

## Assessment of the Blended Wing Body aircraft for military transport

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### ABSTRACT

*The growth in air mobility, rising fuel prices and ambitious targets in emission reduction are some of the driving factors behind research towards more efficient aircraft. The purpose of this paper is to assess the application of a Blended Wing Body (BWB) aircraft configuration with turbo-electric distributed propulsion in the military sector and to highlight the potential benefits that could be achieved for long-range and heavy payload applications. Mission performance has been simulated using a point-mass approach and an engine performance code (TURBOMATCH) for the propulsion system. Payload-range charts were created to compare the performance of a BWB aircraft with various different fuels against the existing Boeing 777-200LR as a baseline. When using kerosene, an increase in payload of 42% was achieved but the use of liquefied natural gas (LNG) enabled a 50% payload increase over a design range of 7500 NM. When liquid hydrogen (LH2) is used, the range may be limited to about 3000 NM by the volume available for this low-density fuel, but the payload at this range could be increased by 137% to 127 000 kg. The results presented estimate the extent to which the efficiency of military operations could be improved by making fewer trips to transport high-density and irregular cargo items and indicate how well the proposed alternatives would compare with present military aircraft. There are no existing NATO aircraft with such extended payload and range capacities. This paper therefore explores the potential of BWB aircraft with turbo-electric distributed propulsion as effective military transports.*

### 1.0 INTRODUCTION

Commercial aviation is a continuously growing market as increasing affordability has enabled the number of passengers travelling by air to more than double over the last 20 years. This growth in mobility is expected to continue and nearly double again to 7.8 billion trips per annum by 2036 (IATA, 2017).

The prediction of exponential air-traffic growth raises serious concern. According to the European Commission in 2017, growth in aviation has led to it accounting for about 3% of the EU's total greenhouse gas emissions and more than 2% of global emissions. With the increasing number of people travelling by air, it is projected that by 2020, emissions from global aviation will be 70% higher and by 2050 could grow by

300% - 700%, relative to 2005, if actions are not taken (European Commission, 2017). Aviation within the military sector is also faced with the need of curbing emissions while maintaining the levels of performance required to ensure national security. The paper explores the potential of Blended Wing Body aircraft with turbo-electric distributed propulsion for efficient future military transport applications. Mission performance is simulated using a point-mass approach and an engine performance code for the propulsion system. The paper presents an assessment of applicability of a new aircraft configuration for military applications based on the research undertaken on the NASA N3-X aircraft. The suitability and possible applications of a Blended Wing Body (BWB) aircraft with a boundary layer ingesting turbo-electric distributed propulsion system is considered here for long-range and heavy-payload applications in a military environment.

Some differences arise between the requirements of a civil cargo aircraft, which focuses more on the speed and efficient delivery of containers to well-equipped terminals, and a military cargo aircraft that relies more on its ability to carry items of large volume and irregular size and/or high density, have a quick response to emergencies, and unload at poorly-equipped airfields.

For military application, the blended wing body configuration is particularly attractive for cargo, tanker and arsenal aircraft missions and is proposed by Funk, Harber and Morin (2006) to help alleviate governmental spending and potentially replace the C-5 fleet and add to the C-17. Due to its wide airframe, the possibility of refuelling multiple aircraft at the same time occurs. However due to the large span of the airframe, folding tip mechanisms may need to be considered. For high payload applications, the blended wing body is particularly attractive in terms of wing bending relief. A BWB aircraft with distributed propulsion systems is considered to be one of the most promising disruptive technologies under research. The innovative aircraft design offers high aerodynamic and propulsive efficiency savings and better payload capacity than a conventional technology aircraft with similar take-off weight (Liebeck, 2004).

This paper assesses the application of the N3-X configuration to military missions and its potential for improving fuel consumption while reducing emissions. This is achieved through a synergistic mix of technological improvements to the airframe and propulsion system, and though the use of different fuels for the propulsion system, namely kerosene, hydrogen and liquified natural gas (LNG).

## 2.0 STATE OF THE ART

The Antonov An-225 (enlargement of the Antonov An-124) is the largest aircraft used to transport heavy payload. It can carry a maximum of 250,000 kg over a range of 2444 NM and has a ferry range of 8363 NM (Airliners). It was originally built to carry the Buran spaceplane and was later used to carry military supplies including a record load of four main battle tanks. Only one An-225 was completed, but it remains in operation.

