

RESEARCH PROJECT MANAGEMENT

Document n°	INDIGO - D7.4	
Exploitation roadmap with strategic directions for the TRL development of DHEP-LARW and NRT technologies		
Issue date	A01 - 30/09/2026	
Revision History Table		
Version n°	Issue Date	Reason for change
A01	30 September 2026	Final Version

Exploitation roadmap with strategic directions for the TRL development of DHEP-LARW and NRT technologies

Project: 101096055

INtegration and Digital demonstration of low-emission aircraft technologies and airport Operations

INDIGO

Deliverable D7.4



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Abbreviations

Term	Meaning	Term	Meaning
A320	Airbus A320, INDIGO reference aircraft	KER	Key exploitable result
ANSP	Air navigation service provider	LAE	A-weighted sound exposure level
ATM	Air traffic management	LAQ(N)	Local air quality (and noise)
BC	Black carbon	LARW	Large-aspect-ratio wing
BESS	Battery energy storage system	Lden	Day-evening-night noise level
BPF	Blade-passing frequency	LES	Large-eddy simulation
CAA	Computational aeroacoustics	LTO	Landing and take-off
CFD	Computational fluid dynamics	MDO	Multidisciplinary design optimisation
CPACS	Common Parametric Aircraft Configuration Schema	NRT	Noise-reduction technologies
DHEP	Distributed hybrid-electric propulsion	PM	Particulate matter
DoA	Description of the Action	POD	Proper orthogonal decomposition
EPNL	Effective perceived noise level (in EPNdB)	RANS	Reynolds-averaged Navier-Stokes
EPS	Electrical power system	SBW	Strut-braced wing
FSI	Fluid-structure interaction	SOL10-SOL40	Solution scenarios with increasing INDIGO aircraft share
GFEM	Global finite-element model	TRL	Technology readiness level

1. Executive Summary

INDIGO developed a medium-range aircraft featuring distributed hybrid-electric propulsion (DHEP), a large-aspect-ratio strut-braced wing (LARW) and noise-reduction technologies (NRT). INDIGO aimed at assessing how the integration of such technologies would improve noise and local air quality around European airports. This deliverable reports what the project demonstrated, how mature each result is at the end of the project, and which development and exploitation steps should follow. It responds to Task 7.4 of the Description of the Action (DoA) [1].

What INDIGO demonstrated

- **An integrated digital framework for aircraft analysis and design.** The INDi2 configuration (aspect ratio 21.6, wing area 122.4 m², span about 51.4 m, cruise at Mach 0.6 and 8,000 m) served as the downstream reference airframe. WP5 re-optimised the powertrain, including propeller design, on that fixed airframe, while selected CFD and static-aeroelastic studies provided configuration-specific high-fidelity checks [11]. End-of-project maturity: TRL 3, corresponding to analytical proof of concept for the integrated DHEP-LARW aircraft.
- **A laboratory-demonstrated tonal noise-reduction mechanism.** Wind-tunnel tests of phase-synchronised propellers reduced the first blade-passing tone by about 12-15 dB in the investigated two-bladed cases [11, §3.1]. **End-of-project maturity: TRL 4 for the investigated phase-synchronisation experimental configurations, based on PNWT laboratory evidence.**
- **Airport-level air-quality and noise benefit in the 2035 scenario.** Under SOL40, relative to the corresponding 2035 reference scenario at each airport, the modelled air-quality indicators decrease across Riga, Dortmund, Madrid and Barcelona by approximately 36-60% for CO maximum 8-hour concentration, 50-66% for HC daily mean concentration, 20-53% for NO_x daily mean concentration, 9-39% for NO_x maximum hourly concentration, 20-60% for PM



daily mean concentration and 29-61% for black-carbon daily mean concentration [13, §5.2]. The population exposed above 55 dB(A) Lden decreases by 45-81% across the four airports. These are modelled airport-level concentration and noise-exposure indicators under the fleet-injection scenarios; they are distinct from the aircraft source-emission metric below 900 m.

- **Quieter departures, in a different metric from the DoA target.** On the investigated RIX departure, the DLR full-scale numerical assessment predicts the reference INDIGO configuration to have propeller-tonal LAE approximately 6 dB(A) below the recorded A320 event [11, §3.2; 13, §3.5.1]. Applying the investigated 36° phase offset produces a further approximately 2 dB(A) reduction in propeller-tonal LAE relative to the INDIGO reference configuration on the same trajectory. DLR considers reductions expressed in LAE and EPNL to be comparable, while the absolute values are only approximately related, and cites NASA CR-3406 [21] in support of this interpretation. The cited LAE-EPNL relationship is approximate and is qualified for cases where audible tones are not excessive. Comparable RIX EPNL reference values were not available for this assessment, so no matched EPNL comparison was performed. On this basis, the LAE reduction results provide indirect verification of the DoA 6-8 EPNdB reduction ambition.
- **A method linking technology maturity to design.** For the single-trajectory 1,000-nm reference mission, the uncertainty-based study predicts that the battery energy density remaining after uncertainty propagation reaches a saturation level of about 590 Wh/kg in the 2030 scenario and 700 Wh/kg in 2040 [11, §6.1.2]. In the saturation regime at the loosest robustness limits investigated, and across the two 75.5 and 77.5 dB fly-over EPNL constraints, expected block fuel changes from about 3.35-3.39 t to 2.95-3.00 t and fuel burned below 900 m from about 60-61 kg to 51-52 kg. These are conditional outcomes of the adopted forecast $TRL \geq 7$ battery framework, not demonstrated battery performance or guaranteed availability in those years.

What should happen next. The first priority is to refine the coupling of the completed aerodynamic, structural and propulsion models into one aircraft baseline and check whether the design and environmental conclusions still hold (2026-2028). That result should decide which demonstrations to fund in roughly 2028-2032: a representative electrical powertrain rig, a strut-wing joint or substructure test, an installed noise-reduction test and stakeholder simulation of greener landing and take-off procedures. Selected digital tools can be packaged for reuse in parallel, since they do not depend on hardware. Anything beyond 2032 depends on those gates. The DoA's 2035 horizon is the context for disruptive gains; 2050 is scenario context, not an entry-into-service date (§8).

Exploitation. DLR reports actual reuse beyond INDIGO of the actuator-disk trim method developed in WP3 within the FSDLRControl/TAU workflow, which is already used by other DLR colleagues in other in-house projects [15]. The pre-existing MOTIVATION platform, which was adapted within INDIGO, was also used in the Clean Aviation ODE4HERA project during 2024-2026; this represents external use of the platform rather than uptake of the complete INDIGO KER-03 foreground. Separately, the ZEUS project (grant agreement 101286802) is evaluating an INDIGO aircraft representation for future traffic scenarios and the INDIGO traffic-demand method for fleet estimation [14]. Ownership, access and planned use of the key exploitable results are summarised in §6.



2. Scope and Method

Purpose. Task 7.4 covers the exploitation of INDIGO results [1, Part A, T7.4]. The DoA describes D7.4 as “a route for further TRL escalation and then commercial exploitation” of the LARW, DHEP and advanced noise-reduction technologies [1, Part B §2.2.2]. This report therefore covers five development lines: the integrated DHEP-LARW aircraft, its electrical power system, the strut-braced wing structure, NRT and greener landing and take-off (LTO) operations. It also covers the digital tools that made the assessment possible.

Maturity baseline. The DoA sets the starting points and targets used here [1, Part B §1.1.3 and Table 2]. At the start, the integration of DHEP and LARW and the operational concept were estimated at TRL 0-1, isolated DHEP and LARW technologies at TRL 2-3, NRT at TRL 3-4 (towards the lower end for DHEP-LARW airframes) and the integration methods at TRL 1-2. The end-of-project target is TRL 3 for the integration of DHEP and LARW, which the DoA defines as “Proof-of-Concept Demonstrated Analytically”, and TRL 4 for NRT. A physical aircraft is therefore not required to meet the integration target; analytical evidence that the integrated concept works is. Maturity is judged separately for each assessed object in §3.1 and is not assumed from the DoA target.

Prioritisation. Next steps are ranked in §8 on five criteria: the strength of the evidence already obtained; how much closing the next gate would change an aircraft or operational decision; dependence on other results; whether a bounded demonstration or reuse is feasible in the near term; and whether a credible user or partner exists.

Time horizons. Three planning periods are used: 2026-2028 for baseline and decision work, 2028-2032 for representative validation, and 2032 onwards for routes that depend on earlier results. The DoA refers to “disruptive gains by 2035” and to wider adoption by 2050 [1, Part B §2.1]; these are used as context, not as delivery or entry-into-service dates. The periods are sequencing assumptions and will change once a programme owner sets resources and schedules.

Evidence. The assessment is based on the Description of the Action, project deliverables and partner-confirmed information. Quantitative results are reported only for the configuration, metric, model and operating conditions to which they apply; relevant limitations are stated alongside the corresponding results.

