ENVIRONMENTAL ASSESSMENT OF GARDN II RESEARCH PORTFOLIO

GREENER CANADIAN AEROSPACE
A Look Toward 2030

MARCH 2019

PRESENTED TO

GARDN

GROUP AGÉCO

CIRAIG™
International Reference Centre for the Life Cycle of Products, Processes and Services
**Report presented to GARDN’s Integration Committee**

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**Project Direction**

**Project Management**

**Project Experts**
The Green Aviation Research and Development Network (GARDN) is a non-profit organization that aims to reduce the environmental footprint of the next generation of Canadian aircraft, engines, and avionics systems by funding collaborative and innovative projects. This study assessed the technologies’ contribution to the development of cleaner, quieter, and more sustainable aircraft in Canada and abroad.

### Evaluated technologies

To assess their environmental benefits, the technologies of the nineteen GARDN II projects were grouped in the following nine clusters. They were assessed using the environmental metrics described at the bottom of this page.

- **Greener commercial turbofan** equipped with optimized flight management systems and manufactured with low-waste processes
- **30% blend of sustainable aviation fuel (SAF) from renewable feedstock**
- **Self-launching electric glider**
- **Unconventional aircraft configurations** that reduce drag and noise
- **Other technology clusters**
  - **Greener large turboprop** equipped with quieter and cleaner engines as well as quieter airframe features
  - **Greener small turboprop** equipped with a flight optimization tool
  - **Hybrid unmanned aerial vehicle (UAV)**
  - **Greener business jet** equipped with cleaner engines, quieter airframe features, and lighter landing gear
  - **Green supply chain management (GSCM)**

### Key findings

The technologies of the GARDN II projects have the potential to:

- Contribute to 27% of the Canadian aviation’s carbon neutral growth target in 2030 (0.7 of 2.6 Mt CO₂ eq.). The development of the SAF industry is a key component of success contributing to 98% of this effort.
- Address important environmental issues related to the aviation sector: GHG, NOₓ, and SOₓ emissions, non-renewable energy consumption, and noise, as well as emissions of other air contaminants, such as PAH and lead.
- Help the industry meet ICAO’s noise regulations, which must be met for an aircraft to enter service, and therefore contribute to the competitiveness of the sector.
- Provide very high benefits per flight, especially for electric gliders, greener small and large turboprops, and hybrid UAVs. When benefits are scaled up to an entire fleet and extrapolated to 2030, the greatest benefits are from **greener commercial turbofans** and **SAF**.

### Estimated environmental benefits at the flight level

For each technology cluster, the percentages below represent the reduction of the environmental metrics (i.e. the environmental benefits) of an aircraft flying with green technologies compared to a conventional aircraft.

<table>
<thead>
<tr>
<th>Technology Cluster</th>
<th>NRPEC</th>
<th>NOₓ / PM / SOₓ</th>
<th>Noise</th>
<th>GHG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Greener commercial turbofan</strong></td>
<td>3%</td>
<td>3%</td>
<td>NA</td>
<td>3% per flight</td>
</tr>
<tr>
<td>SAF</td>
<td>13%</td>
<td>0-9%</td>
<td>NA</td>
<td>18% per flight</td>
</tr>
<tr>
<td>Electric glider</td>
<td>93%</td>
<td>37-93%</td>
<td>65%</td>
<td>95% per flight</td>
</tr>
<tr>
<td>Unconventional configurations</td>
<td>13%</td>
<td>13%</td>
<td>16%</td>
<td>13% per flight</td>
</tr>
<tr>
<td>Other technology clusters</td>
<td>0.3-10%</td>
<td>0.3-31%</td>
<td>13-28%</td>
<td>0.3-10% per flight</td>
</tr>
</tbody>
</table>

Environmental metrics:

- NRPEC: Non-renewable primary energy consumption (e.g. jet fuel) as opposed to renewable resources, such as plants
- NOₓ: Nitrogen oxides formed during fuel combustion
- PM: Particulate matter smaller than 100 microns emitted to air during incomplete combustion
- SOₓ: Sulphur oxides emitted to air when burning sulphur-containing fuels

- **Noise**: Depending on the technology cluster, either the change in air pressure due to sound waves or the perceived loudness of the sound
- **GHG**: Greenhouse gases (mostly CO₂ emitted by jet fuel combustion)

### 2018–2030 cumulative GHG benefits at the fleet level

Scaled up to the fleet level, the cumulative GHG reductions of all clusters by 2030 correspond to...