The US Air Force cargo aircraft fleet is mainly comprised of the C-130 Hercules (which also make up 25% of all cargo planes globally). These aircraft can carry a maximum payload of 16330 kg over a range of 2049 NM and have a ferry range of 5200 NM (GlobalSecurity, 2011). Although its payload is only 13% that of the An-225, the aircraft is valued for its optimal combination of low acquisition cost and useful cargo space for medium to large payload applications. The continuing popularity of the C-130 demonstrates the ongoing demand for military airlifters. This is further reinforced by the introduction of the A400M by Airbus. This multi-role heavy-lift aircraft, although of similar wingspan to the C-130, has a maximum payload of 37000 kg and is able to achieve a maximum range of 4800 NM (Airbus).

As a larger-payload aircraft, the C-17 Globemaster is highly valued for strategic airlift requirements but is also versatile in terms of its capability of performing short field landings at full cargo load and acting in tactical airlift and airdrop missions. It can carry a maximum payload of approximately 77500 kg. With a payload of 60000 kg, the C-17 has a range of 5200 NM (FAS, 2000). Like the C-130 it can carry troops and

equipment close to the front lines due to its ability to use short runways. The C-5M Galaxy on the other hand is used to transport heavy payload to military bases. It achieves a range of 5500 NM with a payload of 129000 kg (FAS, 2000).

In terms of air-to-air refuelling capabilities, the Airbus A330 MRTT and the Boeing KC-46 are the current market leaders. With a maximum fuel capacity of 111000 kg and additional space for a payload of 45000 kg, the A330 MRTT is used for special missions such as military transport, refuelling and Airborne Warning and Control System (AWACS). (GlobalSecurity, 2015). However, because this aircraft is derived from the A330, it may prove to be less economical in terms of fuel consumption compared to the newer Airbus fleets. Comparatively, the KC-46A has a fuel capacity of 96300 kg and a maximum payload of 30000 kg. (U.S. Air Force, 2019) However, namely in Poland and South Korea, it failed to secure contracts due to a preference towards the A330 MRTT. Additionally, its delivery to the US Air Force was heavily delayed due to technical difficulties which sparked some criticism within the Pentagon and the US Congress. (Aerotime News Hub, 2019)

In terms of high payload and range with a low fuel consumption and low noise, the BWB aircraft is proposed in this paper as a competitive candidate for strategic airlifting missions and air-to-air refuelling.

### **3.0 CARGO CAPACITIES**

According to Whitford (1999), one of the main requirements for the design of a cost-effective airlifter is to ensure that the cross-sectional area of the cargo deck allows for the regular carriage of irregular equipment and vehicles, including high-priority, low-to-medium density freight. For example, the cargo hold for the C-50 airlifter has a width of 4 m (height of 3.7 m and length of 17 m) which allows the transport of light vehicles side-by-side.

Mari (2015), found that the N3-X sized BWB aircraft has a total storage volume of approximately 590 m<sup>3</sup> which is greater than the Airbus A400M, which has a cargo volume of 270 m<sup>3</sup>. Though less volume than the C-5 (656 m<sup>3</sup>) or the AN-225 (1100 m<sup>3</sup>), the greater width of the BWB aircraft's cargo hold may allow better use of the space available. Additionally, for shorter flight ranges, the cargo capacity could be increased by reducing the storage space allocated for fuel by installing removable tanks. Figure 3.1 illustrates potential storage spaces in the N3-X. The deck for passengers could accommodate 300 people, while the storage space allocated for the main cargo (width of 5.9 m, length of 14.3 m and height of 2 m) allows the carriage, for example, of up to 9 lightweight Range Rover vehicles. The two side cargo decks each provide additional 31 m<sup>3</sup> of storage space.

