Note on the non-CO_2 mitigation potential of hybrid-electric aircraft using "eco-switch"

Malte Niklaß*, Benjamin Lührs† and Majed Swaid‡
German Aerospace Center (DLR), 21079 Hamburg, Germany

Nomenclature

ATR_{20} = Average temperature response over 20 years
m_{Fuel} = Fuel mass
$\dot{m}_{\text{FF}}$ = Fuel flow
$\dot{m}_{\text{HEA,FF}}$ = Fuel flow of hybrid-electric aircraft

I. Introduction

The climate impact of aviation is expected to increase as the projected growth rates in passenger kilometers (4-5 % per year) [1] exceed the annual fuel efficiency improvements of about 1-2 % [2, 3] by a large margin. In addition to CO_2, aviation affects the environment by non-CO_2 effects, like the formation of contrail induced cloudiness and changes in the atmospheric composition of ozone and methane, which cause about two-thirds of total global warming [4–6]. Non-CO_2 effects largely depend on meteorology, showing a large daily variability [7–9]. In fact, it is the daily variability of weather patterns, that adds a great level of uncertainty to these effects. However, their high dependency on the weather situation can also be effectively used for climate impact mitigation, e.g. for daily adjustments of the aircraft routing. Contrails, for instance, only persist, grow, and evolve into natural looking induced cirrus clouds if the relative humidity with respect to ice exceeds 100 %. These so-called ice supersaturated regions (ISSRs) frequently occur in the tropopause region and are rather thin in terms of height (in the order of 500 m) [10]. ISSR can be detected during flight with several types of hygrometers [11–13] as well as on the ground with calibrated and corrected RS80A radiosondes [10]. Consequently, it is possible to reduce a substantial fraction of the climate impact caused by contrail induced cirrus clouds by flight level changes of less than 2000 ft (≈ 600 m) up or down (14; see Fig. 1). Although climate-optimized re-routing results in increased fuel burn, slightly longer flight times and higher operating costs, this method has been shown to bear a vast savings potential regarding climate impact. Prior analyses [6, 15–26] showed that climate-optimized re-routing can reduce the climate-impact of a trajectory by up to 60 % compared to a mission that, for instance, operates along a cost-minimized routing and flight altitude. However, since the presented operational measures

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*Scientist, Air Transportation Systems, malte.niklass@dlr.de
†Scientist, Air Transportation Systems, benjamin.luehrs@dlr.de
‡Scientist, Air Transportation Systems, majed.swaid@dlr.de

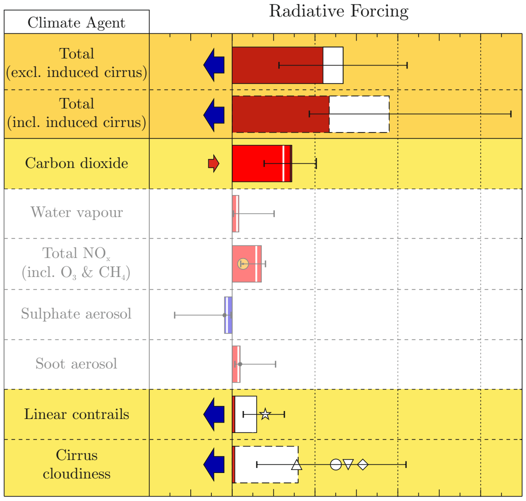


Fig. 1 **Re-routing flights around ISSRs, slightly increasing fuel burn (CO_2) but eliminating a substantial fraction of the climate impact caused by contrail cirrus.**

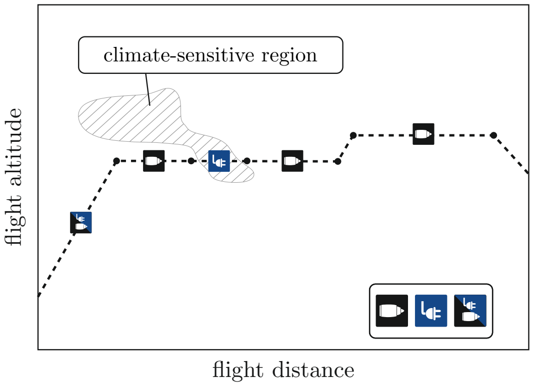


Fig. 2 **HEA offer the capability to mitigate non-CO_2 effects by switching to electric mode while passing highly climate sensitive areas like ISSRs**

