Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Environmental-impact assessments at airport level of Clean Sky 2 technologies

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Abstract. GREENPORT2050 is a project within Clean Sky 2 Technology Evaluator. Its objective is to assess the environmental impact up to 2050 at airport level of technologies developed in the Clean Sky 2 Programme for fixed-wing aircraft. With these assessments, it complements the environmental-impact assessments of those technologies at the other two levels in Clean Sky 2 Technology Evaluator: aircraft and air-transport system level. This paper provides an overview of the systematic approach for airport-level assessments in GREENPORT2050 and of the indicators to quantify impacts in these assessments.

1. Introduction

Set up in 2014, the Clean Sky 2 Programme aims to develop cleaner air transport technologies for earliest possible deployment. That means integrating, demonstrating and validating technologies capable of reducing CO_2, NO_X and noise emissions by 20% to 30% compared to 'state-of-the-art' aircraft entering into service as from 2014 (cf. Article 2 in [8]). These technologies are mainly developed in Clean Sky 2's Innovative Aircraft Demonstrator Platforms (IADPs) and Integrated Technology Demonstrators (ITDs). IADPs operate demonstrators at vehicle level for large passenger aircraft, regional aircraft, and rotorcraft. ITDs use demonstrators at system level with respect to airframe, engine, and systems. The key demonstrators are depicted in Figure 1.

Cross-positioned in the programme, Clean Sky 2 established for its entire duration an independent technology evaluator, called: Technology Evaluator (TE). The TE's main task (cf. Article 12 in Annex I to [8]) is to monitor and assess the environmental and societal impact of the technological results arising from individual IADPs and ITDs across all Clean Sky 2 activities. More specifically, TE aims to quantify the expected improvements on the overall noise, greenhouse-gas and air pollutants emissions from the aviation sector in future scenarios in comparison to baseline scenarios.

Rather than assessing the impact of individual Clean Sky 2 technology bricks, TE assesses the impact of these innovative technologies, when integrated into concept aircraft. Clean Sky 2 concept aircraft are defined by IADPs and ITDs. TE then assesses the environmental impact of those concept aircraft in terms of noise, CO_2 and NO_X emissions at three complementary levels:

- Aircraft level: Compare the environmental impact of a Clean Sky 2 concept aircraft on relevant missions with that of its reference-technology counterpart. These comparisons constitute the basis to evaluate the level of success towards the Clean Sky 2 environmental goals.
- Airport level: Compare the environmental impact at representative European airports for a typical day for a fleet with and without Clean Sky 2 concept aircraft.

- Air-transport system level: Compare the environmental impact at global scale for a year for a fleet with and without Clean Sky 2 concept aircraft.

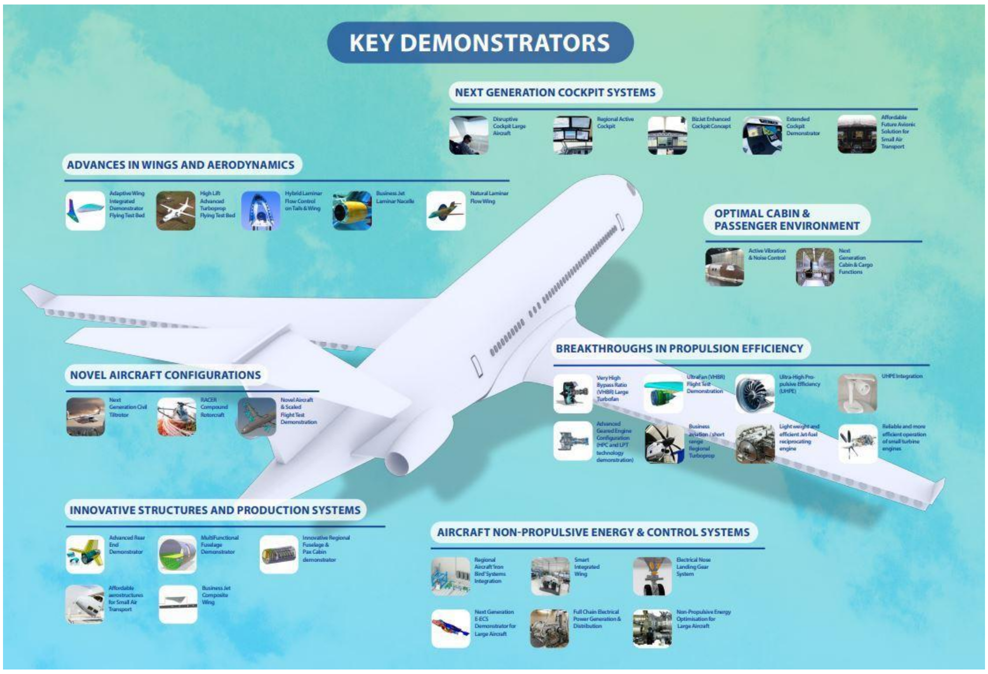

Figure 1. Clean Sky 2 key demonstrators [Source: `www.clean-aviation.eu`].