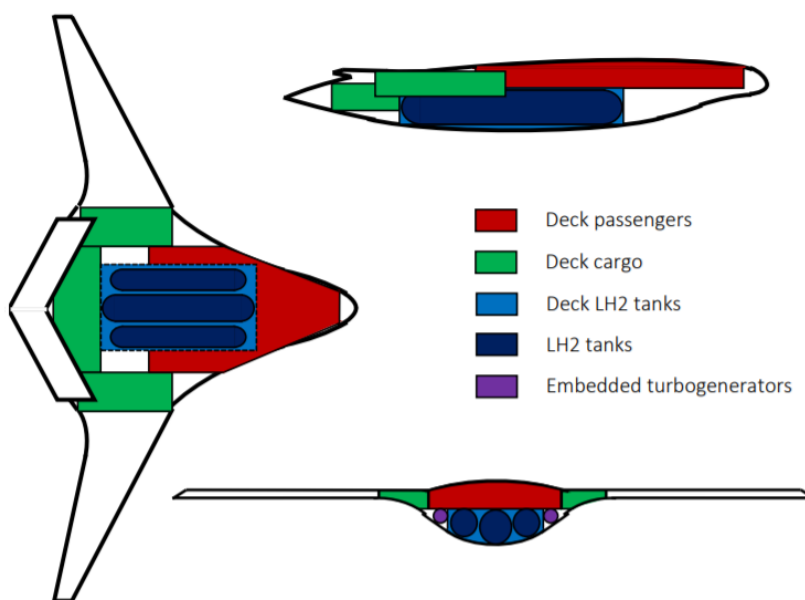


Figure 3-1: Cargo Spaces for the N3-X (Mari, 2015)

### 3.0 ALTERNATIVE FUELS

The main alternative fuels considered are LNG and LH2 which according to Brewer (1976) are the most “reasonable” alternatives for future aircraft applications. Due to its availability, natural gas is gaining in popularity throughout the world as an alternative fossil fuel and potential biofuel. With approximately 93% of LNG being methane, the lower carbon to hydrogen ratio gives a reduction in carbon emissions. However, using hydrogen would totally eliminate carbon emission in aviation if the production of liquid hydrogen could be carbon-free.

With a specific energy approximately 2.8 times higher than kerosene, a hydrogen fuelled aircraft can have a lower take-off weight for a given payload. Although the operating empty weight of the aircraft will increase due to the additional structural weight of the cryogenic tanks, a reduction in mission-level energy consumption can be predicted (Goldberg, 2018). This benefit is further enhanced if the range of the aircraft is increased. The major drawback of using liquefied hydrogen is its low density which even in its liquid state (-253 °C) requires four times as much volume as kerosene. An increase in the volume of the airframe has a negative impact on aerodynamic efficiency, though BWB airframes reduce this downside.

LNG offers a compromise between increased specific energy and increased fuel volume relative to kerosene and LH2. The density of methane is closer to that of kerosene, so a lower volume is required to store the same mass of fuel compared to hydrogen, but the lower heating value (LHV) of methane is also closer to kerosene. When compared to hydrogen, although the volume required is reduced, a greater mass of fuel needs to be stored due to its lower energy content (2.4 times lower than hydrogen). Density is the dominating factor and there is a net reduction in volume compared to liquid hydrogen, and a potential improvement in lift to drag ratio depending on the modifications made to the aircraft.

With the successful flight of the LNG-fuelled Tupolev aircraft in 1989, it was demonstrated that it would be feasible within a short timeframe to introduce LNG into aviation. With the added advantage of higher combustion performance (higher stability limits) than kerosene, LNG is a strong candidate for the initial transition from kerosene. Research is currently still ongoing regarding the implementation of hydrogen in

aviation. It is expected to take longer than LNG to be introduced to the market (European Commission, 2018).

## 4.0 METHODOLOGY

The approach used is an extension of previous research work conducted on the NASA N3-X aircraft (Felder et al., 2011). One of the main aims was to assess the potential of this novel configuration to achieve NASA’s N+3 goal of a 60% improvement in terms of energy saving by 2035 compared to the 2005 best in class baseline aircraft (Boeing 777-200LR). Through TERA (Techno-economic and Environmental Risk Assessment), a holistic evaluation was obtained which integrates the performance of the airframe and the propulsion system, economics, environmental impact, noise, emissions and cost in a modular framework (Ogaji et al., 2007). The assessment was performed on the kerosene and LH2 variants of the aircraft and the results were summarised by Goldberg (2018). The performance assessment was also extended to the LNG variant due to the favourable properties of this fuel which offers benefits compared to kerosene (higher LHV) and hydrogen (higher density).