are associated with a direct cost increase, we searched for technological alternatives to implement non-CO_2 mitigation and identified the hybrid-electric aircraft (HEA) technology as a promising candidate. With electric drives forming no contrails and binding all life-cycle emissions to the ground, HEA offer the capability to mitigate non-CO_2 effects by switching to full-electric mode while passing highly climate sensitive areas, such as ISSRs (see Fig. 2). Considering the fact that electric motors are not yet available in the megawatt power class for aerospace applications, and electric energy storage technology is far from approaching the energy density level of Jet A-1, it is highly unlikely that a viable all-electric power drive for commercial aviation will be feasible in the near future, other than by significantly reducing the mission range. For large passenger aircraft it will probably be possible to implement hybrid-electric propulsion systems with electric motors much sooner, which offers a superior efficiency and a flexible power management (see i.a.[27–32]). Although the required power supply for the electric motors remains the most significant technological challenge, some available battery technologies, e.g., lithium polymer cells, might be sufficient for short-term power supply (boosting). If aircraft could be equipped with a serial hybrid-electric powertrain providing at least sufficient capacity for short-term non-emission operations, the limited power could be spent for achieving a maximum climate impact mitigation.

The primary target of this study is to provide a thought-provoking impulse, how the technology of hybrid-electric aircraft could be utilized to mitigate non-CO_2 effects. This work is therefore not addressing the design and optimization of aircraft to reduce HEA energy consumption. Instead, it is focussing on a parametric investigation of HEA's non-CO_2 mitigation potential for a short term switch to full-electric mode while passing highly climate sensitive areas, like ISSRs.

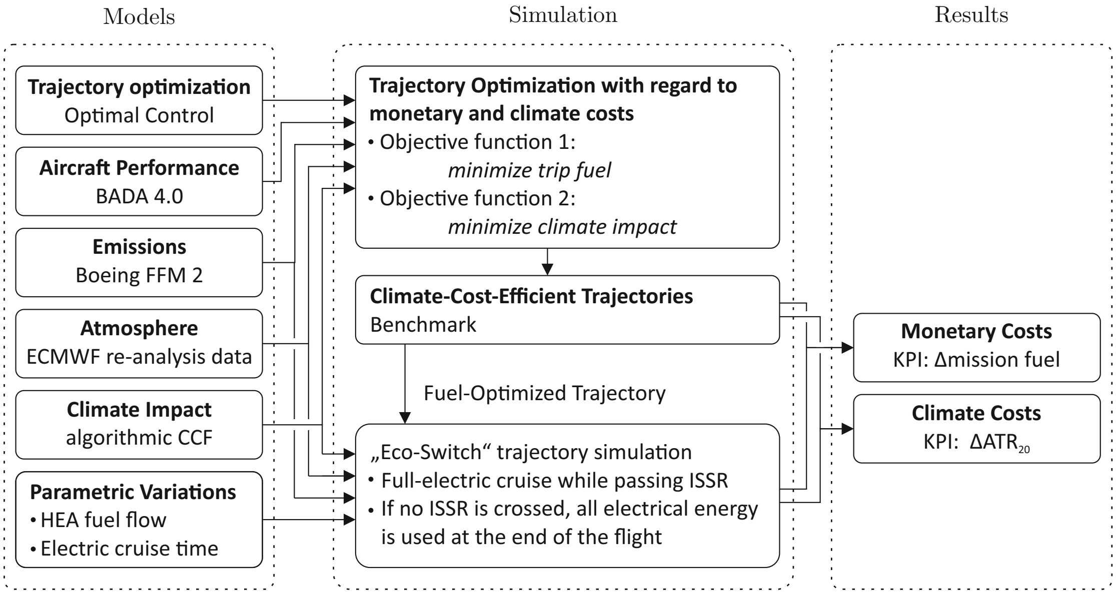


Fig. 3 Systems analysis approach of the eco-switch concept.

II. Methodology

For investigating the general feasibility and effectiveness of the concept, a cost-benefit assessment of eco-switch trajectories is performed for two flights from Scandinavia (Sweden, Finland) to the Canary Islands (Spain) and benchmarked against the mitigation potential of climate-optimized re-routings (see Fig. 3). Climate-optimized trajectories are simulated by applying a multi-criteria trajectory optimization with regard to monetary costs (here: trip fuel) and climate costs (here: average temperature response over 20 years, ATR_{20}) (see [15]).

The aircraft performance model used in this study is provided by the Base of Aircraft Data (BADA) Family 4 models of EUROCONTROL and documented in [33]. Aircraft emissions are simulated according to the Eurocontrol modified Boeing Fuel Flow Method 2 [34, 35] assuming a constant Mach number of 0.82 and a load factor of 80 %. The climate impact evaluation method for obtaining ATR_{20} of a flight is based on algorithmic climate change functions (aCCF). Climate change functions (CCF) enable the assessment of the global climate impact of local aircraft emissions as a function of emission location and time [8, 24], taking into account carbon dioxide and water vapor emissions, persistent contrail formation, as well as ozone and methane changes induced by NOx emissions. aCCFs allow a fast-time climate impact assessment [17, 22, 36], taking standard weather forecast data into account, such as humidity, temperature, and geopotential, that is already available for flight planning. All meteorological information is taken from re-analysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF) for 18 December 2015.