3. Achievements and End-of-Project Maturity

INDIGO’s principal achievement is a project-level digital chain linking aircraft design to airport environmental impact, supported by discipline-specific numerical checks and experiments. Several aircraft configurations were used, and each result must be read against the right one [11; 12; 13]:

- **INDi1:** the early conceptual reference, built on preliminary low-fidelity estimates.
- **INDi2:** refined after landing-gear, structural-weight and flight-mechanics corrections, and the reference airframe for downstream work (aspect ratio 21.62, wing area 122.4 m² [11, Table 1]; the span of about 51.4 m follows from these values). **INDi2RIX:** the WP6 configuration combining the fixed INDi2 airframe with a fixed powertrain architecture and sizing. In the WP6 studies, the optimisation varied mission-control variables rather than aircraft or powertrain sizing. **D6.2 sensitivity configurations:** a separate WP6 sensitivity branch retains the INDi2



airframe but re-optimises the powertrain for battery specific energies of 400, 600 and 800 Wh/kg. These cases are distinct from the fixed-powertrain INDi2RIX reference configuration.

- **INDi3s and INDi3m:** WP5 branches that re-optimised the powertrain, including the propellers, on the INDi2 airframe. They did not redesign the airframe or feed back into the WP6 airport studies.

3.1 Maturity by Assessed Object

Table 1 summarises maturity by assessed object. The TRL assigned to an integrated technology or concept is not the maturity of an individual numerical solver or modelling method; the digital modelling capabilities are treated separately in §5. Numeric ratings are used for the integrated DHEP-LARW concept and the NRT because the DoA defines explicit end-of-project targets for those objects.

Table 1 - Maturity of INDIGO results at the end of the project

Assessed object	Start → DoA target	End state	Basis and main gap
A1. Integrated DHEP-LARW digital aircraft (INDi2)	TRL 0-1 → TRL 3 (analytical proof of concept)	TRL 3 - analytical proof of concept for the integrated DHEP-LARW aircraft.	Basis: multidisciplinary design and optimisation with targeted high-fidelity aerodynamic and static-aeroelastic verification for the INDi2 reference configuration [11, §§4-7]. Gap: the completed discipline models were not recoupled into a final aircraft optimisation, and no physical integrated-aircraft demonstration was performed. (§3.3)
A2. Phase-synchronisation NRT	TRL 3-4 → TRL 4 (NRT)	TRL 4 - laboratory validation of the phase-synchronisation mechanism for the investigated propeller configurations.	Basis: PNWT wind-tunnel testing demonstrated phase-dependent first-BPF tonal-noise reduction for the investigated configurations. Five-bladed experiments additionally supported preliminary assessment of the hybrid RANS-CAA model [11, §§3.1-3.2]. Gap: installed broadband noise, control robustness and representative/full-scale experimental validation remain open; the full-scale 36° result is numerical.
A3. DHEP components and electrical architecture	TRL 2-3 → no separate target	Numerically assessed architecture; no single end TRL.	Basis: four generators, four propulsion batteries and eight electric propulsion units, sized and analysed for power flow, faults and transients [4, §4; 5, §§8-9]. Gap: thermal management, protection and physical integration; sizing, transient and optimisation models remain separate.
A4. LARW and strut-braced wing structure	TRL 2-3 → no separate target	Numerical structural proof of concept; no hardware TRL.	Basis: progressive structural development from beam models to a shell-based GFEM, including minimum-mass sizing, distributed-propulsion loads, landing-gear integration, redesign of the fuselage-strut attachment and refinement of the wing-strut junction for aerodynamic continuity, load transfer and composite manufacturability [7, §6]. Gap: wider load envelope, fatigue, manufacturing and physical correlation.
A5. Greener LTO and future traffic scenarios	TRL 0-1 → no dedicated target	Airport-specific fast-time simulation and feasibility screening; no operational TRL or approval.	Basis: four-airport procedure ranking, feasibility and modelling capability [9; 13]; SOL10-SOL40 air-quality and population-above-55-dB(A)-Lden noise-exposure results for Riga, Dortmund, Madrid and Barcelona [13, §5.2]. Gap: safety, capacity and ATM assessment with stakeholders; model-specific limitations of the environmental assessment are stated in §3.3.

Assessed object	Start → DoA target	End state	Basis and main gap
A6. Digital integration and LAQN methods	TRL 1-2 → TRL 3 (integration methods)	Project-level digital proof of concept linking the design, uncertainty and airport-impact workflows; maturity differs by tool.	Basis: outputs from design, uncertainty, aerodynamic, structural, acoustic and air-quality/data-fusion methods were linked across the project workflow [7; 10; 11; 12]; the completed discipline models were not all recoupled into a final aircraft optimisation. Gap: model-specific validation and packaging for reuse (§5).

3.2 Evidence Against the DoA Impact Ambitions

The DoA set three impact ambitions relative to state-of-the-art aircraft: up to 50% lower pollutant emissions below 900 m, 6-8 EPNdB lower noise below 900 m, and up to 50% improvement in airport LAQN integral metrics [1, Part B Table 11]. It frames the pollutant ambition as the effect of the aircraft “if employed in substitution of all current conventional mid-range vehicles” [1, Part B §2.1.1]. Table 2 compares each ambition with what INDIGO assessed. A result counts against an ambition only when the metric, reference and scenario match.

Table 2 - DoA impact ambitions compared with INDIGO results

Ambition	What was assessed	Result	Comparison with the ambition
B1. Pollutant emissions below 900 m: up to 50% lower	Source pollutant emissions for the INDIGO aircraft were evaluated from phase-dependent emission rates and integrated emitted masses, with specific attention to operating segments below 900 m [11, §4.4; 12, §3]. In the WP6 airport assessment, REF- and SOL-scenario emission rates were assigned to the corresponding trajectory segments and used as inputs to the subsequent dispersion and concentration calculations [13, §3.3.2].	REF- and SOL-scenario source-emission rates were calculated and used within the airport-assessment chain, but the project does not report a standalone matched percentage reduction in emitted pollutant mass below 900 m for the INDIGO aircraft relative to the conventional reference.	Because the project does not report a standalone like-for-like percentage reduction in emitted pollutant mass below 900 m, the DoA up-to-50% source-emission ambition cannot be quantified directly as a separate B1 indicator. Fuel burned below 900 m and the airport-level concentration reductions reported in B3 are separate metrics and are not used as substitutes for this comparison.
B2. Noise below 900 m: 6-8 EPNdB lower	Propeller-tonal LAE for the INDIGO aircraft on the investigated RIX departure trajectory at the NMT2 lateral monitor, compared with a recorded A320 event of 83.3 dB(A) on the corresponding RIX reference trajectory [11, §3.2; 13, §3.5.1].	The reference INDIGO configuration is predicted to have propeller-tonal LAE approximately 6 dB(A) below the recorded A320 event. A preliminary landing-gear contribution increases the predicted INDIGO level by approximately 0.5 dB(A). Applying the investigated 36° phase offset produces a further approximately 2 dB(A) reduction in propeller-tonal LAE relative to the INDIGO reference configuration on the same RIX trajectory.	DLR considers reduction deltas in LAE and EPNL to be comparable, while their absolute values are only approximately related, citing NASA CR-3406 [21]. The cited relationship is approximate and subject to the applicability conditions stated in that reference. Comparable RIX EPNL reference values were not available for this assessment, so no matched EPNL comparison was performed. On this basis, the LAE reduction results provide indirect verification of the DoA 6-8 EPNdB reduction ambition.