In Clean Sky 2, there are two full assessment cycles. TE completed the first of these cycles in 2020, with assessment results reported in the public documents [2]. The second full assessment cycle is planned to be completed by end of 2023 and reported by mid-2024, at programme closure.

Thus, there are also two assessment cycles at airport level. For technologies developed for fixed-wing aircraft, both are carried out by Royal NLR – Netherlands Aerospace Centre in two successive Clean Sky 2 TE projects. These projects are ‘Clean Sky 2 – Airport Environmental Impact Assessments for Fixed-wing Aircraft’ (CLAIRPORT – 2017-2021; [1]) and ‘Clean Sky 2 Technologies for Greener Airports by 2050’ (GREENPORT2050 – 2021-2023; [10]), respectively.

This paper provides an overview of the assessment approach taken in GREENPORT2050, together with the indicators emerging from it. Being CLAIRPORT’s successor, GREENPORT2050 naturally capitalises on the systematic and credible approach successfully applied in CLAIRPORT (cf. [4]).

2. Approach to airport-level assessments

GREENPORT2050 provides the airport-level contribution for fixed-wing aircraft to Clean Sky 2 TE’s second assessment cycle. Its main objective is to quantify the environmental impact up to 2050 at airport level of technologies developed in Clean Sky 2 for fixed-wing aircraft. More specifically, GREENPORT2050 aims to quantify the reduction in noise- and gaseous-emissions impact, and the contribution to improved air quality, which these technologies will bring at timeframes 2035, 2040, 2045 and 2050. At the same time, GREENPORT2050 investigates whether aircraft equipped with Clean Sky 2 technologies can be introduced and accommodated smoothly into daily airport operations, while maintaining safety. It is noted that the gaseous-emissions impact focuses, in line with the Clean Sky 2 objectives (cf. Article 2 in [8]), on the impact of CO_2 and NO_X emissions only.

As aforementioned, GREENPORT2050 assesses the impact of innovative Clean Sky 2 technology bricks, when integrated into Clean Sky 2 concept aircraft. In its assessment, GREENPORT2050 addresses Clean Sky 2 concepts for fixed-wing aircraft defined by IADPs Large Passenger Aircraft (LPA) and Regional Aircraft (REG) only. As such concepts, LPA defined an advanced and an ultraadvanced short-/medium-range aircraft, and a long-range aircraft, whereas REG defined an advanced 90-seat turboprop aircraft and an innovative 130-seat turboprop aircraft.

Obviously, as the successor to CLAIRPORT, the overall concept of GREENPORT2050 is fully consistent with the one successfully applied in CLAIRPORT (cf. [4]):

- Firstly, GREENPORT2050 carries out its assessments for the same set of airports: European airports Amsterdam Airport Schiphol, Rome Fiumicino Airport, Stockholm Arlanda Airport, Hamburg Airport, and Toulouse Blagnac Airport; and generic airport CAEPport. CLAIRPORT selected these airports through an airport-categorisation scheme (by categorising the large heterogeneous mix of European and generic airports into more homogeneous groups) and an airport-selection scheme (by defining criteria for the selection of airports from each airport category). The selected airports are considered to cover a broad range of airports and to deliver sufficient representative information for TE's airport-level assessments.
- Secondly, with a combination of airport and timeframe given, an assessment in GREENPORT2050 is founded on the comparison of the noise- and gaseous-emissions performance of two airport-traffic scenarios. The first scenario (or reference scenario) is a one-day flight schedule with existing and Clean Sky 2 (regional, short-/medium-range, and long-range) reference-technology aircraft. The second (or Clean Sky 2) scenario is identical to the first, except for Clean Sky 2 concept aircraft replacing reference-technology aircraft according to a forecast of the replacement rate.