### 4.1 N3-X Propulsion System Modelling

The concept consists of a blended wing body airframe powered by an array of Boundary Layer Ingesting (BLI) fans as shown in Figure 4.1. The propulsion system is made up of two embedded turbogenerators which create enough power to drive 15 BLI propulsors and additionally just enough thrust at design point to overcome their inlet momentum drag. Power is then assumed to be distributed to the propulsion array using superconductors and cryo-cooled transmission systems, which are required to reduce losses and improve efficiency without incurring a significant weight gain. An efficiency of 99.8% was used to account for transmission losses. The turbogenerators were modelled using TURBOMATCH (Macmillan, 1974), Cranfield’s in-house engine performance software. A twin-spool configuration was assumed and the design-point parameters were set according to previous research work by Felder et al. (2011).

The fans are designed at the top of climb to produce 119 kN of net propulsive force which is divided equally among the propulsors (Felder et al., 2011). Their performance was predicted using the inlet flow characteristics by averaging the properties of the boundary layer and free stream at the inlet of each propulsor. Hence, using conventional thrust and drag bookkeeping methods, the performance of the array was estimated. Similarly, for the off-design operation, the mass flow at the inlet was varied according to the thrust requirements. Therefore, variable nozzle area was assumed for the propulsor array.

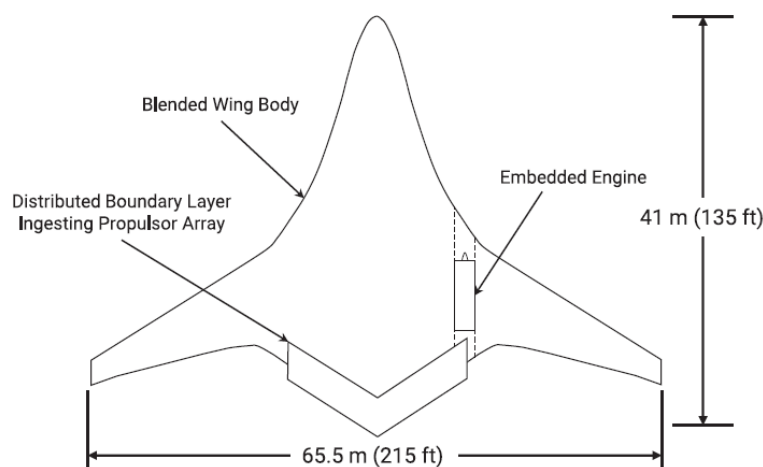


Figure 4-1: N3-X Configuration (Goldberg, 2018)

## 4.2 Flight Performance Model

The flight performance results were generated using a point-mass approach and an in-house code specifically designed to account for the novel architecture and propulsion system of the N3-X. The mission performance results were calculated by obtaining the block fuel burn of several flight segments, namely: taxi, take-off, climb, cruise, descent and landing. The cruising altitude was taken to be 40000 ft at a Mach number of 0.84. The N3-X is estimated to have a higher speed at cruise (Mach 0.84) compared to the C-17 which flies at a Mach number of 0.77. Apart from fuel required for the mission, additional reserve fuel was stored which includes fuel required for a 200 NM diversion to an alternative airport and an additional 5% of total fuel weight. The dimensions of the airframe model were obtained from public domain (Moore, 2014) and the weight from previous research work (Goldberg, 2018).

With the Boeing 777-200LR as the baseline aircraft, the performance of the N3-X variants were assessed in terms of their ability to meet NASA’s subsonic fixed wing goals (Felder et al., 2011). Due to a higher lift to drag ratio and through the use of boundary layer ingestion within the propulsion system, the blended wing body is predicted to achieve a better performance in terms of fuel consumption compared to the baseline aircraft.

## 5.0 RESULTS

A payload range chart was used to assess the differently-fuelled variants of the N3-X and to compare them against the Boeing 777-200LR with a passenger capacity of over 300 and a design range of 7500 NM with maximum payload. (In 2006 Boeing considered a derivative KC-777 Strategic Tanker in response to the USAF KC-X request for proposals (Tirpak, 2009).) The key weight characteristics of the baseline aircraft and the proposed N3-X variants are summarised in Table 5.1.