- 20 million passengers
- 25,000 passengers
- 3 million passengers
- 1 million passengers

...travelling between Toronto and Vancouver. In 2016, Canada’s air traffic GHG emissions were equivalent to 66 million passengers travelling this distance.

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NA = not applicable

* Environmental benefits of unconventional configurations would occur from 2035. Therefore, they were estimated over a 2035–2047 period and were excluded from the total.
EXECUTIVE SUMMARY

Launched in 2014, the second program of the Green Aviation Research and Development Network (GARDN II) has funded nineteen collaborative research projects for a total value of more than $20M. The projects tackled environmental challenges of the aerospace industry such as fuel burn, air emissions, noise, and more. This study assessed, in a standardized way and based on selected relevant environmental metrics, the potential environmental benefits of the technologies developed as part of the GARDN projects. The evaluation was carried out in two phases: 1) the individual evaluation of the technology benefits for one flight and 2) the benefits evaluation for an entire fleet of aircraft equipped with the green technologies for the 2018–2030 period.

For the individual technology evaluation (phase 1), a baseline scenario (e.g. a typical flight) was defined and its environmental metrics quantified. To calculate the environmental benefits at the flight level, the environmental metrics for a similar scenario implementing the green technology were then evaluated. The difference between the environmental metrics of the two scenarios represents the environmental benefits.

In the second phase of the study, the technologies were grouped together in clusters based on their compatibility, and their combined environmental benefits were evaluated for an entire fleet over the 2018–2030 period (fleet-level technology clusters). The benefits were calculated by extrapolation using the estimated national and international market penetration rates and market shares of the different technologies for the different categories of aircraft and flights provided by project leaders and other sources. A total of nine technology clusters were assessed, comprising the technologies of the nineteen GARDN II projects:

- 30% blend of SAF (sustainable aviation fuel) made of renewable feedstock, namely forest residues and used cooking oil
- Unconventional aircraft configurations that reduce drag and noise
- Greener commercial turbofan equipped with optimized flight management systems and manufactured with low-waste processes
- Self-launching electric glider
- Greener large turboprop equipped with quieter and cleaner engines as well as quieter airframe features
- Greener small turboprop equipped with a flight optimization tool
- Hybrid unmanned aerial vehicle (UAV)
- Greener business jet equipped with cleaner engines, quieter airframe features, and lighter landing gear
- Green supply chain management (GSCM)

Environmental benefits were evaluated using a total of eight environmental metrics:

- GHG: Greenhouse gases (mostly CO₂ emitted by jet fuel combustion), which cause global temperatures to increase and in turn impact climate patterns
- NOx: Nitrogen oxides formed during fuel combustion and linked to smog and acid rain
- PM: Particulate matter smaller than 100 microns emitted to air during incomplete combustion and which are harmful to the respiratory system
SO\(_x\): Sulphur oxides emitted to air when burning sulphur-containing fuels, also linked to acid rain and smog formation

Non-renewable energy: From non-renewable resources (e.g. jet fuel) as opposed to renewable resources, such as plants

Cumulative noise: Depending on the technology cluster, either the change in air pressure due to sound waves or the perceived loudness of the sound

Noise footprint: Area within which noise levels of 70 dB or higher are experienced during the take-off and landing events

The results of this assessment include a percentage of the environmental metric reductions for one flight and cumulative reductions by 2030, which allowed to formulate the following findings:

- These technologies could contribute to **0.7 of Canadian aviation’s 2.6 Mt CO\(_2\) eq.** reduction target (neutral growth) for 2030. 98% of this reduction is attributed to SAFs.
- They could address important environmental issues related to the aviation sector: GHG, NO\(_x\), and SO\(_x\) emissions; non-renewable energy consumption; noise; as well as emissions of other air contaminants, such as PAH and lead.
- They could help the industry meet ICAO’s noise regulations, which must be met for an aircraft to enter service.
- Electric gliders, greener small and large turboprops, and hybrid UAVs have great benefits per flight. When benefits are scaled up to an entire fleet and extrapolated to 2030, the greatest benefits are obtained from greener commercial turbofans.
- To achieve GHG reduction targets, the development of the SAF industry is key.

