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Evaluation of the Climate Impact Reduction Potential of the Water-Enhanced Turbofan (WET) Concept

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Abstract: Aviation faces increasing pressure not only to reduce fuel burn, and; therefore, CO_2 emissions, but also to provide technical solutions for an overall climate impact minimization. To combine both, a concept for the enhancement of an aircraft engine by steam injection with inflight water recovery is being developed. The so-called Water-Enhanced Turbofan (WET) concept promises a significant reduction of CO_2 emissions, NO_x emissions, and contrail formation. Representative missions for an A320-type aircraft using the proposed new engine were calculated. Applying a first-order one-dimensional climate assessment prospects the reduction of more than half of the Global Warming Potential over one hundred years, compared to an evolutionarily improved aero-engine. If CO_2-neutrally produced sustainable aviation fuels are used, climate impact could be reduced by 93% compared to today's aircraft. The evaluation is a first estimate of effects based on preliminary design studies and should provide a starting point for discussion in the scientific community, implying the need for research, especially on the formation mechanisms and radiation properties of potential contrails from the comparatively cold exhaust gases of the WET engine.

Keywords: climate impact; steam injection; heat recovery steam generator; water condensation; water recovery; aircraft engine; contrails; cirrus; climate-neutral flight

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1. Motivation: Climate Change Targets of Politics and Industry

The aviation industry has set itself challenging targets with regard to its contribution to carbon dioxide (CO_2) emissions. The Air Transport Action Group states that "by 2050, net aviation carbon emissions will be half of what they were in 2005" [1]. This includes offsetting parts of the CO_2 emissions. Referring to the qualitative illustration published in this context by the International Air Transport Association (IATA) [2] (p. 10), offsetting should play a significant role in a transition period between 2020 and say 2035, enabled by the International Civil Aviation Organization (ICAO) offsetting scheme CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation). Realization of the potential of "known technology, operations and infrastructure measures" would also cut a significant part of the CO_2 emissions, compared to a no-action path. Most of the reduction; however, results from supposedly CO_2-neutrally produced Sustainable Aviation Fuels (SAFs) as well as "new-generation" technologies.

The European Union (EU) sets even more aggressive goals, since its Green Deal asks for a 90% reduction of greenhouse gas emissions compared to 1990's levels until 2050 for the European transport sector [3]. This scale of claim for emission reduction is unprecedented. From a technical standpoint, it is even more impressive, since many parameters in aircraft and engine design are approaching the known physical limits. There is currently no established way to achieve a substantial part of these goals through evolutionary technical solutions. This is why revolutionary aircraft and engine concepts are investigated throughout the industry, notwithstanding that there are inherent enormous development risks. Furthermore, the Green Deal refers to "greenhouse gases" in general and not only to CO_2, which means that non-CO_2 effects will be taken into account as well.

Apart from CO_2, aviation contributes to global warming mainly by the emission of nitrogen oxides (NO_x) and the formation of contrails and contrail cirrus. These climate effects have not yet been taken into account in any global industrial or regulative initiatives, since there is no common understanding to which exact extent these effects are relevant, of which operational aspects they depend on, neither which metric should be used for evaluation. However, apart from the mentioned EU Green Deal, the currently developed Strategic Research and Innovation Agenda (SRIA) for the European Union's "Clean Aviation" framework uses the term "climate neutrality" as opposed to CO_2 neutrality: "The ultimate objective is to reach net-zero greenhouse gas emissions, and to enable a climate-neutral aviation system in Europe by 2050" [4] (p. 14). This is comparable to the above-mentioned EU Green Deal objective. However, no scientifically and politically reliable metric has been defined yet, by which such climate impact has to be measured. In the research community, several metrics have been used for many years, (e.g., Global Warming Potentials, Global Temperature Potentials, Average Temperature Response). The reference time horizons (e.g., 20, 50, 100 and 500 years) have been defined by the respective scientists [5–8].

Probably due to scientific uncertainty, aviation's climate impact has not yet been included in the certification process of aircraft and engines. For comparison, NO_x have been regulated for a long time via the ICAO Landing and Take-Off (LTO) cycle certification rules, with a clear objective to reduce effects on local air quality. Due to the lack of certified emission levels at altitude, current climate emission calculation methods use these values certified for low altitudes to derive cruise emissions (e.g., using the Boeing 2 method) [9].