On the selected day, both flights are characterized by a disctinct weather situation with regard to non-CO_2 effects, as contrails are only formed on origin-destination pair (OD-pair)—*Luleå (ESPA) to Tenerife (GCLP)*—but not on OD-pair B—*Helsinki (EFHK) to Gran Canaria (GCTS)*. Both selected flights were operated by an Airbus A321-111, have a similar flight distance (approximately 2500-2700 nm) and are ranked in the top 10 in terms of available seat kilometers (ASK) within the European airspace (intra-ECAC region) on this day.

Sensitivity analyses are conducted to investigate the impact of the full-electric cruising time and the HEA fuel flow ($m_{\mathrm{HEA,FF}}$) on the eco-switch mitigation potential, both factors representing crucial quality indicators of the designed hybrid-electric aircraft. Since the resulting mass of the electric propulsion system can have a significant impact on the total fuel burn, depending on the yet unknown subsystem mass, this uncertainty is taken into consideration by varying the HEA fuel flow inside a defined interval. The boundary values regarding fuel flow are therefore estimated based on a hybrid-electric aircraft with comparable dimensions. Assuming a comparable technology level for both aircraft, the additional weight of a dual propulsion system will most likely lead to a degradation of fuel efficiency compared to the reference aircraft. In a simplified manner, the fuel flow according to the BADA flight performance model of a A321-111 with a CFM56 engine is therefore scaled between 95 % and 110 % of this reference value. The maximum achievable cruising time in full-electric operation mode is varied between 0 and 30 minutes. Furthermore, we assume that the electric propulsion system is primarily used when crossing ISSRs. If no contrail-sensitive regions are crossed however, the utilization of the electric propulsion is shifted to the last mission phase, promoting a quick decrease of aircraft mass due to fuel burn in early mission segments. This concept is in favor of reduced fuel-for-fuel effects and therefore increases the overall efficiency.

III. Results

A. Climate impact mitigation potential of climate- and cost-optimized flying (benchmark)

In Fig. 4 lateral and vertical flight profiles of the fuel-optimized trajectory (base case) are shown for the flights ESPA-GCLP (OD-pair A, a-d) and EFHK-GCTS (OD-pair B, e-h). Wind speeds, wind directions and algorithmic climate change functions are evaluated with mean aircraft parameters at mean cruise altitude (map plots) and along the trajectory (altitude plot) respectively. Blue curves represent great circle connections. Eco-Switch mode of 10- and 20-minutes cruise equivalent are visualized in different shades of gray.

For the ESPA-GCLP flight (OD-pair A), the base case trajectory (black curve in Fig. 4a, fuel- and CO_2-optimal case in Fig. 5a) is shifted southeast of the great circle trajectory (blue curve) to utilize more favorable wind conditions prevailing in that area but crosses an ISSR at about 40 % of the total flight time (t/t_f) (dark red region in Fig. 4b,d). By successively increasing the climate weighting factor from zero to one, the optimizer concentrates more and more on minimizing flight time and emissions in regions with particularly high climate sensitivity. In this example, the easiest way to bypass the ISSR is to reduce the cruise altitude. On the one hand, this leads to the desired ATR reduction, but on the other hand also to higher fuel burn and hence additional fuel costs.

In Figure 5, the relative increase of trip fuel mass (y-axis) is plotted over the climate mitigation potential (in