This assessment demonstrated the importance of investing in the research and development of greener technologies in the aerospace sector to achieve the international and national climate change targets. It also shows that the benefits of greener technologies tend to grow over time and consequently stresses the relevance of investing early in their development. In the context of a renewed GARDN program, it is recommended to:

- Select projects that have the potential to be implemented in a large fleet of aircraft. Technologies achieving the highest environmental benefits at the flight level do not necessarily end up contributing the most to cumulative fleet-level benefits.
- Focus on technologies applicable to aircraft that are operated or that will be operated in the country to increase GARDN’s contribution to Canada’s neutral growth target in aviation.
# Table of Contents

Executive Summary ........................................................................................................... iv  
Table of Contents ................................................................................................................ vi  
Abbreviations and Acronyms .............................................................................................. viii  
1. Introduction and Context ................................................................................................. 9  
2. Methodology Summary ................................................................................................... 10  
   2.1 Scope ......................................................................................................................... 11  
   2.2 Environmental Assessment Framework ....................................................................... 12  
      2.2.1 Flight-Level Technology Isolation ......................................................................... 12  
      2.2.2 Fleet-Level Technology Clusters ............................................................................ 13  
   2.3 Environmental Metrics ............................................................................................... 16  
3. Estimated Environmental Benefits .................................................................................. 17  
   3.1 Flight-Level Reductions of Clustered Technologies ...................................................... 17  
      3.1.1 Clean and Sustainable Air Transportation Systems ............................................. 17  
      3.1.2 Other Sustainable Air Transportation Systems .................................................. 18  
      3.1.3 Quiet Air Transportation Systems ........................................................................ 19  
   3.2 2018–2030 Fleet-Level Reductions ............................................................................. 20  
   3.3 GARDN II’s Contribution to a Greener Canada ........................................................... 22  
      3.3.1 Greenhouse Gases (GHGs) ................................................................................... 23  
      3.3.2 Other Air Contaminants ....................................................................................... 24  
      3.3.3 Non-Renewable Primary Energy Consumption (NRPEC) .................................. 25  
      3.3.4 Noise ................................................................................................................... 25  
3.4 Result Limitations .......................................................................................................... 27  
4. Conclusions and Recommendations ................................................................................ 28  
5. References ......................................................................................................................... 30  
Appendix A — Evolution of the Canadian Transportation Sector Emissions ......................... 31
LIST OF TABLES

Table 1: GARDN’s Research Categories ................................................................. 10
Table 2: Technology clusters .............................................................................. 14
Table 3: Assumptions used for the fleet-level assessment ..................................... 15
Table 4: Environmental metrics .......................................................................... 16
Table 5: Relative environmental benefits for one flight of clean and sustainable air transportation systems ............................................................. 17
Table 6: Relative environmental benefits for the manufacturing of one aircraft part of other sustainable air transportation systems ......................................................... 18
Table 7: Relative environmental benefits for one flight of quiet air transportation systems ................................................................. 19