In the next subsections the fundamentals of GREENPORT2050's assessment approach are elaborated. Subsection 2.1 addresses the assessment-process baseline, describing the underlying methodology for the assessments, including indicators to quantify. Based on this baseline, Subsection 2.2 describes the process for the simulation of aircraft traffic and the quantification of the environmental impacts, expressed in the indicators specified in Subsection 2.1. Finally, Subsection 2.3 gives a brief description of a flexible computation framework that integrates the models with their databases, and that supports and facilitates the simulation and calculation processes.

2.1. Baseline

GREENPORT2050's assessment-process baseline specifies the assessment methodology, together with the indicators to quantify the environmental benefits up to 2050 that Clean Sky 2 technologies will bring at and around airports. This baseline capitalises of course on the one from GREENPORT2050's predecessor CLAIRPORT (cf. [4]), and is founded on European Union (EU) Directives, international standards and best practices. For every step in the assessment process, its methodology is described below. With GREENPORT2050 focusing on environmental impacts, firstly the baseline for the noise assessment and the one for the gaseous emissions (and contribution to air quality) assessment are addressed. After that, the baseline to derive an indication whether or not Clean Sky 2 concept aircraft can be accommodated smoothly and safely into daily airport operations is touched upon.

2.1.1. Noise. The European Environmental Noise Directive [6] is a legislative instrument for the assessment and management of environmental noise at and around airports. It describes the determination of exposure to environmental noise through noise mapping, by methods of assessment common to EU Member States, as well as ensures that information on environmental noise and its effects is made available to the public. Evidently GREENPORT2050 adopts this instrument as a basis for its noise assessment. As a consequence, it considers noise indicators based on L_{den} and L_{night} contours for significant noise levels (i.e. above 55 dB(A) L_{den} and 50 dB(A) L_{night}, respectively).

Further, noise is a growing concern among both the general public and policy-makers in Europe for evidence has accumulated regarding health effects of environmental noise. The World Health Organisation's Regional Office for Europe (WHO/Europe) proposes an updated set of public health recommendations on exposure to environmental noise (cf. [13]). Logically GREENPORT2050 adopts these recommendations as well.

In summary, GREENPORT2050 quantifies the surface area of L_{den} and L_{night} contours for significant noise levels and the population exposed to these noise levels, as well as the population highly annoyed (for L_{den} only) and highly sleep-disturbed (for L_{night} only).

2.1.2. Emissions and air quality. The International Civil Aviation Organisation (ICAO) document ICAO Doc 9889 [12] is internationally recommended, widely adopted and best practice for addressing emissions and (contribution to) air quality at and around airports. It focuses on aircraft operations below 3,000 feet, i.e. on the landing and take-off cycle including ground operations. GREENPORT2050 adopts this guidance as a starting point for its CO_2 and NO_X emissions assessment.

Consequently, GREENPORT2050 quantifies the key emissions indicators: Total amount of CO_2 and NO_X emitted below 3,000 feet as well as so-called 4D emissions inventories. Moreover, for CAEPport, these emissions inventories are expanded with emissions from other gaseous-emissions sources than aircraft engines, to enable an air-quality assessment from these expanded emissions inventories.

2.1.3. Capacity. To indicate whether Clean Sky 2 concept aircraft can be introduced and accommodated smoothly into daily airport operations, GREENPORT2050 applies an airport-capacity indicator. For consistency, it applies the same indicator as its predecessor CLAIRPORT: runway throughput per rolling hour (which is defined as the number of arrivals and departures during a full-hour period for any moment in time *t*. This full-hour period extends from *t* minus 30 minutes to *t* plus 30 minutes, and is calculated every five minutes, for instance). It is emphasised that this indicator is only used to provide an indication of potential feasibility of the connected environmental potential of Clean Sky 2 technologies for fixed-wing aircraft (i.e. whether or not additional air-traffic management or airport-operations measures are required to accommodate Clean Sky 2 concept aircraft into daily airport operations). In cases where such measures would be necessary, the related research to alleviate infeasibility falls beyond the scope of GREENPORT2050.

With GREENPORT2050 assessing impacts up to 2050, it investigates relevant (anticipated) future developments for the airports considered. For example, GREENPORT2050 inventories relevant developments and improvements in airport and airspace layout and operations emerging from the European Programmes SESAR/SESAR2020 and (in case available) from Airport Master Plans.

2.1.4. Safety. Third-party risk is defined as the risk posed to the safety of persons who live near an airport and are involuntary exposed to accidents due to aircraft take-offs and landings at this airport. It is therefore considered well to serve the purpose to indicate whether Clean Sky 2 concept aircraft can be safely introduced and accommodated into daily airport operations.