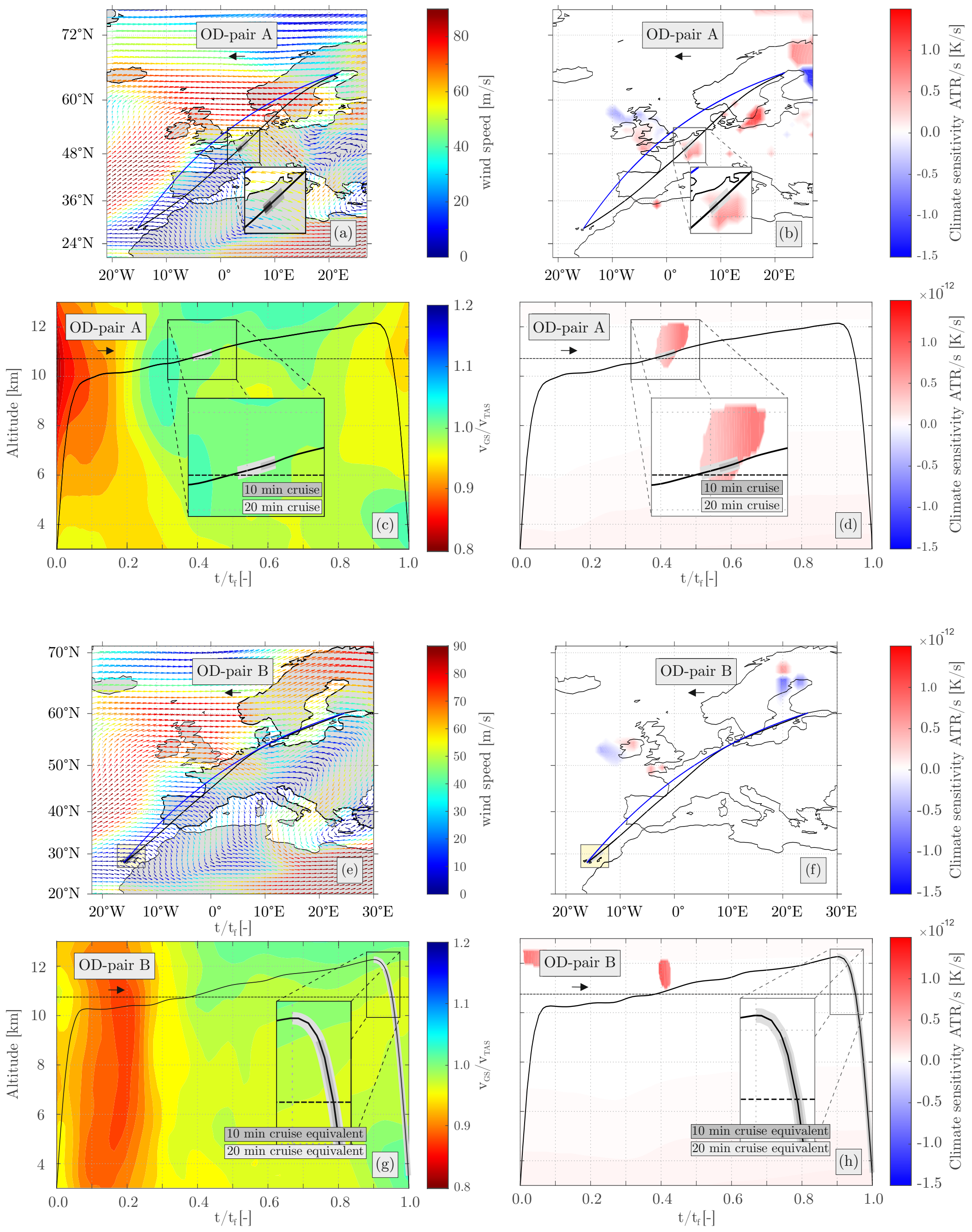
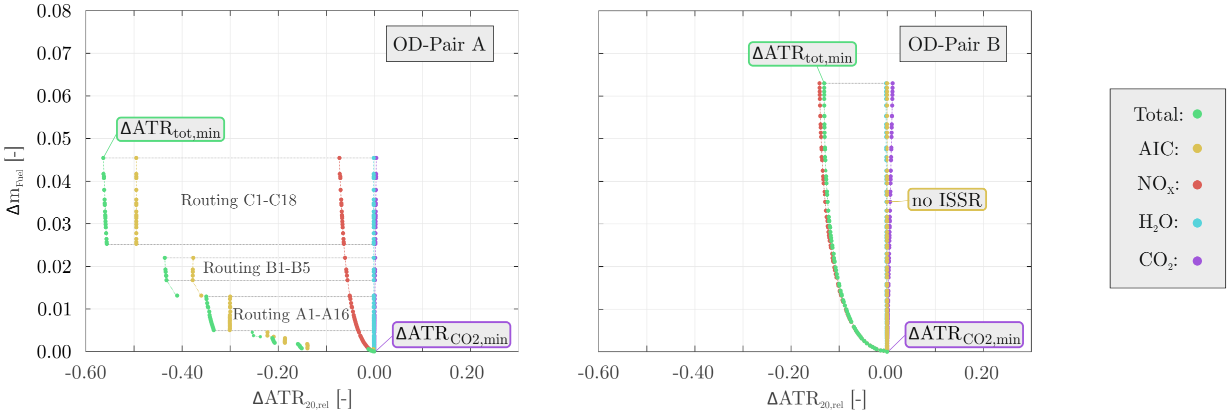


Fig. 4 Lateral and vertical flight profiles in the fuel-optimized base case for the flights ESPA-GCLP (OD-pair A, a-d) and EFHK-GCTS (OD-pair B, e-h).

