energy efficiency rates, illustrates are the main conclusions regarding UAM economical aspects.

- The EE of UAS increases when the load factor and distance travelled rise
- In the best-case scenario (case n. 6.6), when maximum 4 people are travelling, the EE is comparable to or better than fossil fuelled cars, petrol fuelled motorcycle, midi Bus during off-peak hours, metro or tram/light rail during off-peak hours
- Compared to the electric or hybrid cars, the electric UAS have worse energy efficiency, which is related to the greater amount of energy required to lift the UAS
- Transportation of great number of people in buses, trains, especially during the peak hours, is incomparably more energy efficient than any UAS
- Although some of the ground transport modes are more efficient than UAS, it is important to remember that using aircraft for people transportation is performed much quicker (4–12 times) and is more comfortable.

This evaluation makes it clear that for mass passenger transport, there is no comparison in terms of the energy efficiency advantage of using UAS compared to trains and buses. Compared to the use of a conventional aircraft for passenger transport, the use of UAS is slower

and less fast.

5.9.3. Carbon footprint for selected scenarios

From the charts above describing the environmental impact, the following conclusions can be made.

- Small aircraft with little payload have a low carbon footprint during their operations compared to bigger UAS
- Carbon emissions are strongly related to the electricity mix in a country of operation
- The greater the contribution of fossil fuels in electricity mix, the greater the carbon footprint
- There is a correlation between the concept of operation, infrastructure, aircraft specification and the carbon footprint generated during specific phases of the aircraft life cycle
- Total base carbon emissions during operations with the use of small cargo drones related to kilogram-kilometre are high compared to more capacious cargo aircraft
- Passenger UAM services with greater MTOW exhibit higher total base carbon emissions. The more passengers onboard, the lower the base CO₂ emissions related to passenger-kilometre.

Based on the scenarios analysed and the points summarised above, we can say that the smaller the load the less the drone pollutes, and that the location makes a difference in terms of energy mix. It is also shown by these analyses that for both passenger and cargo transport, in total terms, small drones have a greater carbon footprint than conventional, larger aircraft that carry more cargo and passengers on a single flight.

Bearing in mind that the aircraft in the UAM fleet will use the electric propulsion as the most efficient and tested, the information about the GWP of lithium battery must be estimated. To do so, data from literature ([Ferrovial Foresight Unit Innovation and Digital Strategy, 2020](#)), have been considered and resulted in the average value for lithium battery GWP.

5.10. Discussion

In summary, what emerges from the analysis is that undoubtedly, the biggest financial contribution to the UAM operations must be made at the initial stage when all the infrastructure and aircraft must be purchased. The magnitude of this cost ranges from 3.5 M EUR for small cargo transportation up to 12 M EUR for passenger transportation. In the operational phase of UAM, in which energy, operational, delay and deadhead, environmental and end of life cost can be distinguished, the operating costs account for nearly 99% of all identified costs. Putting it in numbers, this cost category ranges from 471 k EUR/year for small cargo transportation up to nearly 2.5 M EUR/year for passenger transportation. In small/medium cargo flights, the dominant subcategories are cost of flight, general administrative expenses and depreciation costs, while in passenger and big cargo flights, the increased impact of fees associated with flight and non-operational time, passenger service costs (for cargo flight it is loading/unloading parcels) can be observed. Energy costs vary from around 300 EUR/year to 26 k EUR/year. It is worth remembering that most of this cost is related to the aircraft energy consumption during flight, while the rest is used by ground infrastructure. What is more, the energy cost is strongly correlated with the distance travelled and the size of the aircraft. The longer the flight and the bigger the aircraft, the higher is the energy cost. Another cost source for UAM providers and operators is relative to potential delays. These can cause up to 45 k EUR/year of refunds for parcels' recipients and up to 900 EUR/year for UAM passengers. Depending on the size of an aircraft and the distance travelled in a single operation, the total environmental costs can vary between 1 k EUR/year for small cargo transportation and up to 8 k EUR/year for passenger transportation. The biggest contribution to these costs is the carbon emission charges. The end of life (recycling) cost in the context of other costs is relatively low. When

referring to the yearly cost, this varies between 128 EUR/year and 564 EUR/year. These numbers are correlated with the number of available aircraft and their lifetime. When considering the profitability of UAM operations, the deadhead ratio is information significant value for all UAM providers in the area of passenger transportation. Because to the repositioning of aircraft required in case of their unavailability at a given vertiport, the assumed 20% of all operations may not be monetized and thus lower the net profit of UAM providers.