With reference to [5] and [11], there are two main European methods for third-party risk: One from the United Kingdom (UK) and one from The Netherlands. GREENPORT2050 adopts the best practice of The Netherlands as it is found more suitable (e.g. it has different formulations for large and regional airports and considers the different aircraft tracks or routes, whereas the one from the UK is calibrated using global accident data and based on extended runway centrelines).

Consistent with the adopted best practice, GREENPORT2050 considers two main and complementary third-party risk indicators: individual risk and societal risk (or risk to groups). Individual risk describes the risk to a person located permanently in the surrounding of an airport and is defined as the probability that a person (permanently residing at this particular location) is killed as a direct consequence of an aircraft accident. Societal risk describes the risk a group of persons who are actually present in the vicinity of the airport are exposed to as a direct consequence of the operations of the airport. It is defined as the probability per year that a group larger than *N* persons is killed due to a single aircraft accident.

2.2. Simulations and calculations

As briefly addressed in the opening lines of Section 2, an assessment in GREENPORT2050 is founded on the principle to compare the performance of two airport-traffic scenarios in terms of the indicators listed in Subsection 2.1. For a given combination of an airport and an associated scenario (i.e. one-day flight schedule), the quantification of these indicators essentially consists of three steps. The first step is a realistic simulation of the aircraft traffic in the airport's local airspace (basically in the terminal manoeuvring area). This simulation generates (among other output) for each flight in the scenario a complete trajectory in this airspace, which respects the airport and airspace operational procedures and rules. In the second step, these trajectories are individually processed to determine per flight the generated noise, CO_2 and NO_X emissions. In the third and final step, the output of the preceding two steps is aggregated to obtain the noise and gaseous emissions, capacity, and third-party risk indicators of interest. These three steps are elaborated in the next three subsections, respectively.

2.2.1. Step 1: Airport simulations. To realistically simulate each aircraft in the flight schedule in the airport's local airspace, GREENPORT2050 (like CLAIRPORT) uses the fast-time airport and airspace simulation platform AirTOp. For an airport, AirTOp is (in addition to the flight schedule for the simulation at hand) fed with airport and airspace layout and operations data, and with aircraft performance characteristics.

Airport and airspace layout is the airport infrastructure (such as runways, taxiways, aprons, and stands) and airspace control areas (such as control-zone and terminal-manoeuvring area). Airport and airspace operations relate to flight procedures and rules, including the way aircraft are handled at the ground and in the air by air-traffic control. GREENPORT2050 enriches these data on layout and operations from CLAIRPORT with relevant (anticipated) future developments and improvements emerging from SESAR/SESAR2020 and Airport Master Plans, as mentioned in Subsection 2.1.3.

Aircraft performance characteristics are data to ensure that the simulated aircraft movements respect the technical envelope of the aircraft. One can think for instance of information on (minimum, normal and maximum) speed, climb/descend rates, turn rates, and acceleration/deceleration. For their Clean Sky 2 reference-technology and concept aircraft, LPA and REG provided these performance characteristics, whereas for existing aircraft these data are available in AirTOp.

Having AirTOp fed with all required data, it then realistically simulates the aircraft movements at and around the airport (i.e. at the ground and in the air). Its high-fidelity output contains per flight a 4D-trajectory in the airport's local airspace (including taxi and ground movements), which respects safety requirements regarding (horizontal and vertical) minimum separation between aircraft. Hence, these flights constitute a set of conflict-free aircraft trajectories. These aircraft trajectories are subsequently processed in the next two steps. Figures 2 and 3 provide an example of simulations with AirTOp of aircraft movements at the ground and in the air, respectively.

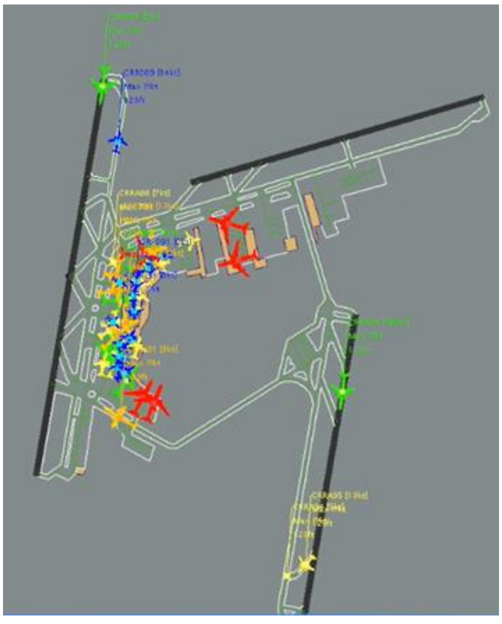

Figure 2. Simulation with AirTOp: Aircraft ground movements [Source: Royal NLR].