ATR_{20}; x-axis) for a set of different routings, which all refer to the same OD-pair. Each routing is Pareto efficient as determined in one of 100 optimization runs with varying climate- and cost-weighting factors. On the left hand side, the three groups A to C respectively mark a subset of routings with individual assignments of an acceptable vertical and lateral detour level. Due to the highest assigned level of acceptable detour values, the maximum total ATR savings potential can be observed in group C. The routings of group A on the other hand show a comparably



(a) (b)

Fig. 5 Climate mitigation potential (in ATR_{20}; x-axis) and operating costs (trip fuel, y-axis) of cost- and climate-optimized flying for OD-pair A (ESPA-GCLP) and OD-pair B (EFHK-GCTS)

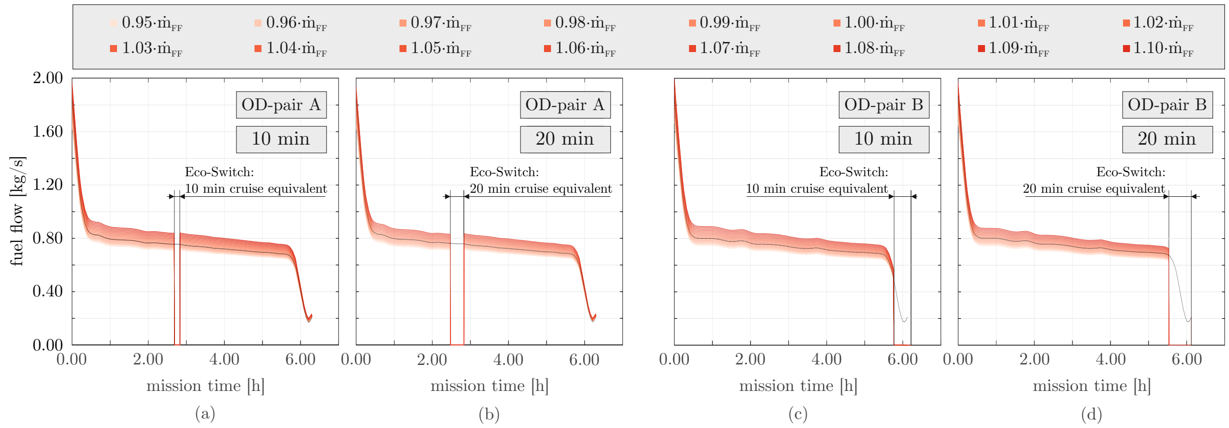
small ATR savings potential, corresponding to the low accepted detour values. Among the investigated cases, the topmost marked routing represents the climate optimum ($\Delta ATR_{tot,min}$). The bottommost marked routing represents the conventional fuel-optimized trajectory ($\Delta m_{fuel,min}$, $\Delta ATR_{CO2,min}$), which will be referred as cost-optimal case in the following. Individual colors show the contributions of CO_2 (purple), H_2O (cyan), NO_x (turquoise), and aviation-induced cirrus cloudiness (AIC; yellow) to the total climate mitigation potential (green).

Due to the comparably small extent of ISSRs in vertical dimension, even small changes in altitude may hold high optimization potentials regarding ATR due to a considerable reduction of flight time crossing these regions. The significant, discontinuous variance of ATR saving potential values between groups A and C therefore mostly arises from vertical trajectory adaptation measures for ISSR avoidance (yellow dots in Fig. 5a). A total avoidance of ISSR (Routing C1-C18) provides an ATR reduction potential of almost 50 %. The ATR mitigation potential further increases to a maximum of approximately 58 % (climate-optimized case), if all non-CO_2 effects are considered in the trajectory optimization, resulting in an increased fuel burn of additional 4.5 %. For OD-pair B, the fuel-optimized EFHK-GCTS flight does not cross any ISSRs (see Fig. 4b,d). Since no contrails are formed here, the total mitigation potential on this flight is significantly smaller than on Route A (blue dots in Fig. 5b), with a maximum ATR value of about -15 % for an increased fuel burn of approximately 6.5 %. In this case, changes in the atmospheric composition of ozone (indirect effect of NO_x emissions, red dots) offer the highest potential for climate impact reduction.

B. Climate impact mitigation potential of hybrid-electric aircraft

Instead of re-routing flights around ISSRs (Sec. III.A), the HEA technology is capable of mitigating climate impact by switching to full-electric operation mode when passing climate sensitive regions.