Table 5-1: Key Weight Parameters of the Various Configurations

	N3-X Variants			Baseline
	Kerosene	LH <sub>2</sub>	LNG	777-200LR
Maximum Take-off Weight (kg)	267400	267400	267400	347450
Operating Empty Weight (kg)	121290	126770	122600	155530
Maximum Payload (kg)	53570	53570	53570	53570
Maximum Fuel (kg)	120284	12910	94100	162750

The maximum take-off weight of the aircraft is made up of the operating empty weight, payload and fuel. The operating empty weight of the N3-X (kerosene version) was obtained from previous research (Felder et al., 2011) as well as the maximum take-off weight (Goldberg, 2018). Due to structural capability of the airframe, the maximum take-off weight is constant across all variants. This leads to the LH<sub>2</sub> variant being underutilised as the sum of its OEW, maximum payload and maximum fuel being less than its MTOW. This

is seen in figure 5.1 where for the LH<sub>2</sub> variant, the point at the maximum payload range and at the maximum fuel range coincide.

The sizing of the tank was performed for the LH<sub>2</sub> and LNG variants to take into consideration the additional thickness required to insulate the tanks to prevent excessive boil-off of the fuel and maintain the structural integrity of the tank at the varying tank pressures throughout the flight (Goldberg 2018). Integrally insulated tanks were assumed to prevent the deposition of ice on cold surfaces. This increase in tank weight increased operating empty weight for both the LH<sub>2</sub> and LNG variants as can be seen in Table 5.1.

Because the volume allocated for fuel storage was assumed to be the same as for the kerosene version, the maximum fuel mass varied for the alternative fuels based on their density and insulation thicknesses. However, higher heating values partially compensated for the lower densities.

With the design payload fixed to 53570 kg, the payload range chart obtained is shown in Figure 5.1.

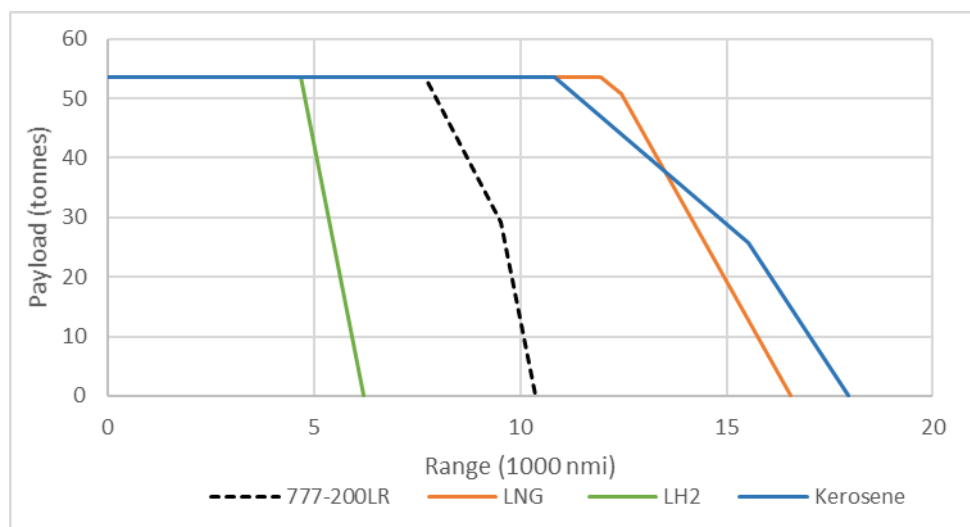


Figure 5-1: Payload-Range chart at a fixed maximum design payload of 53570 kg.

The LNG variant of the N3-X was initially designed to produce the same net propulsive force at the aerodynamic design point as the kerosene-fuelled N3-X model. This was a reasonable assumption given that it was assumed that only the fuel changes and that the two aircraft have similar weight and drag at top of climb on a maximum take-off weight limited mission. Given that the fuel capacity in the LNG version is restricted, it can only carry 85.5% of the energy of the kerosene version. However, due to its lower density, the maximum mass of LNG carried is only 78% of the maximum mass of kerosene. As a consequence, its range at maximum payload exceeds that of the kerosene fuelled N3-X by about 10%, but its maximum ferry range is about 10% less.

The impact on range due to fuel storage capacity is even more severe when considering LH<sub>2</sub>. In this case, the maximum payload range was reduced by approximately 56% compared with the kerosene version. The fact that there is no difference between the maximum payload range and maximum fuel range means that the aircraft is highly underutilised and that more high density payload can be stored.

Figure 5.2 shows the extent to which the maximum payload may be increased.