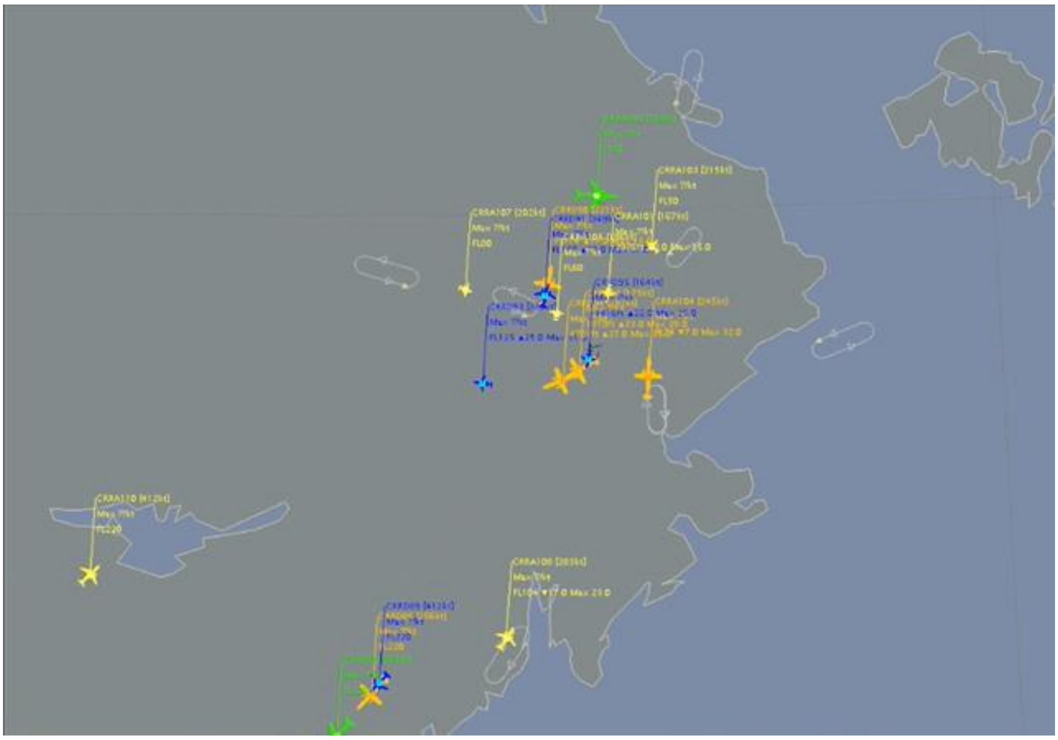

Figure 3. Simulation with AirTOp: Aircraft movements in local airspace [Source: Royal NLR].

2.2.2. Step 2: Noise, CO_2 and NO_X emissions calculations. The trajectories generated by AirTOp in Step 1 are individually processed to quantify their contribution to noise, CO_2 and NO_X emissions at and around the airport.

The noise indicators are all based on L_{den} and L_{night}. EU Directive 2015/996 [7] refers to the European Civil Aviation Conference (ECAC) Doc 29 methodology [3] for the determination of L_{den} and L_{night}. In the spirit of this methodology, GREENPORT2050 performs its noise calculations. To this end, the noise emissions are expressed in Sound Exposure Level (SEL). Depending on the aircraft type associated with a flight, a dedicated noise model is used to process its 4D trajectory from AirTOp. The noise model from LPA is used for Clean Sky 2 reference-technology and concept short-/medium-range and long-range aircraft. The one from REG is used for Clean Sky 2 reference-technology and concept regional aircraft. For all other aircraft Royal NLR's fully ECAC Doc 29-compliant noise model Tuna is used.