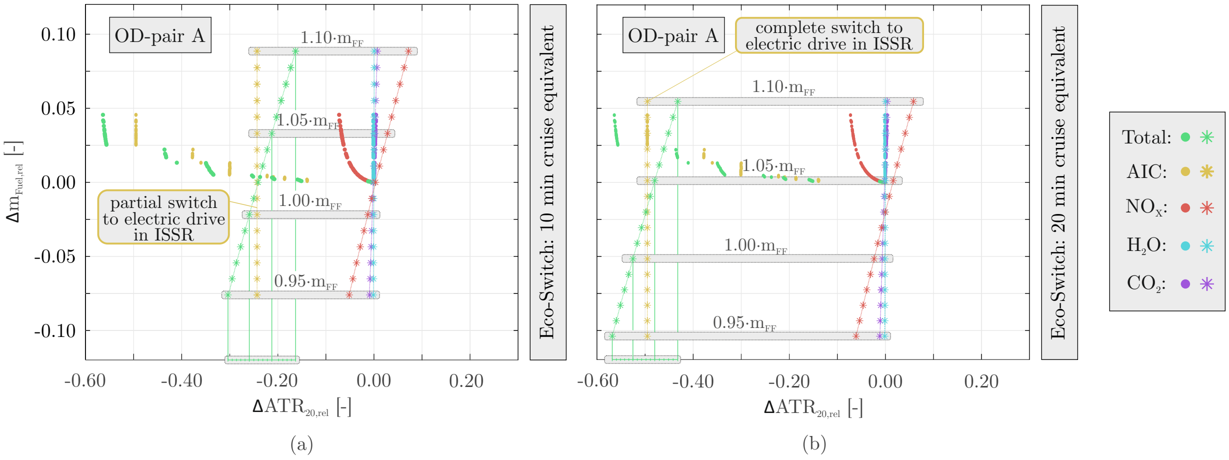
A parametric estimation of the HEA fuel flow ($\dot{m}_{HEA,FF}$) is plotted in Fig. 6a,b for a 10- and a 20-minute full-electric cruise inside the ISSR. Using the fuel flow of the purely fuel-optimized A321-100 trajectory as a reference (black dotted line), we apply varying scaling factors between 95-110 % (different shades of red) for a rough estimation of the HEA fuel flow. In combination with a full-electric cruise of 10 and 20 minutes, respectively, these fuel flow variations cause changes in the volume, timing and distribution of CO_2 and non-CO_2 emissions (in particular H_2O, and NO_x) along the flight trajectory. The climate impact evaluation of eco-switch HEA trajectories is based on applying algorithmic CCFs.



(a) (b) (c) (d)

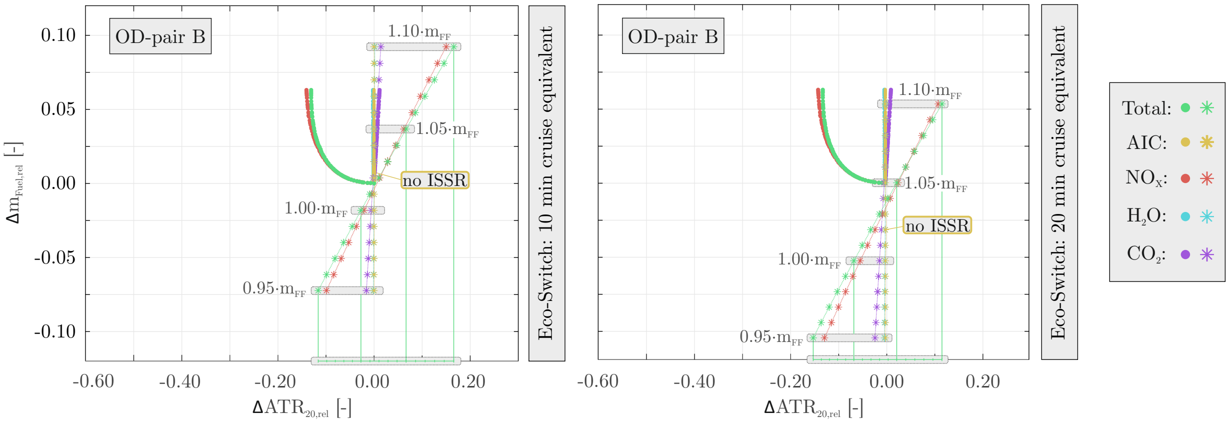
Fig. 6 Parametric HEA fuel flow estimation for a 10- and 20-minute full-electric cruise on OD-pair A (ESPA-GCLP) and OD-pair B (EFHK-GCTS).