Even if no evaluation standard is existing yet with regard to climate impact, an increasing number of stakeholders acknowledge that the effect of NO_x and contrails on climate change is of the same order of magnitude as that of CO_2 itself. As an example, compensation portals apply a multiplier between two and three on the CO_2 value to factor in the additional effects for the compensation amount [10]. As stated in "Clean Aviation", reducing aviation's climate impact requires considering all effects. A minimization of the CO_2 balance is not sufficient.

2. Revolutionary Engine Concept and Emission Reduction Potential

The Water-Enhanced Turbofan (WET) engine concept, discussed in this paper, tackles all of the above-mentioned effects. MTU Aero Engines has presented the novel cycle at an early stage of development, in a three-part publication series [11–13], in order to give an insight on MTU's initiatives towards climate-neutral flying. This paper aims at launching the discussion in atmospheric sciences on the influence of the concept on climate impact, more particularly on the formation of contrails.

The WET concept is introduced in more technical detail in [11] (at that time called Steam Injecting and Recovering Aero Engine, SIRA). Figure 1 shows a half-side schematic of the presented concept. Exhaust-heat generated steam is injected into the combustion chamber. The humidified mass flow contains significantly more extractable energy than air. The pumping of the utilized liquid water up to the necessary pressure requires two magnitudes less power than the compression of air, which reduces the engine's internal power demand. Both lead to a noticeable increase in specific power compared to a conventional gas turbine. The recovery of typically unused exhaust heat back into the system yields a significant increase in thermodynamic efficiency. Through a condenser, downstream of the steam generator, the water is brought back to its liquid phase and then recovered from the exhaust gas–steam mixture. The condenser is air-cooled (e.g., from the propulsion system's bypass or from a separate blower).

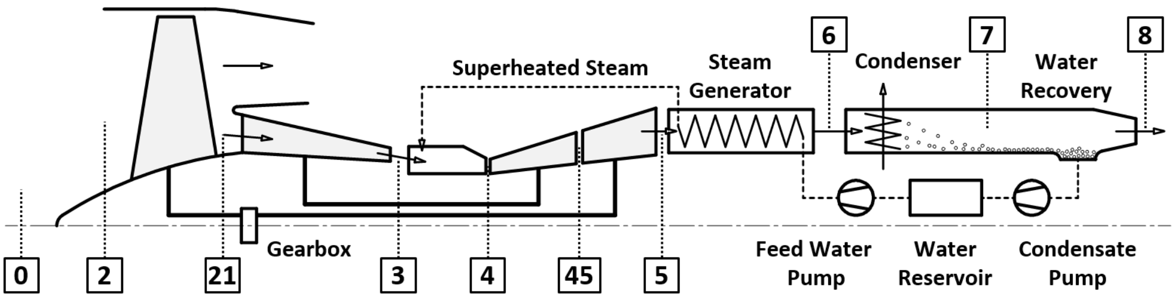


Figure 1. Scheme of a half-side arrangement of the proposed water-enhanced turbofan concept with station nomenclature (taken from [11]).

According to preliminary potential studies outlined in [11], the proposed water-enhanced gas turbine concept is expected to decrease Specific Fuel Consumption (SFC) in cruise conditions by about 15% to 20% compared to a conventional aero-engine of the same technology level. Considering the increase of system mass and drag due to the necessary components, such as the heat exchangers, the fuel burn saving and thus the CO_2 reduction potential is about 10% to 15% compared to an evolutionary gas turbine engine.

The injected steam causes a more homogenous temperature distribution during the combustion, which reduces NO_x formation. According to studies on stationary gas turbines [14] (their Figure 3), a combustion with 20% (by weight) of water vapor led to a reduction of NO_x formation by around 80% at temperatures that are typical for aircraft engine operations. The layout of the cited study (laboratory combustor) enabled proper premixing, which means that the dry baseline had already low NO_x emissions. Today's aircraft engines; however, use NO_x emission reduction technologies that are compatible with operational stability requirements. Their relative NO_x emission levels are; therefore, higher than that of the cited laboratory combustion experiment, which makes direct comparison to its results difficult. Logically, injecting water vapor in an aircraft engine would lead to even more significant relative NO_x reduction between the conventional and the water-enhanced combustion. On top of these fundamental considerations, new combustor designs may enable further homogenization of the combustion process. Consequently, a reduction in the order of 90% of NO_x emissions compared to today's aircraft engines is considered ambitious but feasible, and has; therefore, been chosen as reasonable order of magnitude for this study.