Ambition	What was assessed	Result	Comparison with the ambition
B3. Airport LAQN integral metrics: up to 50% better	SOL10-SOL40 fleet-injection scenarios for 2035 at Riga, Dortmund, Madrid and Barcelona, compared with the corresponding reference scenario at each airport. Air-quality performance was assessed through pollutant-specific concentration metrics and noise through the population exposed above 55 dB(A) Lden [13, §5.2]. Actual INDIGO substitution depends on the route-replacement and flyability rules.	Under SOL40, the reductions across the four airports are: CO maximum 8-hour concentration 35.75-59.66%; HC daily mean 50.28-66.44%; NOx daily mean 20.15-53.27%; NOx maximum hourly 8.99-39.22%; PM daily mean 19.61-60.07%; and black-carbon daily mean 28.74-61.14%. Population exposed above 55 dB(A) Lden decreases by 78% at Riga, 77% at Dortmund, 81% at Madrid and 45% at Barcelona (Table 3).	Improvements of approximately 50% or more are obtained for several individual LAQ indicators: HC daily mean at all four airports; CO maximum 8-hour concentration at Dortmund and Madrid, with Riga close to 50%; and daily-mean NOx, PM and black carbon at Barcelona. For noise exposure, the SOL40 reduction in population above 55 dB(A) Lden exceeds 50% at Riga, Dortmund and Madrid and is 45% at Barcelona. D6.2 reports LAQ and noise indicators separately rather than as one composite LAQN percentage; the DoA ambition is therefore assessed indicator by indicator. SOL40 does not represent full substitution of the conventional fleet.
B4. Technology sensitivity and uncertainty outlook (no numerical target; DoA Objective 3)	(a) Sensitivity study with the INDi2 airframe fixed and the powertrain, including propeller-design variables, re-optimised for 400, 600 and 800 Wh/kg battery-specific-energy performance scenarios. The resulting configurations were propagated through the Riga environmental-assessment chain using 13 virtual LAQ probes, an approximately cross-trajectory wind condition and a 2.5-hour assessment window [13, §4]. (b) Year-dependent uncertainty study for the single-trajectory 1,000-nm reference mission, propagating the adopted 2030 and 2040 battery-technology forecasts through the robust MDO framework [10; 11, §§5-6.1.2].	(a) From 400 to 800 Wh/kg, block fuel decreases from 3.11 to 2.10 t and fuel burned below 900 m from 80.98 to 51.74 kg. Mean CO, NOx, PM and UHC concentrations across the 13 probes decrease by approximately 38-44%. The mean noise indicator varies by only 0.43 dB across the three configurations and shows no monotonic trend with battery specific energy. (b) The energy density remaining after uncertainty propagation (EDachieved) saturates at approximately 590 Wh/kg for the 2030 scenario and 700 Wh/kg for 2040. In the corresponding saturation regime, expected block fuel changes from approximately 3.35-3.39 t to 2.95-3.00 t and fuel burned below 900 m from approximately 60-61 kg to 51-52 kg.	The two analyses answer different questions and must not be combined into a single battery-maturity ladder. The 400/600/800 Wh/kg cases in (a) are assumed battery-performance scenarios used to measure aircraft and environmental sensitivity; they do not correspond one-to-one to years or TRLs. The 2030/2040 results in (b) are conditional uncertainty-propagation outcomes under the forecast TRL ≥ 7 framework, not demonstrated technology states. Their quoted fuel ranges describe the saturation regime at the loosest investigated robustness limits and span the two 75.5 and 77.5 dB fly-over EPNL constraints rather than one unique design point. Absolute fuel values remain dependent on the aerodynamic representation used in the optimisation (§3.3).

Ambition	What was assessed	Result	Comparison with the ambition
B5. Health and economic effects (no numerical DoA ambition)	BenMAP-CE assessment of health effects associated with the modelled changes in PM and NO _x concentrations, together with noise-related population-exposure, annoyance and sleep-disturbance indicators. The economic assessment monetises changes in LAQ-related all-cause mortality using the Value of a Statistical Life (VSL), with results reported by airport and concentration-response function [13, §§3.6, 6-7].	Under SOL40, D6.2 reports estimated avoided all-cause mortality ranges of 83-189 deaths for PM and 39-45 for NO_x at Riga; 4-10 for PM and 10-11 for NO_x at Dortmund; 86-94 for PM and 85-100 for NO_x at Madrid; and 5-6 for PM and less than one for NO_x at Barcelona. These ranges span the concentration-response functions evaluated for each pollutant; they are not statistical confidence intervals and the PM and NO_x estimates are not additive. Noise-related health indicators also improve under SOL40. The modelled annoyed population and highly sleep-disturbed population decrease respectively by 42% and 39% at Riga, 54% and 74% at Dortmund, 31% and 49% at Madrid, and 17% and 9% at Barcelona. Using country-specific Value of a Statistical Life estimates adjusted to 2023 prices and expressed in euros, D6.2 reports SOL40 monetised all-cause-mortality benefit ranges of €361-820 million for PM and €172-196 million for NO_x at Riga; €33-75 million and €50-57 million at Dortmund; €90-103 million and €86-98 million at Madrid; and €17-19 million and €1.95-2.23 million at Barcelona. These are alternative concentration-response-function estimates of the same pollutant-specific endpoints and are reported separately rather than pooled. Noise-related health effects and morbidity are not monetised. D6.2 designates Orellano et al. (2024) as the primary PM mortality concentration-response function and Kasdagli et al. (2024) as the primary nitrogen-dioxide mortality reference; complementary functions are retained to assess sensitivity and consistency.	The health and economic results are scenario- and model-based impact estimates derived from the airport concentration and noise assessments. Estimates from different concentration-response functions represent alternative epidemiological assessments and are therefore reported separately rather than added or treated as a single pooled estimate. The economic results cover monetised changes in LAQ-related all-cause mortality; noise-related health effects and morbidity are not monetised.

Table 3 gives the per-airport values behind B3. The substitution rules allow the INDIGO aircraft to replace a conventional aircraft only where it can fly the route, so the realised share differs from the nominal label; at Riga, 452 of 1,112 flights (40.65%) are flown by the INDIGO aircraft in SOL40 [13, §§1-2].

Table 3 - Reduction in modelled airport environmental indicators, SOL40 relative to the 2035 reference scenario

Pollutant (metric)	Riga	Dortmund	Madrid	Barcelona
CO (maximum 8-hour)	49.34%	52.69%	59.66%	35.75%
HC (daily mean)	50.28%	52.70%	64.96%	66.44%
NO_x (daily mean)	20.15%	29.40%	37.95%	53.27%
NO_x (maximum hourly)	16.08%	39.22%	36.06%	8.99%
PM (daily mean)	19.61%	32.99%	44.84%	60.07%
Black carbon (daily mean)	28.74%	33.14%	45.42%	61.14%
Population exposed above 55 dB(A) Lden	78%	77%	81%	45%

Source: [13], §5.2. LAQ values are average reductions in the indicated modelled concentration metric relative to the corresponding airport reference scenario. The noise row reports the reduction in population exposed above 55 dB(A) Lden. NO_x results are NO_x rather than NO₂ and are not regulatory compliance metrics. SOL40 is a fleet-injection scenario subject to airport-specific replacement and flyability rules and does not represent full fleet substitution.



3.3 Limits That Apply to All Results

The following limits apply throughout this report. They are stated once here and referred to elsewhere.

- The coupling of the design models needs refinement.** The WP5 optimisation used a VSPAero wing-and-strut aerodynamic representation supplemented by separate aircraft-level contributions, while the CFD/POD model includes the wing, strut, fuselage and nacelles, excludes the horizontal and vertical tails, and retains finite propeller loading. On the closest available component-consistent comparison, including the MDO fuselage parasite-drag contribution reduces the drag-coefficient difference to approximately 0.0068 at $C_L = 0.67$ and 0.0362 at $C_L = 1.17$. The remaining difference is strongly lift-dependent and reflects combined differences in aerodynamic fidelity, component representation and propulsion state; it should not be interpreted as an isolated error of the MDO model or corrected by a constant drag increment. The completed discipline models were not recoupled into a final optimisation, so absolute mission-performance results should be reassessed on a configuration-consistent baseline [11, §§4.2.1, 7.1.1].
- Validation is model-specific.** The CFD/POD aerodynamic surrogate [7, §3] and the optimisation's aerodynamic model are different models, so validation of one does not carry over to the other. The same applies to the electrical sizing, transient and optimisation models, and to the acoustic methods of different fidelity.
- Acoustic results use a single-event metric.** The full-scale results are numerical predictions from the DLR full-aircraft acoustic assessment. The reference INDIGO configuration is predicted to have propeller-tonal LAE approximately 6 dB(A) below the recorded A320 event, while the investigated 36° phase-offset case produces a further approximately 2 dB(A) reduction relative to the INDIGO reference configuration. A preliminary landing-gear contribution increases the propellers-only prediction by approximately 0.5 dB(A). DLR considers reduction deltas in LAE and EPNL to be comparable, while their absolute values are only approximately related, citing NASA CR-3406 [21]. The cited LAE–EPNL relationship is approximate and is qualified for cases where audible tones are not excessive. Comparable RIX EPNL reference values were not available for this assessment, so no matched EPNL comparison was performed.
- Fuel burned** below 900 m and source pollutant emissions are distinct metrics. Fuel burn is used in the aircraft-design and optimisation studies, whereas source-emission performance is assessed from pollutant-emission rates or integrated emitted masses for the corresponding operating cases.
- The air-quality chain rests on stated assumptions.** The airport studies use an aircraft performance model calibrated for Riga and transferred to the other airports, a hybridisation factor of 0.9 near the airport, and a POD-RBF correction model derived from paired RIX LES and AERMOD fields [12, §§7-8; 13, §1]. The correction is parameterised by wind direction, wind speed and average engine mass flow. Its reconstruction error is assessed pollutant by pollutant through leave-one-out analysis, with quantitative examples reported for CO. For application, the reconstructed correction is transferred from the RIX reference grid to the airport receptor grids and added to the AERMOD concentration field. For Dortmund, Madrid and Barcelona, the spatial transfer uses runway-relative coordinates normalised by runway length,

with a decaying extrapolation outside the region supported by the RIX reference pattern [12, §§7-8]. The quantitative airport results use the 14-snapshot RIX LES/AERMOD correction basis documented in D6.2, from which a 14-mode POD basis is constructed [13, §3.4.4]. The five-minute concentrations are project-specific averages rather than regulatory metrics, and NO_x results cannot be read as NO₂. For particulate matter, the WP6 low-fidelity workflow derives the INDIGO-aircraft PM emission rate from the RAMS Plus fuel-flow output using an A320 reference PM-to-fuel factor from the EEA/EMEP inventory, with the CFM56-5B4/P used as proxy. The resulting PM emission rate is supplied to the AERMOD dispersion workflow. D6.2 treats the PM indicator as PM_{2.5/10}, including volatile and non-volatile particulate matter, while black carbon is calculated and reported separately [13, §§3.3.2, 5.1].