6. Conclusions

Both, in the case of passenger and goods transport UAM is not just about the deployment of flying cars – but the development of an entire ecosystem surrounding it – and requires the ability to control and synchronise the activities of logistics. Opportunities and challenges within this system exist in tandem and for those players that get it right, the rewards can be expected to be substantial. While the type of mobility solution available to the end users are changing so is the way in these solutions are delivered or made available to customers. The growth of shared mobility, on-demand services and pay-per-use models has recently challenged the way mobility has traditionally been conceived. In order to understand the development potential of this transport service, with a view to integration with other modes, research on ELCC has been carried out, which can provide concrete elements on the costs of these services, in order to better develop a discussion with the institutional stakeholders engaged, with technicians and in collaboration with civil society consultation. The abundance of new data on mobility preferences and pricing will further enable mobility service providers to anticipate demand for UAM, prioritise the most attractive corridors manage network efficiency and integrate different transport modes into a seamless experience.

The conducted ELCC calculations allow to estimate the cost of UAM at the very beginning of its implementation into the cities. Although many assumptions come from general aviation and were adjusted to the UAM environment, the obtained values show the magnitude of costs that cities may employ for their urban planning activities.

It is worth remembering that once more accurate data is available from the drone industry, the ELCC assumptions and thus results may be refined for better reflection of this means of transportation. Yet, at this stage of knowledge and data available, the obtained results allow for the rough comparison of UAM and other means of transportation in terms of: total cost, energy effectiveness and carbon footprint.

At the moment, UAM seems to be more expensive and less energy effective compared to ground transportation making it economically infeasible. However, it is expected to be more competitive with further development of UAM services and products by reducing fixed and variable costs.

In terms of carbon footprint, new configurations of UAM aircraft rely on electric energy. Since it is a derivative of energy mix at each country, the greater the contribution of renewable energy in the mix, the lesser carbon footprint generated. It should be noted that the green transformation of transportation should go in pair with energy generation means to make it truly environmentally friendly.

Complex cost analysis should be able to support decision makers in the definition of Sustainable Urban Mobility Plans and their principles of integration, participation, monitoring and evaluation. SUMP should be able to integrate the urban air modes with the other transport modes, both for freight and passenger transport, knowing the real values of ELCC. This detailed knowledge, which should be able to be deepened for all modes of transport, provides important elements of detail to be able to define the sustainable transport mode and thus be integrated with Sustainable Urban Mobility Plans. The paper's weak points are to be found in the fact that as the topic of UAM is still in the experimental phase, there are little-consolidated data with respect to field experience, and little data available on ELCC from other studies, in relation to UAM. Thus, while the research is original, it will be necessary to be able to draw

on more consolidated and widespread data over time. This is also the direction in which the research should head in the next steps. Look for more consolidated data and information, both with respect to the implementation of Sustainable Urban Mobility Plans that also considers the UAM marking, as well as more consolidated data with respect to many real and field applications, as well as experiments. A future research direction may be to report on the results of stakeholder's involvement (activities now underway in the ASSURED-UAM project) and to verify their specific views and needs (Falcone et al., 2019). For a future research perspective, the recommendation is to also follow what we may call Walzer's "Spheres of Justice" approach to define the benefits of transport, access, as a sphere that deserves a non-market-driven distribution, with a focus on an even distribution of benefits for users, across space and network type (private and public transport) (Martens et al., 2021), as well as consider a Multilevel Perspective on Sustainable Transitions (MLP) to evaluate how the transition into sustainable urban mobility is evolving (Marx et al., 2015).

Credit author statement

Adam Liberacki: Conceptualization, Software, Data curation, Supervision. Barbara Trincone: Methodology, Writing – original draft preparation, Supervision. Gabriella Duca: Investigation, Visualization, Resources. Luigi Aldieri: Writing-Reviewing and Editing, Validation. Concetto Paolo Vinci: Investigation, Visualization. Fabio Carlucci: Supervision, Writing – original draft preparation, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

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