The recovery of water through cooling of the exhaust gas stream below its dew point also offers the potential to reduce or even avoid the formation of contrails. The climate impact of contrails does not only depend on the quantity of water in the exhaust, but also on its physical conditions (temperature, presence of condensation nuclei, droplet size etc.), and over and above the atmospheric conditions such as humidity and temperature or natural cloud coverage. Most previous contrail research has focused on kerosene-fueled turbofan engines with high exhaust temperatures. The WET's exhausts differ so significantly from existing engines that no precise evaluation of contrails, nor their radiative properties, can be presented today. A set of considerations motivate a substantial contrail impact reduction: The concept will have the lowest possible exhaust temperature whilst avoiding icing conditions, presumably around 10 to 30 °C. If more water is condensed out of the exhaust flow than what is needed for the wet combustion, the relative humidity significantly decreases. Additionally, the SFC reduction for the same thrust level translates into lower relative humidity in the exhaust flow. The Schmidt-Appleman criterion; therefore, suggests less contrail formation. Alternatively, presuming the availability of actual meteorological information, the condensed water can be kept in a water tank and only released when the surrounding atmospheric conditions are not prone to contrail formation anymore.

Disposing of more detailed research results on the resulting contrails is a prerequisite for the subsequent design of a WET engine. The ultimate goal of the WET concept would be to avoid contrail impact entirely. However, specific operational cases might prevent from taking the full advantage of the WET's potential. This could be the case if the chosen exhaust properties do not suffice to avoid contrail formation in specific atmospheric conditions, or the installed water reservoir is too small to fly through a very wide contrail-sensitive region, before the collected water is dumped at once.

The reduction of the impact of contrails and contrail cirrus of the WET concept has not yet been substantiated by atmospheric modelling nor testing. The current technology readiness level of the concept gives fundamental tradeoffs concerning weight, drag, and installation effects that were evaluated based on a preliminary engine layout (not shown). There is room to design to specific quantities of condensed water-theoretically from the percentage to be fed back in the combustion to 100%, and also its temperature at exhaust can be influenced. Both parameters have an impact on the required size and performance of the supplemental engine modules (e.g., heat exchangers). If a water reservoir is necessary to avoid water emissions in contrail-sensitive regions, its size is also limited by the aircraft's weight and geometry. Previously, aircraft and engines were evaluated with regard to their impact on climate once the design was terminated. The WET engine offers the opportunity to take into account specific requirements beforehand in order to minimize contrail and contrail cirrus-induced climate impact. These requirements are to be defined by atmospheric sciences. The flexibility to design to specific exhaust properties is inherent to the WET concept and offers room for optimization that is unique in the current landscape of future propulsion concepts for aviation.

By reason of both the introducing general effects of lower relative humidity and the inherent freedom to design to specific exhaust gas conditions, a 90% contrail impact reduction is assumed realistic in this evaluation.

In order to evaluate the benefits of this revolutionary concept, conventional aero engine technology from 2015 and its evolutionary further development until 2030–35 shall be compared to each other and to the WET concept. Table 1 summarizes the assumptions taken for the climate evaluation of all engines. The delta in fuel burn and emission performance between the evolutionary engine and the WET engine relates to the improved thermodynamic cycle, that is enabled by the supplementary installation of the WET components (especially phase-changing heat exchangers). The propulsive efficiency is equal, since on the same technology level. The chosen time frames relate to already defined roadmaps and do not translate into an operational availability of the WET engine in the same time frame. Its development might take longer. However, the physical effects of the concept have to be evaluated against a common technology level.

Table 1. Assumptions for climate impact reduction in percentage versus the 2015 Reference engine.

Engine	Specific Fuel Consumption SFC	Emission Indices for NOx EINOx	Contrails and Cirrus Climate Impact
2015 Reference engine	Reference	Reference	Reference
2035 Evolutionary engine	−5% to −10%	Same as Reference	Same as Reference
WET engine	−19% to −28% [1]	−90%	−90%

[1] −20% versus the 2035 Evolutionary engine.