- **Scenario inputs are not achievements.** Battery energy densities, traffic forecasts and fleet shares are assumptions used to explore outcomes. They show what the method can do, not the state of the technology or the market.

4. Development Roadmaps

Each line below starts from what INDIGO established, names the barrier to the next maturity step, and defines the gate that would justify further investment. Periods are indicative and can overlap; a programme owner would set detailed schedules, acceptance thresholds and validation standards. The five lines are brought together in §8.

4.1 Integrated DHEP-LARW Aircraft

Established. WP5 retained the INDi2 airframe as the fixed reference and used the TOPAZ framework, built on the open-source GEMSEO library, to re-optimize the powertrain, including propeller design. The single-trajectory campaign used the 1,000-nm reference mission, while the multi-trajectory campaign used selected Riga missions with the same fixed INDi2 airframe; the latter retained the 1,000-nm reference mission as a feasibility-only case. These studies generated the INDi3s and INDi3m powertrain branches rather than a redesigned airframe [11, §§4, 6]. The optimisation objective combined block fuel and fuel burned below 900 m, with fly-over EPNL limits of 75.5 and 77.5 EPNdB investigated.

Source emissions are evaluated separately from the fuel objective. The gas-turbine/combustion model provides CO, NO_x and UHC emission rates as a function of engine operating condition and integrates them over the mission, including the airport-vicinity segments below 900 m [11, §4.4; 12, §3]. Particulate matter is handled separately in the airport-emissions workflow described in §3.3.

Selected CFD and static-FSI studies provide configuration-specific checks of the aerodynamic assumptions. In the matched-lift RANS comparison, the effect of static flexibility on drag is negligible at the lower end of the verified range and reaches -4.43% at $C_L \approx 0.98$, corresponding to a +4.63% change in lift-to-drag ratio. These are aerodynamic sensitivities for the investigated conditions, not mission-fuel benefits [11, §7.2].

Barrier. The remaining system-level task is to reconcile the aerodynamic component definitions and propulsion states, recouple the completed discipline models and reassess mission performance. The diagnostic polar differences do not establish the magnitude or direction of a correction to the complete aircraft's fuel consumption (§3.3).



Next gate (2026-2028). Recouple the final aerodynamic, structural-mass and aeroelastic models with the mission and powertrain models on one versioned INDi2 baseline. Re-run the reference and Riga missions and report the change from the WP5 results in block fuel, fuel below 900 m, source pollutant emissions below 900 m, structural mass, lift-to-drag ratio, load margins and noise.

The decision is whether the design conclusions survive: a stable result supports the choice of demonstrators, while a material change reopens the architecture and powertrain trades. The lifting system was already optimised through twist and taper changes using VSPAero. Following establishment of the recoupled baseline, further development should investigate constrained, multipoint refinement of section shapes, fuselage and nacelle contours, and junction fairings. The CFD-identified shock, separation and interference features provide specific design targets rather than an established efficiency limit of the architecture. Candidate changes should be evaluated at mission-relevant lift, trim and propulsion states, checked by direct CFD and propagated through the aircraft power and mission models. Improvements from geometric redesign should be reported separately from changes caused by updating the analysis models. [11, §7.1.6]

Then (2028-2032). Wider high-fidelity assessment including off-design and failure cases, and selection of the subsystems that merit representative demonstration (§§4.2-4.4).

Users and route. Aircraft manufacturers' design and MDO teams, research institutes and collaborative aircraft-technology programmes such as Clean Aviation and Horizon Europe Cluster 5 [16; 17]. ZEUS is evaluating an INDIGO aircraft representation for future traffic scenarios [14]; this concerns the aircraft representation, not the complete design framework.

4.2 DHEP and Electrical Power System

Established. The architecture has four generators, four propulsion battery units and eight electric propulsion units [5, §9]. It was sized with the Strathclyde Systems Tool (SST), analysed for power flow and faults, and simulated in the time domain with MATLAB/Simulink models of generation, propulsion, battery and DC/DC conversion [4, §4; 5, §§8-9]. In the Riga sensitivity study the battery mass is 13.7-16.3 t out of a 79 t take-off mass. It rises with pack energy density because the optimiser shifts power from the turboshaft towards the battery [13, §4.1, Table 17]. The 400, 600 and 800 Wh/kg cases are battery-performance sensitivity scenarios and should not be interpreted as a year-by-year or TRL progression; the separate uncertainty-based technology outlook is summarised in §3.2.

Barrier. The sizing, transient and optimisation models answer different questions and were not merged. INDIGO did not demonstrate a physical electrical system, a complete thermal-management solution or integrated protection behaviour, and battery specific energy remains the dominant technology uncertainty.

Next gate (2026-2028). One integrated electrical assessment covering nominal, fault and extreme cases, with thermal, control and protection effects, using demand cycles from the recoupled missions (§4.1). Success means the component ratings meet explicit power, thermal and safety criteria agreed with an aircraft integrator. Any aerodynamic shape refinement should be assessed together with structural and installation constraints, so that gains from redesign are distinguished from changes caused only by higher-fidelity modelling.



Then (2028-2032). A representative powertrain rig testing the voltage and power architecture, protection, thermal transients and credible failures. A failed thermal or protection case would send the architecture back for redesign before any larger demonstrator.

Users and route. Electrical-system integrators, electrified-propulsion developers and aircraft manufacturers' system teams, for example through Clean Aviation hybrid-electric work [16]. Certification planning would follow EASA's special condition for electric and hybrid propulsion systems, SC E-19 [19].

4.3 Large-Aspect-Ratio Strut-Braced Wing

Established. The strut-braced wing was developed through beam and GFEM analysis, automated structural sizing with composite-manufacturing constraints, refinement of the wing-strut junction, landing-gear integration and a wing-mass surrogate for aircraft studies [7, §6]. The aeroelastic and loads framework covers trim, stability, manoeuvre and gust cases [7, §5]. Wing-box tip deflection stays below 3% of the semispan in the cases analysed [11, §7.2]. The complementary static-FSI verification indicates that aeroelastic effects remain of the order of a few percent in aerodynamic efficiency over the verified RANS range, but it covers selected conditions only and does not include coupled aircraft trim or free-flight inertia relief.

Barrier. Structural mass was held fixed during the optimisation (§3.3), and loads cover selected cases only. There is no physical correlation, fatigue or manufacturing validation. The span of about 51.4 m places the aircraft in ICAO aerodrome code D, whereas the A320 it would replace is code C (§7).

Next gate (2026-2028). Connect the GFEM mass response to the aircraft model within its valid range, extend the critical load cases, and test how junction stiffness, composite allowables, landing-gear loads and strut geometry affect mass and the span benefit. Assess folding wing tips or a shorter span against the aerodynamic benefit.

Then (2028-2032). A representative joint or substructure test, accepted when measured stiffness, load transfer and damage behaviour correlate with the model over a stated range.

Users and route. Airframe structural-design teams, aerostructures suppliers and research groups working on high-aspect-ratio wings.

4.4 Noise-Reduction Technologies

Established. Anechoic wind-tunnel tests on two-bladed 9-inch propellers at 12 m/s, 5,000-9,000 rpm (three speeds) and 0-15° wing angle of attack reduced the first blade-passing tone by about 12-15 dB at a 60° phase difference, and by roughly 7-32 dB at 90°, depending on observer position, advance ratio and angle of attack [11, §3.1]. For five-bladed propellers, closer to the aircraft design, measured directivity is not yet fully understood, and the hybrid RANS-CAA method at the current stage does not include the noise effects stemming from the geometrical imperfections of the model propellers and control system uncertainties [11, §3.2]. A multi-fidelity acoustic toolchain and an acoustic surrogate built from 144 simulations support design use [7, §4].

Barrier. The evidence covers a tonal mechanism at small scale. Installed broadband noise, control robustness and representative full-scale experimental validation remain open, while the full-scale phase-synchronisation result remains a numerical LAE prediction rather than a matched EPNL

assessment, because comparable RIX EPNL reference values were not available for this assessment (§3.3).

Next gate (2026-2028). A common benchmark, with the same propeller, installation, receivers and metric, used for both experiment and computation. It should include phase error under realistic motor dynamics, wing and strut scattering, and broadband terms, and should compute EPNL for INDIGO and the A320 on the same trajectory.

Then (2028-2032). An installed-source demonstration testing the phase-control loop, off-design operation and failures. If the benefit is confined to a narrow tonal condition, the route narrows to control research and design tools.

Users and route. Propeller and airframe acoustic designers, propeller manufacturers and aeroacoustic laboratories.

4.5 Greener Landing and Take-Off Operations

Established. D4.2 ranked candidate greener LTO procedures and assessed their feasibility at Riga, Dortmund, Madrid and Barcelona [9]. D6.2 then simulated 2035 traffic with increasing INDIGO shares, using RAMS fast-time simulation, AERMOD dispersion corrected with LES data, and Lden noise mapping, for operations below 3,000 ft [13, §§1-3]. Air-quality and population-above-55-dB(A)-Lden noise-exposure results for Riga, Dortmund, Madrid and Barcelona are summarised in §3.2.