In Fig. 7a, the climate mitigation potential (in ATR_{20}; x-axis) and trip fuel (m_{Fuel}, y-axis) of Route A is plotted for a 10-minutes switch to a full-electric cruise within the ISSR over Belgium at a mission time of about 42 % (see Fig. 4b,d) relative to cost-benefit potential of cost- and climate-optimized flying. Given that the climatic impact of this flight is largely dominated by contrail cirrus (compare Fig. 5a), this partial switch already leads to a climate impact mitigation



(a) (b)

Fig. 7 Climate mitigation potential (ATR_{20}) and trip fuel (m_{Fuel}) of cost- and climate-optimized flying (colored dots) and the HEA eco-switch concept (colored crosses) on OD-pair A for a 10- and 20-minute full-electric cruise and varying fuel flow scaling factors (95-110 %)



(a) (b)

Fig. 8 Climate mitigation potential (ATR_{20}) and trip fuel (m_{Fuel}) of cost- and climate-optimized flying (colored dots) and the HEA eco-switch concept (colored crosses) on OD-pair B for a 10- and 20-minute full-electric cruise and varying fuel flow scaling factors (95-110 %)

potential between -16 % ($1.10 \cdot \dot{m}_{\mathrm{FF}}$; $\Delta m_{\mathrm{Fuel}} \approx +9$ %) and -31 % ($0.95 \cdot \dot{m}_{\mathrm{FF}}$; $\Delta m_{\mathrm{Fuel}} \approx -7.5$ %). If the HEA fuel flow is smaller than $1.02 \cdot \dot{m}_{\mathrm{FF}}$, climate mitigation coincides with fuel burn reduction.

An increased maximum cruise time in full-electric mode of 20-minutes results in even higher mitigation potential values (see Fig. 7b). In our given case, a 20-minutes full-electric cruise flight is already sufficient to pass the entire ISSR without producing any emission and without forming any contrail-cirrus. This would reduce the climate impact by -43 % ($1.10 \cdot \dot{m}_{\mathrm{FF}}$) to -57 % ($0.95 \cdot \dot{m}_{\mathrm{FF}}$) while fuel burn would change between -11 % ($0.95 \cdot \dot{m}_{\mathrm{FF}}$) and +6 % ($1.10 \cdot \dot{m}_{\mathrm{FF}}$). Here, climate mitigation would coincide with fuel burn reduction (Δm_{Fuel}) for a HEA fuel flow smaller than $1.05 \cdot \dot{m}_{\mathrm{FF}}$.

On Route A, we see significant ATS saving potentials for both cases, 10- and 20-minutes full-electric cruise equivalent, regardless of the HEA fuel flow level.

In our second case, the electrical energy of the HEA system is used at the end of the mission as no contrail-sensitive region is crossed at the fuel-optimized flight from Helsinki to Gran Canaria (see Fig. 4e-h & Fig. 6c,d). For a full-electric segment of 10- and 20-minutes cruise equivalent at the end of the mission, there is a considerably smaller climate mitigation potential. As visualized in Fig. 8, the ATR reduction potential ranges from -12 % ($0.95 \cdot \dot{m}_{\mathrm{FF}}$) to +17 % ($1.10 \cdot \dot{m}_{\mathrm{FF}}$) for 10-minutes and -16 % ($0.95 \cdot \dot{m}_{\mathrm{FF}}$) to +12 % ($1.10 \cdot \dot{m}_{\mathrm{FF}}$) for 20-minutes. According to these results, eco-switch operations along the last segment of a mission can even increase the climate impact. Such a pattern can be found for HEA fuel flows $> 1.1 \cdot \dot{m}_{\mathrm{FF}}$ (10 min) respectively $\geq 1.4 \cdot \dot{m}_{\mathrm{FF}}$ (20 min). This implies that the emission volume (level of HEA fuel flow) predominates the climate sensitivity along the trajectory of Route B (level of non-CO_2 effects) under the prevailing ambient conditions. In other words, the quality of the HEA design seems to be decisive for the total climate impact of a mission if no contrail-sensitive region is crossed.

IV. Discussion

The initial estimates of the eco-switch mitigation potential naturally depend on existing uncertainties and underlying assumptions. These uncertainties and assumptions comprise the selection of the climate metric (ATR_{20}), the application of pre-calculated climate change functions (CCFs) as well as inaccuracies in weather forecasts (ECMWF re-analysis data), the aircraft performance model (Bada 4.2 Airbus A321-111), the trajectory simulation (TOM), the emission quantification (Eurocontrol-modified Boeing fuel flow method 2) and the simplified parameterization of HEA's fuel flow. Therefore, only normalized values of ATR_{20}, mission fuel and mission time relative to those values of the route-specific fuel-optimal trajectory of the reference BADA aircraft are shown.