Current estimations for an evolutionary engine are in the range of 5% to 10% improvement in Specific Fuel Consumption (SFC) compared to the 2015 reference. The WET engine would yield another 15% to 20% improvement in comparison to the evolutionary engine. Multiplying both results in a SFC reduction between 19% and 28% for the WET engine compared to the 2015 reference engine.

Since all climate impacts sum up linearly, it is straight forward to evaluate the effect of an updated assumption on the total result of the study. The major non-linear effects of aircraft design (Breguet range equation) were covered in the aircraft study by giving a bandwidth of SFC reduction.

In the following, the range of SFC improvement is represented in most results, which is not to be confounded with uncertainty ranges of climate impact evaluation. This is not subject of this study and we explicitly do not pretend to give an estimation of the scientific uncertainties of climate impact evaluation. If only one SFC value is represented in the results, the upper-end of the range is meant (highest considered reduction potential).

3. Climate Impact Assessment

As mentioned before, the lack of standardized metrics to evaluate the climate impact of aircraft or engine technologies prevents a commonly recognized comparison of concepts. However, there have been several attempts of integrating environmental impacts in the design process, for example in several theses [15–20]. It appears that such methodology has not yet been industrially applied.

3.1. Choice of Climate Metric

Climate impact from aviation has been evaluated in terms of Radiative Forcing (RF) of the entire aviation until a certain reference year for quite some time [21–25]. Such RF values cannot be directly used for the evaluation of new engine or aircraft technologies for several reasons:

1. The quantity of emissions of an aircraft depends on the respective operational scenario (single aircraft or fleet, stage lengths, payload etc.). This is not comparable to a global emission scenario evaluation, that includes all types of flights and aircraft.
2. The climate impact of emissions changes significantly with flight altitude, but also with geodetic latitude and longitude as well as season and daytime. Future aircraft or engine technologies might have an influence on these parameters (foremost flight altitude) that cannot be taken into account by using globally aggregated results.

In principal, there are two ways of matching these two different system levels—global aviation vs. one aircraft or engine type. The first one works by embedding a new aircraft or engine technology in a fleet and calculating emission scenarios. These are fed into a 3D or 4D atmospheric model, and the scenarios with and without the new technology are compared against each other. The second way of matching derives a response surface from an atmospheric model, that gives climate feedbacks of all constituents by altitude, latitude and longitude of the emissions, as well as time (daytime, seasonal influence). The climate impact of a supplemental emission (e.g., of one aircraft mission) can then be evaluated based on this response surface.

The latter approach was pursed in the LEEA (Low Emissions Effect Aircraft) project [26,27]; however, simplified by averaging latitude, longitude and time. Equilibrium radiative forcings per kg emission or per km flown were calculated as a function of the altitude for both NO_x and contrail effects, in 16 atmospheric layers from 16,500 to 48,500 ft [26] (their Table 1). The resulting method for climate impact calculation is applicable for preliminary aircraft design and has; therefore, been used in this study. The potential effect of NO_x or contrails below 16,500 ft or above 48,500 ft is not taken into account. In agreement with the Kyoto Protocol, the Pulse Global Warming Potential (PGWP) over a time horizon of 100 years was chosen as the metric, since it is most widely known to the public. Using warming potentials allows to account for the lifetimes of greenhouse gases, compared to a pure analysis of radiative effects of species that are directly emitted or of which the concentration has been changed by exhaust gases.

With regard to the potential benefits of the WET concept, the PGWP turns out to be conservative, since short-lived effects (NO_x, contrails) are less valued. For comparison, the Sustained Global Warming Potential (SGWP) as defined in [6] would yield higher benefits, since short-lived effects are weighted higher. The same is true if applying shorter time horizons (e.g., 20 years). More recent studies (e.g., [18,28]) use more sophisticated metrics, such as the Average Temperature Response (ATR), with the objective to be more representative for real air traffic emissions scenarios and less dependent on the time horizon.