Barrier. The DoA notes that safety, security and slot rules may leave little room to change LTO procedures [1, Part B §2.1.3]. The results depend on stated modelling assumptions (§3.3), and the slower cruise and larger span also affect traffic and gate use (§7). No aviation-authority consultation on the proposed LTO changes was undertaken within INDIGO; operational stakeholder and authority review therefore remains a subsequent maturation step.

Next gate (2026-2028). Build airport and ATM user cases with airports, air navigation service providers and airlines: select candidate procedures and test safety, separation, capacity and infrastructure alongside the environmental indicators, under common traffic and weather.

Then (2028-2032). Stakeholder-informed simulation at higher fidelity, extended to further airports, traffic states and weather. A trial would need responsible operational actors and approvals.

Users and route. Airports, air navigation service providers, airlines and environmental planners; the SESAR 3 innovation pipeline is the natural route to operational validation [18]. ZEUS is separately evaluating the INDIGO traffic-demand method for future fleet estimation [14]; that is reuse of a method, not adoption of an INDIGO procedure. Potential reuse of the greener-LTO assessment in ZEUS is under evaluation for airport use cases involving trajectory optimisation; if taken forward, this would provide a route for further stakeholder assessment.

5. Digital Tools and Methods

The DoA identifies the common development framework and the enhanced models for noise and pollutant emission and propagation as the INDIGO outputs closest to exploitation, with the LAQN model having the highest commercial potential [1, Part B §2.2.2]. Individual tools can be reused by research and engineering users while the aircraft itself remains at analytical proof-of-concept maturity. A tool described in a deliverable is not automatically a released software package: reuse



needs a defined version, inputs and outputs, dependencies, validity range, validation record and access terms. Table 4 groups the tools by family.

Table 4 - Digital tools: what was demonstrated and the next step for reuse

Tool family (KERs)	Demonstrated in INDIGO	Next step for reuse
Aircraft definition and performance (KER-01, KER-09)	CPACS reference and baseline aircraft [3; 6]; INDi2 performance, mass, centre-of-gravity and inertia model [7, §§6.9, 7].	Versioned INDi2 data set with configuration lineage; support the ZEUS evaluation of the aircraft representation [14].
Design optimisation and uncertainty (KER-02, KER-03)	TOPAZ framework on GEMSEO for deterministic, uncertainty-based and multi-trajectory studies; Dempster-Shafer method linking technology maturity to performance uncertainty [10; 11, §§4-6].	Reproducible package with worked examples; test how results depend on the expert-set uncertainty inputs.
Aerodynamics (KER-06)	RANS/POD surrogates for cruise and two low-speed regimes, with out-of-sample and leave-one-out checks; actuator-disc and actuator-line propeller models [7, §3]. The responsible partner assesses the high-fidelity aerodynamic modelling capability at TRL 7 and the lower-fidelity aerodynamic modelling capability at TRL 3; these are tool-level maturity assessments and are distinct from the TRL of the integrated DHEP-LARW aircraft.	Document the validity range of each aerodynamic representation by operating regime, component set and propulsion state, and use a configuration-consistent baseline when reintegrating the models into aircraft design studies.
Structures and aeroelasticity (KER-07, KER-08)	Coupled aeroelastic, flight-dynamics and loads framework; automated GFEM sizing workflow and wing-mass surrogate [7, §§5-6].	Interface specification and benchmark load cases, keeping the D3.2 loads/aeroelastic framework and the D5.2 static-FSI verification as distinct but complementary evidence.
Propulsion and EPS (KER-10, KER-14, KER-15, KER-16)	Gas-turbine and chemical-reactor-network emission model checked against ICAO data for the CFM56-7B27 and integrated with the aircraft mission/MDO chain to provide fuel flow, CO/NOx/UHC emission rates and mission-integrated emitted masses; SST sizing and EPS surrogate; MATLAB/Simulink transient models; propeller performance maps from the TUBS tool [4; 5; 11, §§4.3.4-4.4; 12, §3].	Component-level packages with separate access terms. For KER-16, the performance-map database and efficiency surrogate use a pre-existing TUBS BEMT model; access is currently consortium-only.
Aeroacoustics and NRT (KER-04, KER-05)	Phase-synchronisation data set and control method; multi-fidelity toolchain (UBR, DLR) and acoustic surrogate [7, §4; 11, §3].	Common-case benchmark data set; uncertainty statement for lower-fidelity tools.
Traffic and greener LTO (KER-11, KER-18)	2035 traffic forecasts, INDIGO fleet-injection rules and RAMS scenarios for four airports; LTO procedure ranking and feasibility method [9; 13, §2].	Reproducible airport-scenario definition; support the ZEUS evaluation of the traffic-demand method [14].
Air quality, noise and health (KER-12, KER-13, KER-17, KER-19)	AERMOD air-quality and Lden workflow; Alya LES of plume dispersion (Alya is BSC background); LES-AERMOD data-fusion correction; BenMAP-CE health and economic workflow [12; 13, §3].	Versioned workflow linking data, correction-model version and units; independent tests at other airports. CRIDA reports that the method transfers to other airports but that the project code needs adaptation, because the INDIGO implementation included grid extension and other case-specific work [15].

6. Exploitation and Continuation

6.1 Exploitation Routes and Users

The DoA targets aircraft integrators (for example Airbus and Leonardo), engine manufacturers (for example Safran and Rolls-Royce), airport operators and civil aviation regulators such as EASA and ICAO [1, Part B §2.2.2]. It also recognises that INDIGO is a low-TRL project for which immediate commercial exploitation is difficult. The realistic routes are:

- **Further research:** methods, models and data used in follow-on projects, theses and courses, including use by the originating partner outside the INDIGO tasks.



- **Integration in another project's tools:** as in the ZEUS evaluation (§6.3).
- **Industrial studies:** use of the design framework or data by aircraft, propulsion or airport stakeholders for their own benchmarking, as the DoA anticipated.
- **Open release:** selected publications, data and other public outputs are deposited through the project's open repositories, including Zenodo; software and model releases are handled at result level, subject to the ownership, background-IP and licensing conditions of each KER (§6.4).
- **Future collaborative programmes:** Clean Aviation for aircraft and subsystem demonstrators, Horizon Europe Cluster 5 for design and environmental studies, and SESAR 3 for airport and ATM validation [16-18]. These are candidate programmes, not confirmed funding.

Dissemination alone does not count as exploitation here. A route is reported as active only when the asset, the user and the activity can be named.

6.2 Key Exploitable Results

Table 5 summarises the 19 key exploitable results identified through the project and partner review. For each result it records the asset, ownership and access basis, use beyond INDIGO to date and the next exploitation step. Methodological reuse is distinguished from validation of application-specific quantitative outputs; in particular, exploitation of the health and economic impact workflow does not by itself validate individual health or monetary estimates.



Table 5 - Key exploitable results and exploitation status.

KER	Asset, form and source	Partner(s)	Ownership and access	Use beyond the INDIGO tasks so far	Next step and indicative horizon
KER-01	Reference (A320) and IND1 baseline aircraft concepts in CPACS format. Form: aircraft data package (CPACS). Source: D1.1; D3.1.	UC3M, DLR	Owner(s): All consortium Background IP used: DLR: CPACS datasets and processes, IMMIS+ tool Access: open results shared in Zenodo.	UC3M: BSc and MSc theses on aeroelastic response. DLR: in-house use of the revised IMMIS+ tool	Maintain the A320/IND1 CPACS package as an open reference asset. ZEUS is evaluating an INDIGO hybrid-aircraft representation for future traffic scenarios at result-family level; no specific reuse of KER-01 has yet been confirmed.
KER-02	Dempster-Shafer method linking technology maturity to performance uncertainty, conditional sampler (Python) and battery belief-mass table for 2026-2040. Form: method, code and dataset. Source: D5.1; D5.2 §5.	CIRA	Owner(s): CIRA Background IP / provenance: CIRA pre-existing UMRIDA/UTOPIAE background, as previously identified by CIRA. Access: consortium only.	CIRA reports use in Master and PhD theses, industrial projects and internal framework-development activities.	Research proposals and internal framework development during 2027-2030, involving potential collaboration with BSC, UC3M, Airbus, Leonardo and IC.
KER-03	MOTIVATION and TOPAZ multidisciplinary analysis and optimisation framework (built on the open-source OpenMDAO and GEMSEO library, respectively), including the uncertainty-based (UMDO) workflow and multi-trajectory formulation. Form: software framework. Source: D5.2 §4-6.	UC3M/BSC, CIRA	Owner(s): UC3M (MOTIVATION), BSC (MOTIVATION, TOPAZ), CIRA (UMDO layer) Background IP used: MOTIVATION and TOPAZ were pre-existing platforms adapted during INDIGO; the epistemic-uncertainty UMDO layer builds on developments from UMRIDA and UTOPIAE. Access: only owners	MOTIVATION was used in the Clean Aviation ODE4HERA project (01/2024-12/2026). Because MOTIVATION pre-dates INDIGO, this is external use of a platform also adapted within INDIGO, rather than reuse of the complete INDIGO KER-03 foreground.	Continued research use and development of the MDAO/UMDO frameworks is envisaged; specific post-project exploitation of the INDIGO-developed UMDO layer is not yet committed.