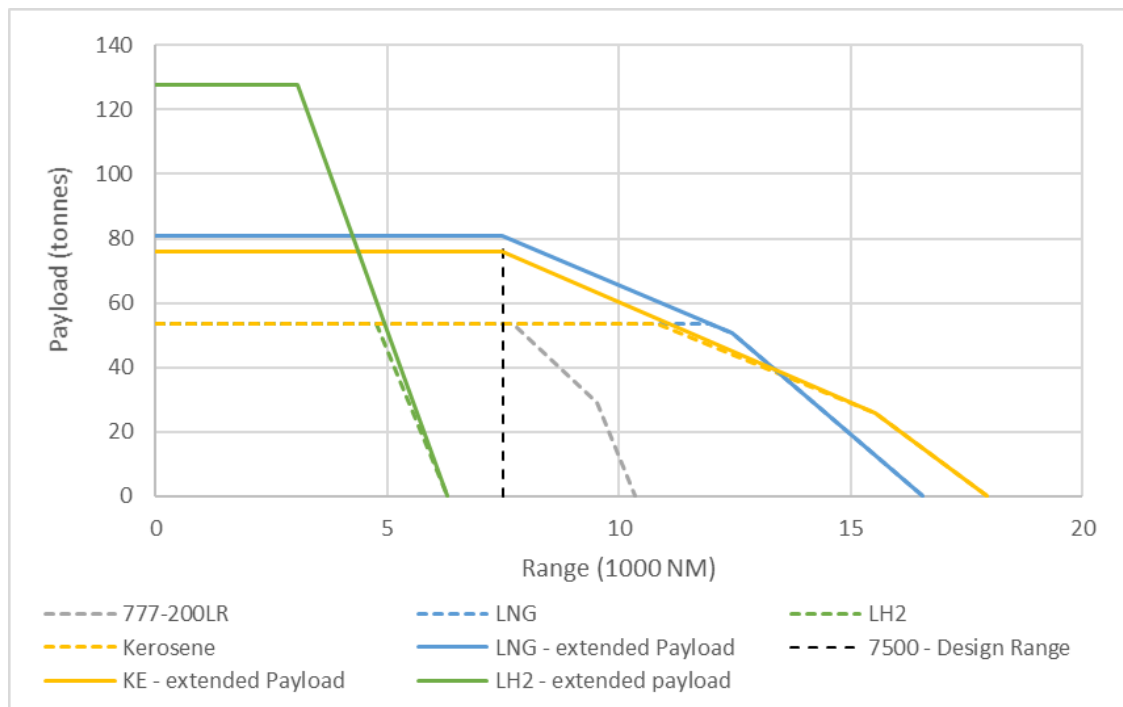


Figure 5-2: Payload-Range Chart for Extended Payload Capacities.

The payloads for LNG and kerosene configurations were increased until maximum payload range coincided with the design range of the baseline aircraft (777-200LR). With LNG, the maximum payload achieved was 80887 kg which is about a 50% improvement over the baseline. For the kerosene version, the improvement was approximately 42%.

Considering the hydrogen variant, the sum of the maximum payload, maximum fuel, and operating empty weight is lower than the maximum take-off weight. If we extend the payload until the maximum take-off weight is reached, the maximum payload would be about 127000 kg which is approximately 137% more payload than the baseline aircraft. However, the maximum payload range would decrease to about 3000 NM, which is approximately the distance between London and Toronto and is classified as a short/medium haul flight. The benefit gained from the low density of hydrogen is slightly reduced due to the higher operating empty weight of the aircraft.

The results were also compared against that of the Airbus A 400M which was built as a tactical airlifter. From Figure 5.3, the superiority of the N3-X in terms of payload and range is demonstrated. Although the attractiveness of the A400M stems from its flexibility of operations, its payload and range do not match variants of the N3-X. For instance, the hydrogen variant could allow for short field take-off at a much superior payload and for longer range.