LIST OF FIGURES

Figure 1: Systems boundaries of the technology assessment .................................. 12
Figure 2: Assessment scenarios and levels for the first phase of the study ................. 12
Figure 3: Technology benefit approach .................................................................. 13
Figure 4: Assessment scenarios and levels for the second phase of the study .......... 13
Figure 5: Worldwide 2018–2030 cumulative direct and indirect reductions .......... 21
Figure 6: Worldwide direct and indirect fossil GHG reductions over time .............. 22
Figure 7: Canadian domestic aviation fossil GHG emission projections ................. 23
Figure 8: Evolution of ICAO Noise Standards ....................................................... 25
Figure 9: Canadian emissions of air contaminants ................................................ 31
### Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>APEI</td>
<td>Air Pollutant Emission Inventory</td>
</tr>
<tr>
<td>BAU</td>
<td>Business-as-usual</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>dB(A)</td>
<td>A-weighted decibels</td>
</tr>
<tr>
<td>EEA</td>
<td>European Environmental Agency</td>
</tr>
<tr>
<td>EPNdB</td>
<td>Effective perceived noise in decibels</td>
</tr>
<tr>
<td>FMS</td>
<td>Optimized flight management system</td>
</tr>
<tr>
<td>GARDN</td>
<td>Green Aviation Research &amp; Development Network</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GSCM</td>
<td>Green supply chain management</td>
</tr>
<tr>
<td>HHV</td>
<td>Higher heating value</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
</tr>
<tr>
<td>LTO</td>
<td>Landing and take-off</td>
</tr>
<tr>
<td>Mt CO₂ eq.</td>
<td>Megatonne (million tonnes) of CO₂ equivalent</td>
</tr>
<tr>
<td>nmi</td>
<td>Nautical mile</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrogen oxides</td>
</tr>
<tr>
<td>NRPEC</td>
<td>Non-renewable energy consumption</td>
</tr>
<tr>
<td>nvPM</td>
<td>Non-volatile particulate matter</td>
</tr>
<tr>
<td>PAH</td>
<td>Polycyclic aromatic hydrocarbons</td>
</tr>
<tr>
<td>PJ</td>
<td>Petajoule (billion megajoules)</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter</td>
</tr>
<tr>
<td>ppm</td>
<td>Part per million</td>
</tr>
<tr>
<td>SAF</td>
<td>Sustainable aviation fuel</td>
</tr>
<tr>
<td>SOₓ</td>
<td>Sulphur oxide</td>
</tr>
<tr>
<td>SPL</td>
<td>Sound pressure level</td>
</tr>
<tr>
<td>TRL</td>
<td>Technology readiness level</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned aerial vehicle</td>
</tr>
</tbody>
</table>
1. Introduction and Context

Created in 2009 with funding from the Business-Led Network of Centres of Excellence (BL-NCE) of the Government of Canada and from the Canadian aerospace industry, the Green Aviation Research and Development Network (GARDN) is a non-profit organization that aims to reduce the environmental footprint of the next generation of Canadian aircraft, engines, and avionics systems by funding collaborative and innovative projects. GARDN’s network, which aims to increase the Canadian aerospace industry’s competitiveness, is comprised of 27 industrial members and 20 research institutions that strive to foster the ongoing development of technology and procedures for a cleaner, quieter, and more sustainable aerospace industry.

Launched in 2014, GARDN’s second program, GARDN II, has funded nineteen collaborative research projects for a total value of more than $20M. These programs are crucial to addressing the environmental challenges of the aerospace industry, such as greenhouse gas emission reduction, aircraft end-of-life management, non-volatile particulate matter and NOx emissions, noise management, etc. GARDN II technologies are innovative and could yield important environmental and economic benefits for Canada.

Although each project has been selected for its significant potential for reducing the aerospace industry’s environmental impacts, a thorough assessment of the program as a whole had not been undertaken. GARDN therefore sought an independent third party to perform an assessment to identify the various environmental benefits, both at the project and program levels. This provides further assurance to the Canadian government that the money invested in the program will generate tangible environmental benefits.

The objective of this study was to assess, in the most standardized way and based on selected relevant environmental metrics, the potential environmental benefits of the technologies developed as part of the GARDN projects. The results were then assessed using national indicators and metrics. In the first phase of the study, the direct and indirect benefits of the technologies occurring during a defined flight were estimated individually. The results served as the building blocks for the second phase of the study, that is to say, the benefits assessment of the deployment of all GARDN II funded technologies for a time horizon until 2030, which is presented in this report.

In the next section, the reader will find a description of the methodology employed for the environmental benefits assessment of the GARDN technologies. It is followed by the results of the assessment, which include flight-level reductions per technology cluster and the cumulative fleet-level reductions by 2030. The key findings of the study, along with recommendations for GARDN on the selection of future projects, are formulated in the last section.
2. Methodology Summary

The environmental benefits evaluation of the GARDN II project technologies was carried out in two phases: 1) the individual evaluation of the technology benefits for one flight and 2) the benefits evaluation for an entire fleet of aircraft equipped with the green technologies for a time horizon until 2030. The methodology described in this section covers the two phases. However, the specific methodology used for the first phase, as well as the results identifying the direct and indirect environmental benefits of each technology, are contained in confidential individual reports reviewed by the GARDN management team and project leaders.

The nineteen technologies covered by the GARDN II program are divided into three categories: clean air transportation systems, quiet air transportation systems, and sustainable air transportation systems. These categories are described in Table 1. Appropriate environmental metrics were selected for each category. The following sections summarize how the environmental benefits of each technology were calculated and describe the selected environmental metrics for each research category.