KER	Asset, form and source	Partner(s)	Ownership and access	Use beyond the INDIGO tasks so far	Next step and indicative horizon
KER-04	Phase-synchronisation control method for distributed propellers and anechoic wind-tunnel dataset (twin propellers with wing, 2- and 5-bladed). Form: method and experimental dataset. Source: D5.2 §3.1; D3.2 §4.4.1.	UBR	Owner(s): UBR Background IP used: UBR in-house-built phase-control program and PNWT wind-tunnel facility. Access: on request	PhD research/thesis, University of Bristol - phase-synchronized propeller experiments used for investigation of DEP-wing configurations at different angles of attack and overlapping-propeller configurations (ongoing, 2026-2027). The technique is currently used in projects involving industry partners and has been included in funding proposals.	Post-processing and further analysis of the experimental dataset for PhD research/thesis and journal publications (2026-2027). Potential extension to three-propeller phase locking in future projects. The technique will be used in future collaborations with industry and grant proposals (2027-2030).



KER	Asset, form and source	Partner(s)	Ownership and access	Use beyond the INDIGO tasks so far	Next step and indicative horizon
KER-05	Multi-fidelity aeroacoustic toolchain (UBR VLM/VPM + FW-H; DLR hybrid RANS-CAA; LBM/VLES) and aeroacoustic surrogate for optimisation built from 144 simulations. Form: methods, software and surrogate dataset. Source: D3.2 §4; D5.2 §4.4.	UBR, DLR	Owner(s): UBR and DLR, per module. Background IP / dependencies: UBR: pre-existing numerical tools/software supporting the VLM/VPM + FW-H workflow; third-party commercial software including PowerFLOW (LBM/VLES). DLR: PIANO-IBM, FWH-NEXT and IMMIS+ solvers. Access: UBR: on request. DLR tools are not open access; DLR-provided surrogate-model results are openly accessible.	PhD research/thesis, University of Bristol - numerical investigation of installed propeller aeroacoustics using the UBR VLM/VPM + FW-H workflow and LBM/VLES (PowerFLOW) methodology (ongoing; LBM/VLES application included in a joint UBR-DLR AIAA Aviation 2025 study). DLR: current use of the relevant tools in national research projects.	UBR: Continued use and development of the UBR VLM/VPM + FW-H numerical aeroacoustic workflow within ongoing PhD research, including installed-propeller synchrophasing and angle-of-attack investigations (2026-2027). The use of the new methods for collaboration with industry and grant proposals (2027-2030). DLR: further reuse of the INDIGO IMMIS+ extension is ongoing



KER	Asset, form and source	Partner(s)	Ownership and access	Use beyond the INDIGO tasks so far	Next step and indicative horizon
KER-06	CFD-based (RANS/POD) aerodynamic surrogate for cruise and low-speed regimes, with actuator-disc and actuator-line propeller models. Form: reduced-order model and CFD dataset. Source: D3.2 §3; D5.2 §7.1.	UST (lead), DLR	Owner(s): UST and DLR, for their respective contributions. Background / dependencies: UST: SU2 with the actuator-line implementation used in INDIGO and the UST POD-RBF code. DLR: meshing and CFD processes. Access: UST plans open-source release via GitHub of the SU2 actuator-line implementation in Q1 2027 and the POD-RBF code in Q2 2027. DLR CFD results: consortium only.	UST: none confirmed. DLR: the actuator-disc trim method implemented in FSDLRControl for operation with TAU is already used by DLR colleagues in other in-house projects; this applies to that specific method, not to the complete KER-06 package.	UST: planned open-source releases in Q1/Q2 2027. DLR: not decided.
KER-07	Coupled aeroelastic, flight-dynamics and loads framework (trim, stability, manoeuvre and gust loads). Form: software. Source: D3.2 §5.	UC3M & BSC	Owner(s): UC3M and BSC Background IP / dependencies: pre-existing aeroelastic and loads-analysis framework of the owners, adapted and extended within INDIGO for the INDi2 DHEP-LARW configuration. Access: owners only.	None confirmed.	Package the framework with configuration-consistent interfaces and benchmark load cases for reuse in future aeroelastic, flight-dynamics and loads studies; indicative horizon 2026-2028.
KER-08	Automated GFEM structural sizing workflow for the strut-braced wing and wing-mass surrogate. Form: workflow and surrogate model. Source: D3.2 §6; D5.2 §4.2.1.	UC3M	Owner(s): UC3M Background IP used: none Access: only owner	UC3M reused the automated GFEM structural-modelling and sizing methodology developed in INDIGO in the CETACEO project with Airbus.	Recouple the GFEM-derived structural-mass response with the aircraft/MDO model and extend the structural assessment to additional load cases and manufacturing constraints; indicative horizon 2026-2028.



KER	Asset, form and source	Partner(s)	Ownership and access	Use beyond the INDIGO tasks so far	Next step and indicative horizon
KER-09	DHEP-LARW aircraft performance model and full-aircraft mass, CG and inertia model. Form: model. Source: D3.2 §6.9 and §7.	UC3M, BSC, RUB, TUBS, UST	Owner(s): UC3M, BSC, TUBS, UST, RUB Background IP used: UST, RUB and TUBS background for the powertrain (electric, combustion chamber, gas turbine, propellers, etc, sizing). UC3M & BSC Background in overall aircraft design and optimization Access: on request	None yet	Potential continuation route: ZEUS (SESAR 3 project) is evaluating an INDIGO hybrid-aircraft representation for use in future traffic scenarios. The exact representation/version has not yet been selected; this therefore does not constitute confirmed reuse of the complete KER-09 model.
KER-10	Gas-turbine performance and combustion-emission model (chemical reactor network, SAF and Jet A), checked against ICAO data for the CFM56-7B27 and integrated in the aircraft mission/MDO chain to provide fuel flow, CO/NOx/UHC emission rates and mission-integrated emitted masses. Form: model and look-up database. Source: D2.1 §2; D2.2 §§4-5; D5.2 §§4.3.4-4.4; D6.1 §3.	RUB, TUBS	Owner(s): RUB: combustion-emission model TUBS: gas-turbine performance model Background IP / dependencies: RUB: pre-existing combustor CAD/model originating from the MYTHOS project (grant agreement 101096286). TUBS - pre-existing gas-turbine performance model. Access: RUB: emission-model lookup database: consortium only. TUBS: gas-turbine performance ROM: consortium only	RUB: no implemented use of the INDIGO KER-10 foreground specifically confirmed; the underlying combustor CAD/model is also used in MYTHOS (Horizon Europe Grant No. 101096286). TUBS - none yet.	RUB: national consortium planned for 2028/29 and potential Horizon Europe opportunities in 2028-2034. TUBS: not decided.



KER	Asset, form and source	Partner(s)	Ownership and access	Use beyond the INDIGO tasks so far	Next step and indicative horizon
KER-11	Traffic forecasts to 2035, INDIGO fleet-injection rules and RAMS fast-time scenario datasets for Riga, Dortmund, Madrid and Barcelona. Form: datasets and workflow. Source: D4.2; D6.2 §2.	CRIDA (lead), RIX	Owner(s): CRIDA; RIX for Riga data. Background / dependencies: STATFOR traffic data, supplemented with ENAIRE data for MAD and BCN and partner/airport data for RIX and DTM; INDIGO fleet rules developed in-house; RAMS FTS used under the applicable ISA Software licence; modelling and simulation performed in-house. Access: traffic data consortium only; fleet rules open as described in D4.2; RAMS scenarios consortium only.	None implemented yet No implemented reuse in ZEUS is confirmed yet. The WP4 traffic-demand method/model is being evaluated for future fleet-estimation scenarios.	ZEUS (SESAR 2025 ER3 WA2.2) is evaluating reuse of the WP4 traffic-demand method/model for future fleet estimation and whether the WP6 RAMS scenarios should be adapted for ZEUS airport use cases. Indicative horizon: from 2026 onwards.
KER-12	Low-fidelity LAQ and noise assessment workflow: RAMS trajectories to AERMOD dispersion; Lden and population-exposure maps. Form: workflow and scripts. Source: D6.1 §2-4; D6.2 §3.3 and §3.5.2.	CRIDA	Owner(s): CRIDA Background IP used: RAMS-to-AERMOD workflow developed in-house; low-fidelity noise-assessment method developed in-house. Access: consortium only for both workflow components.	None yet	Not decided.