With reference to ICAO Doc 9889 [12], GREENPORT2050 applies the (so-called) sophisticated approach for estimating CO_2 and NO_X emissions below 3,000 feet from aircraft engines. As for noise, a dedicated emissions model is used (depending on the aircraft type) which uses the associated aircraft's 4D trajectory from AirTOp as input. So, LPA's emissions model is used for Clean Sky 2 reference-technology and concept short-/medium-range and long-range aircraft, and REG's emissions model for Clean Sky 2 reference-technology and concept regional aircraft. For all other aircraft and acting upon ICAO's recommendation to apply Boeing Fuel-Flow Method 2, Royal NLR's emissions (and fully compliant with this method) model LEAS-iT is used.

2.2.3. Step 3: Aggregation. In the final step the outcomes of Steps 1 and 2 are processed to generate the indicators of interest:

- Noise: The individual noise results are aggregated to generate L_{den} and L_{night} contours for significant noise levels (i.e. above 55 dB(A) L_{den} and 50 dB(A) L_{night}), from which their surface area is obtained. Combining these contours with the widely-used population density database [9] from Joint Research Centre yields the population exposed to these noise levels. Finally, applying WHO/Europe's dose-response relationships (cf. [13]) to the population exposed, provides the population highly annoyed and highly sleep-disturbed for the same noise levels.

- Emissions: The individual CO_2 and NO_X emissions results are aggregated to obtain the total amount of CO_2 and NO_X, respectively, emitted below 3,000 feet as well as the 4D emissions inventories. For CAEPport the NO_X emissions inventories are expanded with emissions from other gaseous-emissions sources than aircraft engines. Using AUSTAL2000, air-quality calculations are performed based on these expanded inventories.
- Capacity: The runway throughput per rolling hour is directly derived from the airport-simulations output generated in Step 1.
- Safety: In line with the best practice of The Netherlands, third-party risk indicators are calculated using Royal NLR's third-party risk model TRIPAC. Individual risk is reported through contours for typical risk levels (e.g. $1 \cdot 10^{-5}$, $1 \cdot 10^{-6}$ and $1 \cdot 10^{-7}$ per year). Societal risk is presented for a number of group sizes.

2.3. Computation framework
In GREENPORT2050's predecessor project CLAIRPORT, a computation framework was developed. This framework enables to efficiently and effectively perform the simulations and calculations in the environmental-impact assessment at airport level. GREENPORT2050 builds on this framework and enhances it to meet the broadened scope of the airport-level assessments.

GREENPORT2050's computation framework integrates all models and their databases that are used in the environmental-impact assessments at airport level. To this end, GREENPORT2050 applies state-of-the-art technologies, offering a flexible environment for integrating new models and databases. Further, this computation framework controls model calculations through hypertext transfer protocol (HTTP) requests. These requests contain all the relevant parameters and data required for the calculation task. The application programming interface (API) offers the services for performing the calculations, and is a representational state transfer (REST) API. With assessments usually involving a sequence of model calculations, these requests are combined into workflows. On top of the REST API, a modern thin-client interface is created to enable the user to create, run, observe progress and finally download results of server-side tools. This interactive user interface is available via a web browser.

3. Conclusion
GREENPORT2050 quantifies the environmental benefits up to 2050 at airport level of Clean Sky 2 technologies developed for fixed-wing aircraft. Its assessment approach (including indicators to quantify) is founded on EU Directives, international standards and best practices; for instance, on the European Environmental Noise Directive and ICAO's airport air-quality manual. Further, in its assessment, GREENPORT2050 applies state-of-the-art tools, such as: the fast-time airport simulation platform AirTOp; Royal NLR's environmental-impact models Tuna, LEAS-iT and TRIPAC listed in the European Civil Aviation Conference / Modelling and Interdependencies Task Group's models inventory; and the aircraft-noise and -emissions models from Clean Sky 2 IADPs LPA and REG.

With its systematic and credible approach established and its advanced tools in place, GREENPORT2050 recently started its simulations and calculations accordingly. In this process, the upgraded and flexible computation framework is an important asset, for it ensures these simulations and calculations to be performed in an effective and efficient manner.

GREENPORT2050 expects to provide in the third quarter of 2023 its contribution to the Clean Sky 2 TE's second assessment cycle. Its assessment results will be published as part of a (public) report on the Clean Sky 2 Second Global Assessment, expanding its predecessor's (i.e. CLAIRPORT's) scope by for example enlarging the set of noise indicators, extending emissions impact to local air quality, expanding the assessment with third-party risk, and assessing Clean Sky 2 concept aircraft equipped with a more mature set of innovative technologies.

Acknowledgement
The GREENPORT2050 project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 101007858. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union.

The document reflects only the authors' views and the JU is not responsible for any use that may be made of the information it contains.

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