3.2. Calculation Methodology

All aircraft design, mission and emission calculations were performed with the aircraft design and performance program “PIANO” [29]. The objective of the study was to evaluate the fuel burn and climate effect of the WET engine in a realistic operational setting, that means installed in an aircraft on representative stage lengths. A single-aisle aircraft with high bypass ratio engine was selected as the baseline for comparison. The aircraft model was tuned to match the mission performance of an Airbus A320. This aircraft type is most widely operated on stage lengths between 300 and 1500 NM. The 800 NM stage length was chosen as the reference stage length for this study, with a 2000 NM stage length for comparison as “long-range mission”. Only 1% of all A320 flights are operated on routes that are longer than 2000 NM (based on an analysis of flightradar24 data). Emissions were calculated by interpolating between the reference emission results in PIANO’s “Mission sequence” function, based on the emission indices of the PW1127 published in ICAO’s Aircraft Emissions Databank [30]. The related fuel flow values were corrected to account for installation effects such as suggested in [9].

For the evolutionary aircraft, no effect on weight nor drag of the evolutionary engine was modelled. Since no substantiated information on future combustion technology for the evolutionary engine was available, NO_x emissions indices were kept the same as for the baseline. This would represent advances in NO_x reduction technologies despite a further increase of combustion temperature and pressure necessary for higher thermal efficiency (supposed to enable lower SFC).

The current development status of the WET engine concept suggests a significant increase of engine weight and penalty in aircraft drag due to the installation of the supplementary components (heat exchangers, pumps etc.). However, the turbomachinery becomes much smaller [11]. The resulting weight and drag penalty was modelled by an increase of the nacelle length by 50% and a decrease of the power plant thrust to weight ratio by 30% in the PIANO model. These values rely on preliminary engine layout (not shown).

A full iteration with constant thrust to weight ratio, constant wing loading, and constant thrust to weight ratio of the power plant systems (except for the correction of the WET engine’s weight) was executed. Consequently the ranges of the resulting aircraft are the same (i.e., their operational performance is comparable). Table 2 shows the characteristics of the three PIANO aircraft models, Table 3 issues the fuel flows and NO_x emission indices used for the emission calculation, and Table 4 gives details on the calculated 800 and 2000 NM missions.

Table 2. Main aircraft model characteristics, results with lower and upper values reflect the bandwidth of the SFC assumptions.

	Baseline	**Evolutionary Aircraft**	**WET Aircraft**
Technology level [year]	2015	2030-35	2030-35
Maximum Take-off Weight MTOW [t]	77.0	72.1 to 73.9	72.6 to 76.1
Operating Weight Empty OWE [t]	43.7	41.9 to 42.6	45.2 to 46.6
Wing surface [m^2]	112	105 to 108	105 to 111
Thrust/weight$_{A/C}$ [–]	0.318	0.318	0.318
Wing loading [kg/m^2]	688	688	688
Payload [t][1]	13.6 t	13.6 t	13.6 t
Range [NM]	3420	3420	3420
Fuel Burn @ 800 NM [kg]	4080	3590 to 3820	3040 to 3460
Delta Fuel Burn [%]	Ref.	−6 to −12	−15 to −26

[1] 150 Pax @ 200 lb.

PIANO issues one value of NO_x emissions for each mission segment, spanning over several flight levels. This value is then redistributed on the altitude layers defined in LEEA (LEEA levels defined in [26]). The PGWP is calculated based on the formulas defined in [6] (Appendix A), using the equilibrium radiative forcings published in [26] (Table 1) and [27] (Table 2), and the parameters published in [17] (Appendix A3). Contrail cirrus is included by a multiplier of five on the line-shaped contrail estimation. Since absolute values for the climate impact of a single flight are of no practical use and the LEEA metric was created to compare technologies, all results are shown as relative values to the baseline aircraft's total PGWP.

Table 3. Fuel flows and NO_x emission indices used for the emission calculation, for upper-end SFC reduction potentials, including installation effects.

LTO Cycle		Baseline	Evolutionary Aircraft	WET Aircraft
Fuel Flow [kg/s]	Take off	0.808	0.727	0.582
	Climb out	0.679	0.611	0.489
	Approach	0.237	0.213	0.171
	Idle	0.088	0.079	0.063
Emission indices NOx EINOx [g/kg]	Take off	18.8	18.8	1.88
	Climb out	15.3	15.3	1.53
	Approach	9.07	9.07	0.907
	Idle	4.84	4.84	0.484

Table 4. Mission calculation for 800 and 2000 NM, for upper-end SFC reduction potentials.