Table 1: GARDN’s Research Categories

<table>
<thead>
<tr>
<th>Environmental Impacts Covered</th>
<th>GARDN II Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean air transportation systems</td>
<td>BA-21 Experimental Validation of Innovative Environmentally Focused Aircraft Configurations</td>
</tr>
<tr>
<td></td>
<td>CMC-21 &amp;22 Flight Management Performance Optimization II &amp; III</td>
</tr>
<tr>
<td></td>
<td>NU-21 Energy Efficient Aircraft Configurations and Concepts of Operation</td>
</tr>
<tr>
<td></td>
<td>OPT-21 Development of an Electric Propulsion System to Convert Gliders for Self-Launch Operations</td>
</tr>
<tr>
<td></td>
<td>PWC-23 Next-Generation Combustor for Small Gas Turbine Engines</td>
</tr>
<tr>
<td></td>
<td>PWC-24 Development of Innovative Aerodynamic Performance Enablers for Gas Turbine Engine Compressors</td>
</tr>
<tr>
<td></td>
<td>PWC-25 Aero Gas Turbine Engine Non-Volatile Particulate Matter (nvPM) Emission Baseline Measurement and Modelling</td>
</tr>
<tr>
<td></td>
<td>SRS-21 Turboprop Flight Advisory System (FAS) for Cruise Fuel Burn Reduction</td>
</tr>
<tr>
<td></td>
<td>SRS-22 Turboprop Flight Advisory Systems Enhancements, Testing and Engine Model Development</td>
</tr>
<tr>
<td></td>
<td>WG-22 Civil Aviation Alternate Fuel Contrail and Emissions Research</td>
</tr>
</tbody>
</table>

| Quiet air transportation systems | |
| Sustainable air transportation systems | |
2.1 Scope

The scope of the assessment of the nineteen GARDN II projects was defined as follows:

- **Temporal boundaries**: In accordance with the current governmental target of reducing Canada’s total GHG emissions by 30% below 2005 levels by 2030, the results associated with the anticipated implementation of the technologies have been provided for both the annual impact reductions and the cumulative impact reductions (for the 2018–2030 period). For technologies in an early development stage and those whose potential environmental benefits are not expected to occur before 2030, a separate assessment is provided in complement of the cumulative impact reduction assessment.

- **Geographical boundaries**: The impact reductions of products and technologies used on the Canadian territory and occurring elsewhere in the world have been distinguished. More specifically, the rules used by Transport Canada for the aviation sector have been applied to distinguish national and international impacts (Government of Canada 2018).

- **System boundaries (see Figure 1)**: The distinction has been made between the direct benefits of a technology (e.g. less fuel burn during flight) and indirect benefits associated with the aircraft’s upstream life cycle stages (e.g. decrease in jet fuel production). The lack of data prevented the end-of-life stage to be included in the study.
2.2 ENVIRONMENTAL ASSESSMENT FRAMEWORK

This study established an assessment framework based on recognized environmental impact reduction quantification methodologies, such as ISO 14064-2 for GHG reduction projects. For each individual technology, two assessment scenarios were defined: the baseline and the technology scenario. The first phase of the study focused on the benefits of each individual technology during one flight (technology isolation). In the second phase of the study, the technologies were grouped together in clusters, and their combined environmental benefits were evaluated for an entire fleet over the 2018–2030 period (fleet-level technology clusters).

2.2.1 FLIGHT-LEVEL TECHNOLOGY ISOLATION

Figure 4 summarizes the assessment framework that was used for this phase.

The purpose of baseline scenarios is to illustrate what would occur if the technologies were not implemented. In other words, what product or technology would be used if the project did not exist? The baseline scenarios are the reference against which the potential environmental benefits of GARDN projects were calculated. As for technology scenarios or project scenarios, they are used to illustrate what would occur if only the technology developed in one project were to be implemented. The equivalence of functions between the technology and the baseline scenarios, that is to say equal...
products or services provided by the scenarios, was required for the purpose of this assessment. The difference in estimated environmental metrics between the baseline and technology scenarios represents the technology’s environmental benefits. Figure 3 illustrates this approach.