KER	Asset, form and source	Partner(s)	Ownership and access	Use beyond the INDIGO tasks so far	Next step and indicative horizon
KER-13	LES-AERMOD data-fusion correction (POD-based reduced-order model) with qualitative and quantitative confidence indicators. Form: method and code. Source: D6.1 §7; D6.2 §3.4.	UST (lead), BSC, CRIDA	Owner(s): UST for the POD-RBF code; BSC for the INDIGO-specific LES datasets generated by BSC. CRIDA acts as application/user of the correction workflow and does not claim ownership of the METAR input data. Background IP / dependencies: UST POD-RBF code; AERMOD is open source; Alya / ALYA AS is BSC Background, and commercial use of ALYA AS or derivative works requires a commercial licence under BSC licence terms. The data-fusion methodology is documented in D6.1 and is not integrated into the POD-RBF code. Access: the data-fusion methodology is open as described in D6.1. UST plans an open-source release of the POD-RBF code via GitHub in Q2 2027. BSC-generated INDIGO datasets are available on request; access to Alya / ALYA AS follows the applicable BSC licence terms.	None yet	Data-fusion application: not decided. UST: POD-RBF code open-source release planned for Q2 2027 via GitHub.



KER	Asset, form and source	Partner(s)	Ownership and access	Use beyond the INDIGO tasks so far	Next step and indicative horizon
KER-14	Strathclyde Systems Tool (SST) for EPS architecture sizing, and EPS mass and efficiency surrogate used in the MDO. Form: software and surrogate. Source: D2.1 §4.2-4.4; D2.2 §8; D5.2 §4.3.4.	UST	Owner(s): UST. Background IP used: UST's pre-existing in-house Strathclyde Systems Tool (SST), originating from a UK national project and extended within INDIGO for EPS architecture assessment. Access: not decided.	UST reports course and in-house use	not decided
KER-15	EPS transient models in MATLAB/Simulink (generation, propulsion, battery and DC/DC converter; failure modes). Form: models. Source: D2.1 §4.5; D2.2 §9.	UST	Owner(s): UST. Background IP used: pre-existing UST electrical-power-system transient models / Modular Transient Modelling capability developed through in-house funding and adapted for the INDIGO EPS architecture. Access: not decided.	None yet	Not decided
KER-16	Propeller performance-map database and efficiency surrogate generated with a BEMT tool. Form: database and interface. Source: D2.2 §6; D5.2 §4.3.4.	TUBS	Owner(s): TUBS Background IP used: TUBS BEMT in-house model Access: consortium only	None yet	Not decided



KER	Asset, form and source	Partner(s)	Ownership and access	Use beyond the INDIGO tasks so far	Next step and indicative horizon
KER-17	Alya large-eddy simulation methodology for aircraft-plume dispersion at airport scale, with precursor databases. Form: method and datasets (Alya is BSC background). Source: D6.1 §5; D6.2 §3.2.	BSC	Owner(s): BSC Background IP used: Alya / ALYA AS is BSC Background; commercial use of ALYA AS or derivative works requires a commercial licence under BSC licence terms. Access to the INDIGO-specific method/datasets: on request; access to the Alya background follows the applicable BSC licence terms.	PhD Thesis	PhD thesis in 2027; possible future EU projects beyond 2027
KER-18	Greener-LTO procedure ranking and feasibility method and results for the four airports. Form: method and datasets. Source: D4.2.	CRIDA	Owner(s): CRIDA Background IP used: greener-LTO procedure-selection method developed in-house. Access: method open as described in D4.2; datasets consortium only.	None implemented yet	Potential reuse in ZEUS for trajectory optimisation of new entrants in airport use cases is under evaluation; if taken forward, indicative horizon 2027.
KER-19	Health and economic impact workflow: dispersion outputs processed for BenMAP-CE, selection of concentration-response functions, valuation using the value of a statistical life. Form: workflow. Source: D6.2 §3.6.	CRIDA	Owner(s): CRIDA Background / dependencies: BenMAP-CE is an external open-source health-impact tool; the INDIGO health/economic assessment workflow and methodology were developed in-house by CRIDA. Access: method open as described in D6.2.	None yet	Not decided



6.3 Continuation Already Under Way

DLR reports a concrete case of use beyond the INDIGO tasks: the actuator-disk trim method developed in WP3 within the FSDLRControl/TAU workflow is already used by other DLR colleagues in other in-house projects [15]. This demonstrated uptake applies to that specific method and does not imply reuse of the complete KER-06 aerodynamic package or external adoption. DLR also reports that the hierarchically refined Cartesian-grid approach used in INDIGO for installed full-scale propeller-noise prediction is already being reused in national research activities and is planned for further use in Horizon Europe 2027 Cluster 5 activities [15].

The MDAO framework also has a confirmed route of use beyond the INDIGO tasks. The pre-existing MOTIVATION platform, which was adapted within INDIGO, was used in the Clean Aviation ODE4HERA project during 2024-2026. This demonstrates external use of the platform but should not be interpreted as uptake of the complete INDIGO KER-03 foreground or of the CIRA UMDO layer. Earlier ELECTRO and HYDROGENATING activities form part of the development provenance of MOTIVATION and TOPAZ, respectively, rather than exploitation of INDIGO-generated results [15].

UC3M also reports reuse of the automated GFEM structural-modelling and sizing methodology developed in INDIGO in the CETACEO project with Airbus, providing a concrete case of application of the structural-design capability beyond the INDIGO tasks [15].

UST also reports two follow-on collaborations with TUBS arising from the partnership established through INDIGO: a Scottish Government International Collaboration Fund activity on propulsive-powertrain design methodologies in November 2024, and the Volkswagen Foundation Scotland-Lower Saxony Excellence Track II project STRIDE, awarded in November 2025, on robust integrated design of electrical propulsion power trains. These activities represent continuation of the collaboration established through INDIGO rather than confirmed reuse of specific INDIGO models or KERs [15].

Separately, ZEUS (grant agreement 101286802) is evaluating two INDIGO results: an INDIGO hybrid-aircraft representation as a possible entrant in future traffic scenarios, and the WP4 traffic-demand method for future fleet estimation [14]. Both depend on the outcome of the ZEUS evaluation. Neither implies reuse of the complete design framework or adoption of INDIGO LTO procedures.

6.4 Ownership, Access and Open Release

Under the Consortium Agreement, Results are owned by the Party that generates them; jointly generated Results are subject to the applicable joint-ownership provisions. Access Rights to Results or Background that are Needed for exploitation of a Party's own Results are granted on Fair and Reasonable conditions, while access to Results for internal research and teaching is royalty-free [2, §§8-9]. Requests for Access Rights must be made in writing and may be subject to conditions concerning purpose and confidentiality; Access Rights to software do not automatically include source code, a particular platform port or documentation in a specified form.

D7.4 therefore treats ownership, background dependencies and access at result level rather than assigning a single project-wide licence. Table 5 records the partner-confirmed basis for each KER. The DoA envisaged a common GitHub-based development environment, but implementation evolved towards result-specific repositories and access arrangements. Public dissemination or



deposit in a repository does not by itself establish software or model release, sublicensing rights or commercial access. For Alya, the Consortium Agreement identifies the solver as BSC Background; commercial use of ALYA AS or derivative works requires a commercial licence.

For KER-13, the data-fusion methodology is openly described in D6.1; UST plans an open-source release of the POD-RBF code via GitHub in Q2 2027, while the BSC-generated INDIGO datasets are available on request. For KER-17, the INDIGO-specific method and datasets are available on request, while use of Alya / ALYA AS remains governed by the applicable BSC licence terms [15].

Project results are preserved through the issued deliverables, public dissemination outputs and result-specific repositories and access arrangements.

6.5 Stakeholder Feedback

The INDIGO Advisory Board brings together representatives of Airbus Defence and Space, Safran Electrical & Power, Dowty Propellers, the Airport Regions Council and Politecnico di Milano [1, Part B §3.2.4 and Table 15]. The DoA established the Board as a direct interface with industrial, airport/community and academic stakeholders and envisaged its participation in project workshops, reviews and assessment of progress. Feedback from Advisory Board representatives during project meetings informed two continuation directions: Airport Regions Council highlighted HORIZON-CL5-2027-03-D5-20 as a relevant route for continuing INDIGO's airport LAQ/noise work, while Airbus Defence and Space expressed interest in further work on DEP loads, flight dynamics and aeroelasticity through future Clean Aviation activities building on HERA. These inputs are stakeholder recommendations and expressions of interest; they do not constitute Advisory Board endorsement or commitments to fund or undertake the proposed work.

7. Barriers and Enabling Conditions

The DoA identified four barriers to adoption [1, Part B §2.1.3]. INDIGO's results now allow each to be stated more precisely (Table 6).