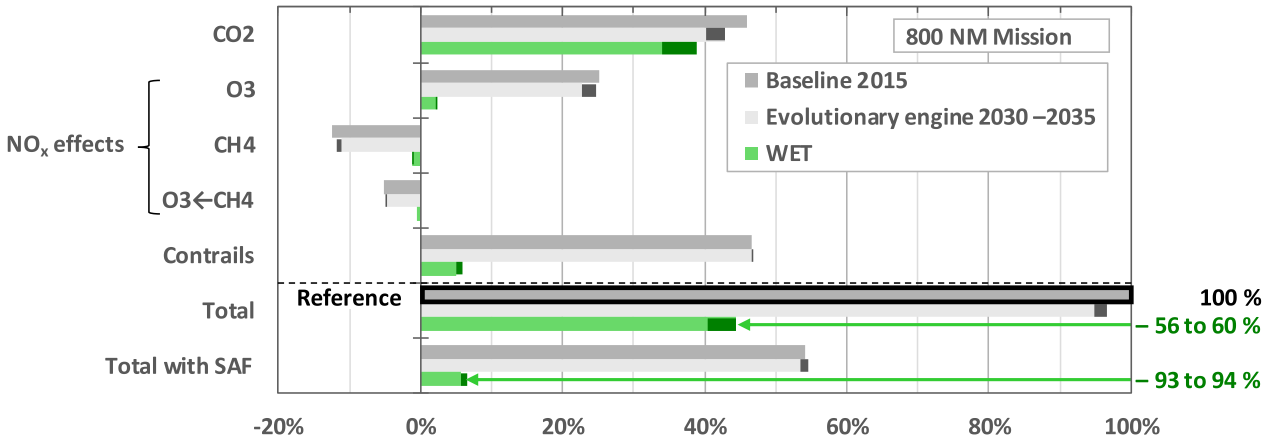
	Baseline	Evolutionary Aircraft	WET Aircraft
800 NM			
Fuel Burn [kg]	4080	3590	3040
Initial cruise altitude ICA [ft]	39,000	37,000	37,000
Cruise $EINO_x$ at ICA [g/kg]	9.8	9.1	1.0
Total mission NO_x [kg]	47.3	39.9	3.3
2000 NM			
Fuel Burn [kg]	9310	8170	6860
Initial cruise altitude ICA [ft]	37,000	37,000	37,000
Cruise $EINO_x$ at ICA [g/kg]	10.2	10.1	1.0
Total mission NO_x [kg]	101.4	86.8	7.4

3.3. Results of the Climate Impact Assessment

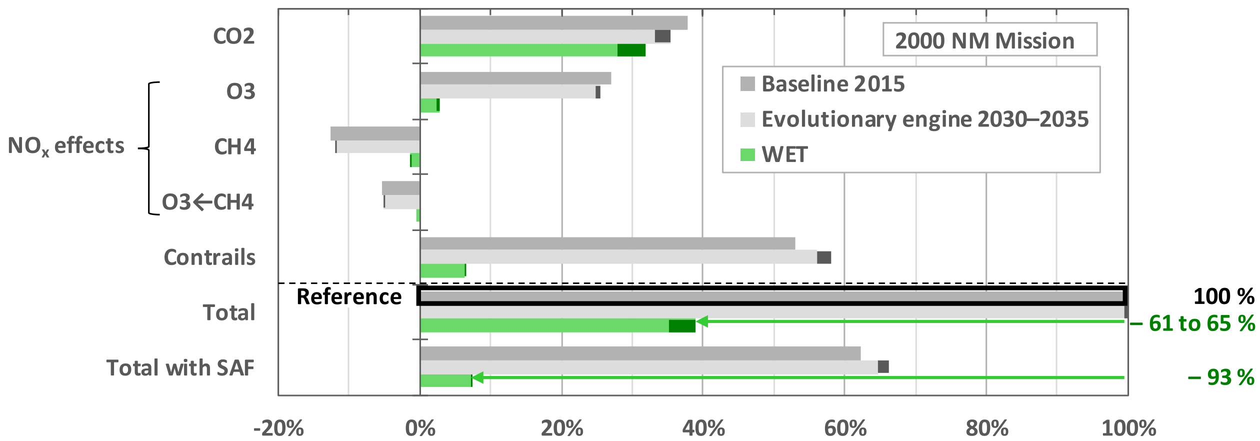
According to the results presented in Figure 2a, the WET engine has, in total, 56% to 60% less impact (PGWP ratio) on climate than the 2015 baseline. Using the SGWP yields 66% to 73% (not shown). Reducing the time horizon to 20 years results in a 76% to 77% climate impact reduction (not shown).