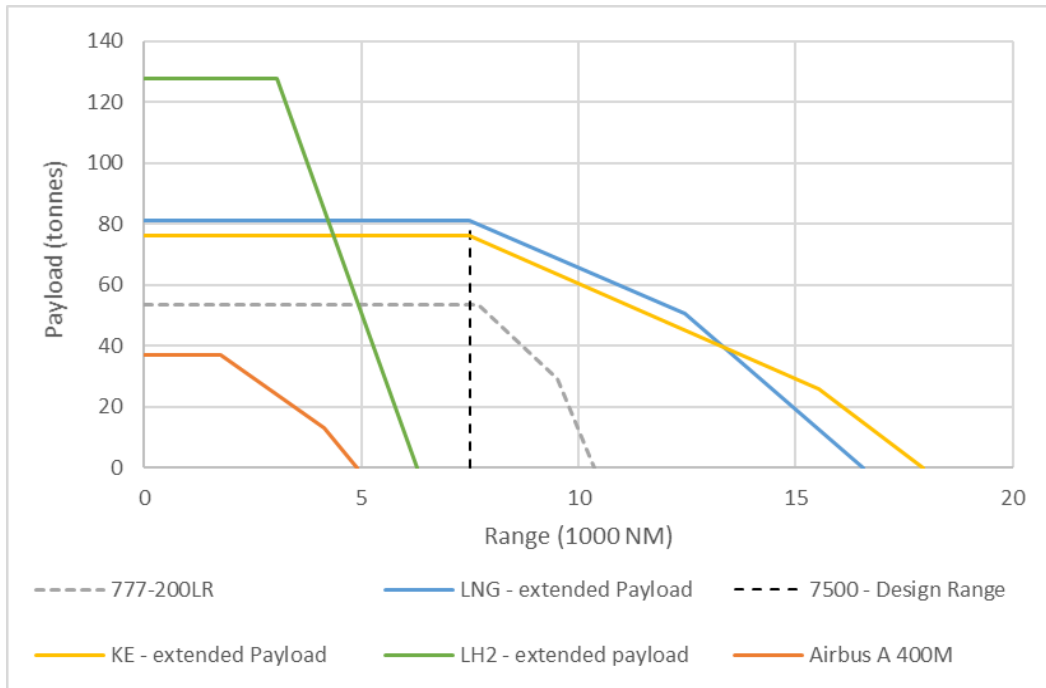


Figure 5-3: Payload-Range performance Compared to Airbus A400M

Due to the different fuels, a separate metric is required to compare the efficiency with which a specific mission is performed. In this scenario, the Energy to Revenue Work Ratio (ETRW) is adopted. It is a measure used in the assessment of an aircraft that provides an indication of how efficiently energy is used to generate revenue. This metric is particularly useful when comparing different technologies. Also, it links the energy efficiency with the ability of the aircraft to generate revenue. Hence using the same metric, different missions can be assessed. A low value indicates high energy efficiency.

$$ETRW = \frac{m_f \cdot LHV}{M_{pl} \cdot g \cdot R}$$

Where  $m_f$  is the mission fuel burn (kg), LHV is the lower heating value of the fuel (MJ/kg),  $M_{pl}$  is the flight payload (kg),  $g$  is the acceleration due to gravity ( $m/s^2$ ) and  $R$  is the flight range (NM).

Using the energy to revenue work ratio, the performance of the variants can be assessed on a common ground regardless of the type of fuel used or range achieved. Figure 5.4 gives a general view of how the “energy efficiency” or ETRW varies with range. The lower the ETRW, the lower is the energy consumption and the higher is the energy efficiency. The baseline aircraft has a much higher ETRW as compared with the N3-X configurations. This is due to the lower lift to drag ratio of the tube and wing configuration, compared with the blended wing body.

Considering the various N3-X variants, when range is increased from 2000 NM, the ETRW decreases because of the relatively lower impact of the weight of the fuel used for take-off and climb as range is increased. As range increases, the advantage of using a lighter fuel becomes more apparent. Hydrogen has the lowest increase in ETRW as range increases.

Compared with the kerosene variant, the ETRW of LNG at a given range and payload is approximately 1% lower, while for hydrogen variant; the index is 8% lower. This is mainly due to the greater similarity of LNG to kerosene in terms of LHV as compared with hydrogen.