Table 6 - DoA barriers: what INDIGO shows and what must be decided next

Barrier (DoA)	What INDIGO shows	Next evidence or decision	Actors
Lower cruise speed	INDi2 cruises at Mach 0.6 at 8,000 m [11, §4], against about Mach 0.78 for current medium-range jets. Longer flights mean more aircraft airborne at once and more ATM demand.	Same-mission trade of block time, fleet and ATM demand against fuel, emissions and noise.	Aircraft manufacturers, airlines, network and ATM planners
Competing energy carriers (hydrogen)	INDIGO assessed battery-fuel hybrid propulsion only; battery mass is 13.7-16.3 t of a 79 t take-off mass in the Riga study [13, Table 17]. The DoA notes that the digital method could be adapted to other carriers.	Comparable mission studies for battery, SAF and hydrogen options, updated as the technologies mature.	Propulsion and EPS developers; programme planners
Wingspan at current airports	A span of about 51.4 m is ICAO code D (36 m up to 52 m); the A320 is code C (24 m up to 36 m) [20]. Meeting code C would need about 7.7 m folded on each side.	Gate, taxiway and stand compatibility study; folding tips or a shorter span traded against the aerodynamic benefit.	Airframe manufacturers; airports
Freedom to change LTO procedures	The airport studies assume procedure changes and a 0.9 hybridisation factor near the airport [13, §1]; no safety or capacity case was assessed.	Safety, separation, capacity and procedure feasibility on real airport and ATM cases before any trial.	Air navigation service providers, airports, airlines, authorities

Further maturity also depends on certification-oriented evidence that INDIGO did not set out to produce: high-voltage, thermal and failure safety of the electrical system, for which EASA's special condition SC E-19 is the relevant framework [19]; structural substantiation of the strut-braced wing; and community-noise assessment in certification metrics. For airport air quality, comparison with limit values requires the exact pollutant, metric and averaging period; in particular, modelled NO_x cannot be compared directly with NO₂ limits.

8. Consolidated Roadmap and Recommendations

8.1 Ranked Priorities

The ranking reflects what to do first with finite resources if the goal is to develop the integrated aircraft. Recoupling comes first because its result can change the case for every subsystem demonstration. Packaging digital tools runs in parallel because it has its own users and does not depend on hardware; for a partner interested only in reusing a method, that route can come first. The recoupled baseline should first be assessed at unchanged geometry, with consistent aerodynamic component accounting, propulsion state and trim. Subsequent aerodynamic refinement can then target the shock, separation and interference features identified by CFD, so that gains from redesign are distinguished from changes caused only by higher-fidelity modelling. [11, §§7.1.1, 7.1.6]

Table 7 - Ranked development priorities

Rank	Priority and gate	Why this rank	Indicative contributors
1	Recouple the INDi2 models and reassess design, mission and environmental results	Decides whether subsystem benefits survive structural and aerodynamic feedback and off-design cases	UC3M/BSC, CIRA, UST, DLR
Parallel	Package selected KERs and complete the ZEUS evaluations	Shorter route to use; independent of hardware	KER owners
2	Integrate EPS thermal, protection and fault behaviour, then a representative rig	Safety and power feasibility gate for aircraft integration	UST
3	Substantiate wing loads, junctions and manufacturing; substructure test; span solution	Mass, strength and airport compatibility decide airframe viability	UC3M/BSC
4	Validate installed NRT benefit and phase-control robustness; compute matched EPNL	The tonal benefit must survive broadband, installation and operating effects	UBR, DLR
5	Airport and ATM stakeholder simulation before any LTO trial	An environmental ranking alone cannot show that an operation is safe or feasible	CRIDA

The contributors identified in Table 7 are indicative, based on the technical roles and capabilities developed in INDIGO. They identify relevant actors for the proposed next steps and do not constitute commitments to undertake, fund or lead post-project activities.

8.2 Timeline and Decision Gates

Figure 1 places the priorities on a time axis. Gate 1, around 2028, closes the baseline work and decides which demonstrations proceed. Gate 2, around 2032, decides whether any line moves towards aircraft-level integration or an operational trial. Each line can stop, narrow or change direction at a gate. The dates are planning periods, not partner commitments.

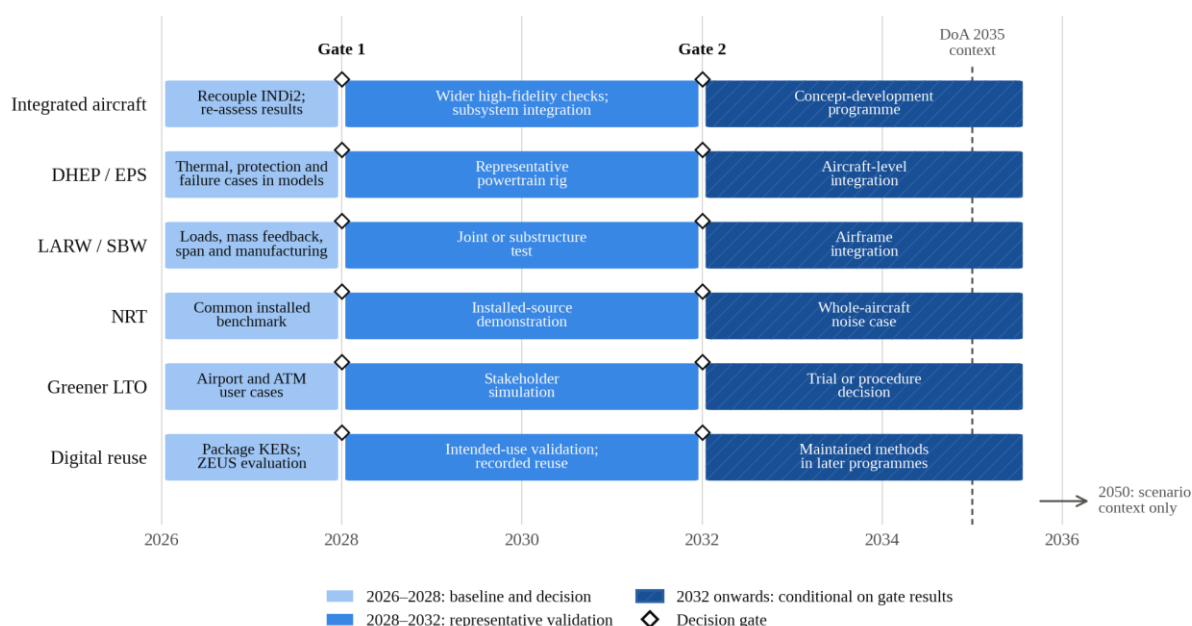


Figure 1 - Indicative roadmap with decision gates. Work after 2032 depends on gate outcomes; 2050 is scenario context, not an entry-into-service date.

8.3 Decisions Required Now

- Select the common INDi2 configuration and mission cases for recoupling, and name the responsible discipline contacts. Define the common aerodynamic component build-up, propulsion state and trim assumptions for that baseline before comparing model fidelities or assessing redesign options.
- Using the partner responses in Table 5, select the first KERs to package, each with a named user, owner and access terms, rather than treating all tools as equally ready for reuse.
- Agree how the ZEUS evaluations will be supported and how their outcome will be recorded.
- Identify candidate calls in Clean Aviation, Horizon Europe Cluster 5 and SESAR 3 for the 2028-2032 demonstrations; eligibility and consortium are decided call by call [16-18].

9. Conclusions

INDIGO developed a medium-range DHEP-LARW aircraft concept to analytical proof-of-concept level and linked its digital assessment to noise and air-quality studies at European airports.

The evidence supports an end-of-project TRL 3 assessment for the integrated DHEP-LARW concept. For phase synchronisation, the PNWT laboratory evidence supports TRL 4 for the investigated experimental configurations. The full-scale 36° case is a separate numerical assessment and is not the basis for the TRL-4 assignment.

In the SOL40 2035 scenarios, modelled local-air-quality indicators improve at all four airports, with four-airport reductions ranging from approximately 36-60% for CO, 50-66% for HC, 20-53% for daily-mean NO_x, 9-39% for maximum-hourly NO_x, 20-60% for PM and 29-61% for black carbon. Population exposed above 55 dB(A) Lden decreases by 45-81% across the four airports. These results support substantial airport-level environmental benefits while remaining metric- and airport-specific rather than constituting one composite LAQN percentage.



The full-scale numerical noise assessment predicts approximately 6 dB(A) lower propeller-tonal LAE for the reference INDIGO configuration than for the recorded A320 event. Applying the investigated 36° phase offset produces a further approximately 2 dB(A) reduction relative to the INDIGO reference configuration. DLR considers LAE and EPNL reduction deltas to be comparable, citing NASA CR-3406 [21]. Comparable RIX EPNL reference values were not available for this assessment, so no matched EPNL comparison was performed. On this basis, the LAE reduction results provide indirect verification of the DoA 6–8 EPNdB reduction ambition.

The next investment should be the recoupling of the discipline models into one aircraft baseline, because its result decides which of the electrical, structural, acoustic and operational demonstrations are worth funding. Digital tools offer a nearer-term route to use, provided their owners define packages and access terms. DLR already reports internal reuse of the WP3 actuator-disk trim method beyond the INDIGO tasks. DLR also reports that the hierarchically refined Cartesian-grid approach used in INDIGO for installed full-scale propeller-noise prediction is already being reused in national research activities and is planned for further use in Horizon Europe 2027 Cluster 5 activities [15]. ZEUS is evaluating reuse of the aircraft representation and traffic-demand method.

The timeline is indicative. It calls for specific decisions and evidence at two gates, around 2028 and 2032, and does not imply funded activity, certification, operational approval or entry into service.

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