The biggest share of these benefits relates to the assumption, that the WET's contrail impact is reduced by 90% (see Table 1). The NO_x effects are less relevant, since a large portion is emitted at low altitudes during climb, where they have a cooling effect according to the LEEA results [27]. They would play a slightly bigger role on longer stage lengths, especially on long-range aircraft that spend more time at cruise altitude. For the estimation of the effect on a A320-type aircraft, a stage length of 2000 NM was also calculated (Figure 2b): In that case, both the NO_x and the contrail benefits of the WET engine lead to even more climate impact reduction (i.e., the WET's PGWP would be reduced by 61% to 65% instead of 56% to 60% on the 800 NM distance). Operating the WET with CO_2 neutrally-produced Sustainable Aviation Fuels (SAFs) would result in a reduction of about 93% of its climate impact compared to today's aircraft (2015 Baseline).

There is also an interesting finding from the 2000 NM stage length calculation: Even if the evolutionary engine consumed significantly less fuel than the baseline, its climate impact in total was not reduced compared to the baseline. This is due to two counter-balancing effects: On the one hand, its CO_2 impact has been reduced linearly with regard to fuel burn. On the other hand, the reduction of installed thrust in line with a smaller SFC makes the aircraft step up to Flight Level 390 later in the mission. However, according to LEEA results [26], Flight Level 370 is more sensible to contrails than Flight Level 390. PIANO optimizes a mission for fuel burn. In this case, optimizing for fuel burn does not minimize climate impact. The effect is even more pronounced for the WET aircraft, both due to a further reduced SFC and a significant increase in weight due to the WET installation. The missions are presented in Figure 3.



(**a**)



(**b**)

Figure 2. Absolute Global Warming Potentials over one hundred years relative to the total of the Baseline 2015 reference aircraft on missions of (**a**) 800 NM, (**b**) 2000 NM. "Contrails" includes contrail cirrus by applying a multiplicator of 5 on the line-shaped results. Ranges are given as range of the SFC reduction potential. No scientific uncertainties concerning the climate impacts are issued.

If PIANO optimized the minimum impact on climate (i.e., if it minimized the PGWP), it would probably result in a different step-climbing sequence, with a minimally increased fuel burn compared to the mission displayed here.

This is a clear indication for the need to integrate design optimization, mission optimization, and climate impact evaluation if one really wants to result in climate-friendly flight operations. Of course, the effect presented here is only an example for multiple interdependencies in aircraft design operations and climate impact. Using a different climate metric, a higher confidentiality response surface from an atmospheric model, or a more sophisticated operational model would certainly modify the results of this study. However, the approach used here appears appropriate given the current technology readiness level of the engine concept and the availability of climate impact metrics for use in aircraft or engine preliminary design studies.

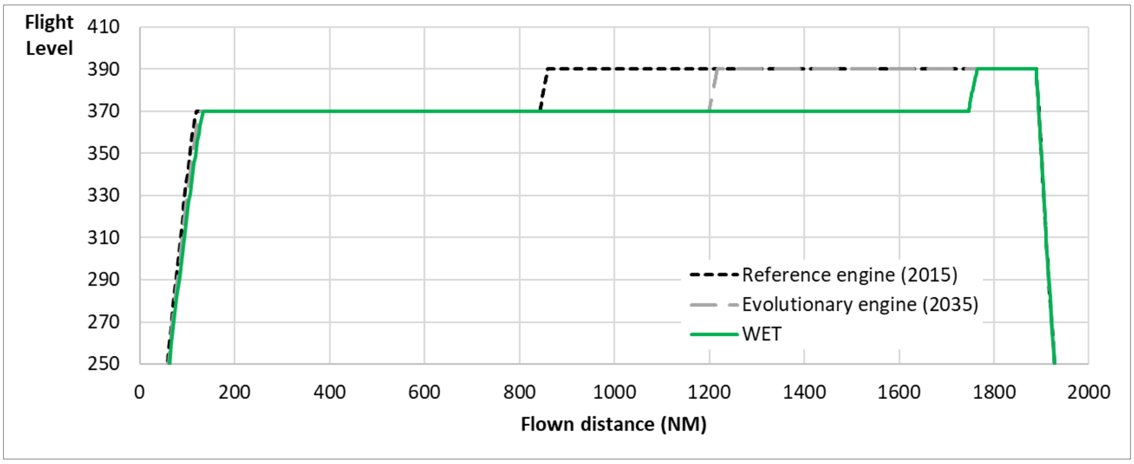


Figure 3. Mission paths of the three different aircraft concepts, for upper-end SFC reduction potentials.