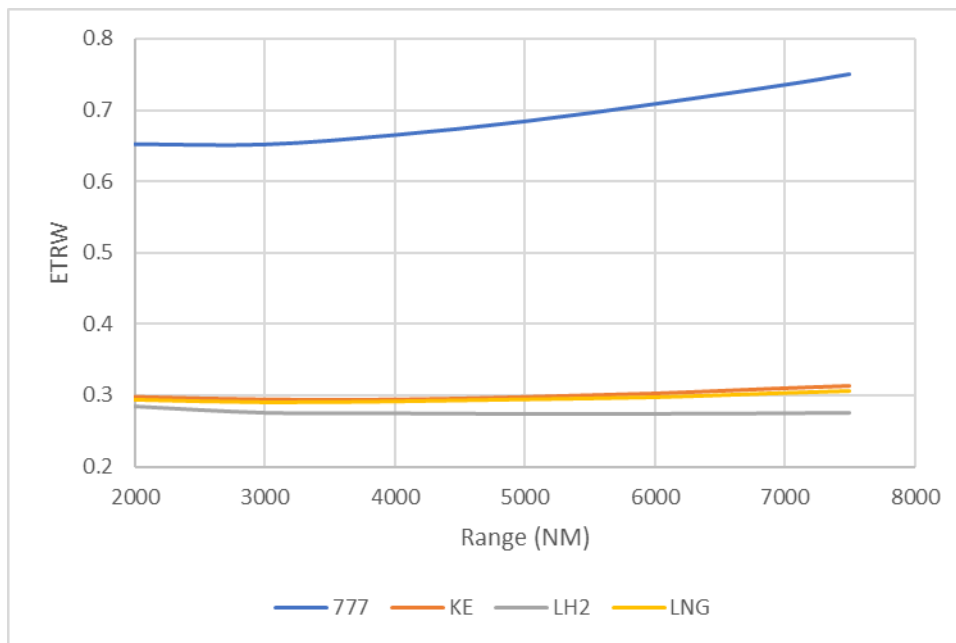


Figure 5-4: Variation of the ETRW index against range for the N3-X variants (Payload: 53570 kg)

The energy saving potential of the N3-X variants was assessed against the baseline aircraft and shown to give significant benefits. According to NASA’s N+3 goals, a target of more than 60% reduction in aircraft energy consumption is targeted by 2035 relative to the 2005 ‘best in class’. In the assessment performed, it was found that the kerosene variant of the N3-X could achieve this reduction above a range of 7000 NM, the LNG variant above a range of 6000 NM and the LH2 variant reaches this target above a range of 5000 NM. With a decrease in payload, this benefit is further improved. The results are summarised in the table 5.1.

Table 5-1: Increase in Energy Saving Potential (%) of the N3-X Variants compared to the Baseline 777-200LR

Payload	53570 kg			44770 kg		
	Kerosene	LNG	LH2	Kerosene	LNG	LH2
Range						
2000	56.7	57.4	58.2	56.8	58.2	59.4
3000	57.1	57.9	59.1	57.3	58.5	60.1
4000	57.8	58.7	60.5	57.9	59.1	61.0
5000	58.7	59.4	61.4	58.9	59.9	62.1
6000	59.4	60.3	62.7	59.4	60.6	63.2
7000	60.1	61.3	64.0	60.3	61.6	64.5
7500	60.5	61.8	64.7	60.7	62.0	65.0

## **6.0 CONCLUSION**

The blended wing body with turboelectric distributed propulsion offers advantages over current military aircraft in terms of its energy efficiency, low noise and low emissions. Additionally, when combined with fuels such as LH2 and LNG, a further decrease in fuel consumption can be obtained, and due to the reduced carbon to hydrogen ratio, CO2 emissions can be further reduced or eliminated. Although the assessed hydrogen-fuelled variant of the N3-X has a shorter range than the others, it could be a competitive alternative to the A330 MRTT or Boeing KC-46A as it can potentially carry 180–340% more payload over 3000 NM. There is also the potential to increase the range of the hydrogen-fuelled N3-X derivative by stretching its airframe to increase its internal volume to accommodate larger hydrogen tanks. Alternatively, the LNG fuelled variant would provide a low emissions alternative to current military aircraft and additional payload and range improvements (70–170% more payload over 7500 NM). This could allow for enhanced aerial-refuelling capabilities, as the airplane could be kept on station for longer or used to refuel a larger number of aircraft. Although this proposal is still at the concept design stage, ongoing research could pave the way towards more energy-efficient and lower-emissions military aircraft offering operational improvements.

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## 8.0 NOMENCLATURE

LNG	Liquefied Natural Gas
LH2	Liquid Hydrogen
NM	Nautical Mile
OEW	Operating Empty Weight
MRTT	Multi-Role Tanker Transport
MTOW	Maximum Take-Off Weight
ETRW	Energy to Revenue Work Ratio