Since this study is not intended to present a detailed aircraft design concept and HEA performance levels are still subject of investigation in research, we have decided to apply a sensitivity study only. According to our results, a HEA configuration that would cause +10 % more CO_2 emissions than a lighter reference aircraft with a comparable level of technology could still mitigate the overall climate impact—*CO_2 and non-CO_2 effects*—by more than 15 % for a 10-minute all-electric cruise within an highly climate-sensitive region, like an ISSR. However, mitigation potentials and fuel penalties might vary widely depending on the route and weather conditions. To further investigate our findings, different weather situations and additional routes will be evaluated in the following studies. But weather forecasts and climate impact forecasts are also subject to uncertainties. Risk analyses that incorporate uncertainties in climate impact assessments are therefore needed to better understand the influence of uncertainties on the calculation of non-CO_2 effects and thus on the potential of setting wrong incentives [37]. For assessing alternative mitigation strategies a collaborative decision making framework has to be developed that quantifies overall performance, potential benefits, associated costs and risks [22]. This also involves the selection of the appropriate mitigation approach for each flight. According to[17, 26], it could already be possible to achieve a large part of the total climate impact reduction potential by focussing only a few routes with a high mitigation potential. In particular, this requires a robust prediction of ISSR in numerical weather prediction (NWP) models. A newly funded EU project, Better Contrails Mitigation (BeCOM), is therefore aiming to address the uncertainties related to the forecasting of persistent contrails and their weather-dependent individual radiative effects [38].

Besides ATR_{20}, the use of other climate metrics would also be possible, which can be described as a combination of a climate indicator (e.g. RF, GWP, GWT), emission scenario (emission course, background emissions, etc.) and time horizon (often 20, 50, 100 or 500 years) [see i.a. 39, 40]. However, since [22] has already demonstrated the robustness of climate-cost-efficient re-routing with respect to the choice of climate metrics –ATR, GTP, and GWP over 20, 50, and 100 years–, this choice does not appear to be crucial for an initial assessment of the mitigation potential of the eco-switch concept.

V. Conclusion and outlook

This work is mainly intended to provide a thought-provoking impulse, how the technology of hybrid-electric aircraft (HEA) could be utilized to mitigate non-CO_2 effects. If aircraft could be equipped with electric propulsion systems providing at least sufficient capacity for short-term non-emission operations, the limited power could be spent for achieving a maximum climate impact mitigation rather than for maximum reduction in fuel consumption. Since electric propulsion systems do not form any contrails and bind all life-cycle emissions to the ground, HEA offer an increased capability of non-CO_2 effect-mitigation by switching to full-electric mode when passing highly climate-sensitive areas, such as ISSRs. For investigating a first estimation of the mitigation potential of the concept, we assume that all available electrical energy is primarily used during the flight through an ISSR. Otherwise, it is used at the end of the mission. We studied the impact of two key factors representing the quality of the designed HEA, which comprise the maximum available cruising time in full-electric operation mode on the one hand, and the resulting mission phase specific fuel flow under consideration of additional HEA system mass on the other hand.

For the non-CO_2 effects included in this study (H_2O, NO_x, AIC), we identified distinct weather-related differences of the HEA eco-switch mitigation potential. If the eco-switch concept is applied while passing highly climate senstive regions, we found a significant ATR saving potential for all combinations of full-electric cruise times and HEA fuel flow levels. We thus have strong evidence that the resulting climate impact of prevailing ice-supersaturated regions is largely driven by the level of climate sensitivities, rather than by emission levels (aircraft design). Quite the opposite is the case, if the eco-switch concept is applied arbitrarily, for example at the end of mission. With increasing HEA fuel flow, there is even an increase in the overall climate impact of the flight; an implication that the emission volume (level of HEA fuel flow) can outweigh the local climate sensitivity. In other words, the quality of the HEA design (favorable aerodynamics, efficient propulsion, light weight construction, etc.) appears to be decisive for the total climate impact of the flight if no contrail-sensitive region is crossed.

Nevertheless, although the application of the HEA system outside of climate sensitive regions has been shown to cause a slightly increased climate impact on a single mission level, statistically representative investigations should be conducted. Therefore, the long-term savings potential of the eco-switch concept needs to be quantified on a global network level in order to investigate, whether the conflicting effects of HEA-operations inside and outside of climate sensitive areas add up to a positive or a negative climate balance from a long-term perspective.

For an effective, weather-independent reduction of the total—*CO_2 and non-CO_2*—climate impact without re-routing, both fuel-efficient HEA designs and eco-switch capability might therefore be needed. Further assets of the eco-switch, in addition to the climate impact mitigation potential, might also arise due to a capability of silent approach operations in airport proximity.

Based on the identified research gap regarding HEA's non-CO_2 mitigation potential, we propose deeper research in this field from the perspective of aircraft design. In future work, the gained insights might directly be integrated into the aircraft design process in order to design more climate-friendly hybrid-electric aircraft with eco-switch capability.

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