4. Further Research Needs and Questions

To further substantiate the WET-specific results presented in this paper and climate impact evaluation of engine concepts in general, several axes of future research and development as well as political choices have been identified:

- Engine design:
  - Integration of supplemental components in the engine architecture, space allocation, and functional integration;
  - Dynamic performance with water vapor injection and condensation constraints;
  - Detailed analysis of NO_x emission quantities for wet combustion in aircraft engine combustor and consequent combustor optimization;
  - Impact of hydrogen combustion on the combustor design;
  - Nature and temperature of water exhaust depending on operational settings and ambient conditions and consequent cycle and engine layout optimization.
- Aircraft design:
  - Integration of WET supplemental modules in the aircraft—either on the fuselage or in the engine pylon;
  - Impact on drag, weight, and center of gravity of the aircraft, thus on flight mechanics, weight, and balance.
- Operations and air traffic control:
  - Definition of representative operational emissions scenarios that are used throughout the industry;
  - Availability of flexible operating options for climate-optimized routing, influence on flight management systems, engine power settings, and operating procedures;
  - Higher level of automation in air traffic control activities to free usable airspace in congested areas.
- Climate impact research:
  - Update on background emission scenarios to make research and development results comparable
  - Contrail and cirrus formation for revolutionary engine concepts, of which the exhaust conditions differ significantly from previous findings, and radiative properties of such contrails;
  - Required system level for climate evaluation depending on the respective research question (e.g., inclusion of climate metric in preliminary design loop versus overall climate impact evaluation of global aviation).
- Political boundaries:

- ◦ Determination of climate metric to be used for evaluation of design, certification or operating cost;
- ◦ Determination of time horizon to be used in climate impact evaluations and, if applicable, confirmation of the 100 years horizon of the Kyoto protocol;
- ◦ Binding and non-binding climate impact reduction objectives;
- ◦ Physically efficient and politically reliable regulations/charges/taxes in order to support long-term research and development goals.

The list above serves a starting point and is certainly far from being complete. The need for interlinking the afore-mentioned topics is obvious. Practically, also tools need to be developed to allow for parallel evaluation of the aspects mentioned above. The WET concept is a perfect example for the need of a higher degree of integration of atmospheric and operational research and industrial development in order to strive for climate-neutral aviation. In order to justify the necessary investments in such revolutionary designs, also a common ground for operational cost estimation is needed.

5. Conclusion and Outlook

The herein-applied first-order estimation of the Water-Enhanced Turbofan (WET) engine's climate footprint reveals a large potential to achieve a reduction of the aviation's overall impact on global warming. If sustainable aviation fuels or hydrogen are used, the operation of an aircraft equipped with WET engine(s) could be almost near to climate neutrality according to the applied climate metric. However, currently, the WET concept is at an early stage of research and development, and further research is needed to confirm the assumptions for fuel burn and NO_x reduction as well as the contrail impact. Since these assumptions sum up linearly in the climate impact evaluation, a consequent sensitivity study is straightforward. The assumptions are best estimates based on current preliminary design studies. The objective of this paper was to evaluate the overall potential of the concept with regard to its impact on climate compared to evolutionary engine design. Increasing the technology readiness level in the next years will refine these assumptions.

On top of the technical uncertainties, the analysis is strongly influenced by parameters that need further substantiation from atmospheric sciences (e.g., contrail effects), political/societal choices (e.g., applicable time horizon), and the upcoming next cycles of aircraft development, where airframe manufacturers will play a major role in accommodating such systems in future aircraft designs. By presenting the subject to the scientific community at such an early stage of development, the authors hope to foster discussion on both the presented engine concept as well as methods and metrics for evaluation. They are the foundation for future engine design to minimize the impact on the climate.

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