**Figure 3: Technology benefit approach**

### 2.2.2 Fleet-Level Technology Clusters

During the second phase of the study, a third assessment scenario was used: the **technology clusters**. These groups of compatible technologies were formed to simplify interpretation of the results. A cluster either regroups technologies applicable to a specific type of aircraft or technologies related to a specific initiative that will impact the entire Canadian aerospace industry. With the technologies of the nineteen projects, nine clusters were formed (see Table 2). Each assessment scenario was then analyzed at two different assessment levels, as shown in Figure 4.

**Figure 4: Assessment scenarios and levels for the second phase of the study (current report)**

At the **flight level**, the assessment considered a scenario for a single aircraft. At the **fleet level**, one mission was scaled up to represent a fleet affected by the technology over the 2018–2030 period (except for the unconventional configurations cluster). The benefits were calculated by extrapolation using the estimated national and international market penetration rates and market shares of the different technologies for the different categories of aircraft and flights provided by project leaders and other sources. Many assumptions were made as part of the fleet-level assessments. The general and technology-specific assumptions are detailed in Table 3.
Table 2: Technology clusters

<table>
<thead>
<tr>
<th>Technology Cluster</th>
<th>Description</th>
<th>Themes</th>
<th>Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainable aviation fuel (SAF; not aircraft specific)</td>
<td>According to ICAO (2017), SAFs achieve net GHG emission reductions over their life cycle, respect biodiversity hotspots, contribute to local social and economic development, and should not compete with food. The introduction of SAFs in aviation does not only affect a single aircraft type, but an entire fleet. Therefore, all SAF-related (biofuel-related) GARDN projects have been grouped in this cluster.</td>
<td>SAF production</td>
<td>NEC-21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SAF distribution</td>
<td>WG-21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SAF combustion (contrail formation)</td>
<td>WG-22*</td>
</tr>
<tr>
<td>Unconventional configurations</td>
<td>Unconventional configurations are major aircraft design changes that reduce drag and noise. Even though such aircraft could be equipped with technologies from other GARDN projects, this project has its own cluster since unconventional configurations are expected to be commercialized after 2030, much later than most of the technologies assessed in this study.</td>
<td>Aerodynamic design</td>
<td>BA-21 BA-23</td>
</tr>
<tr>
<td>Greener business jet (turbofan)</td>
<td>Business jet equipped with turbofan engines have been included in this cluster.</td>
<td>Airframe noise reduction</td>
<td>BA-22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lighter landing gear</td>
<td>HD-21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>New turbofan compressor design</td>
<td>PWC-24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nmPM measurement</td>
<td>PWC-25*</td>
</tr>
<tr>
<td>Greener commercial turboprop aircraft</td>
<td>Commercial airliners larger than regional or business aircraft and equipped with turbofan engines (e.g. Boeing 737) are included in this cluster.</td>
<td>Uncured composite reuse</td>
<td>BC-21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Optimized flight management system (FMS)</td>
<td>CMC-21 CMC-22</td>
</tr>
<tr>
<td>Electric gliders</td>
<td>Gliders are very distinct aircraft. They are either towed or propelled with an electric engine. Therefore, the gliders of the GARDN project have their own cluster.</td>
<td>Electric self-launching gliders</td>
<td>OPT-21</td>
</tr>
<tr>
<td>GSCM (not aircraft specific)</td>
<td>Green supply chain management is the integration of eco-design and environmental thinking into supply chain management and is not specific to a type of aircraft.</td>
<td>Green supply chain management</td>
<td>QC-21*</td>
</tr>
<tr>
<td>Greener large turboprop aircraft</td>
<td>For this study, large turboprop aircraft have 20 seats or more.</td>
<td>Airframe noise reduction</td>
<td>BA-22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quieter turboprop engines</td>
<td>PWC-22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cleaner turboprop engines</td>
<td>PWC-23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nmPM measurement</td>
<td>PWC-25*</td>
</tr>
<tr>
<td>Greener small turboprop aircraft</td>
<td>For this study, small turboprop aircraft have 19 seats or less.</td>
<td>Flight optimization tool for turboprop</td>
<td>SRS-21 SRS-22</td>
</tr>
<tr>
<td>Hybrid unmanned aerial vehicle (UAV)</td>
<td>UAVs are small aircraft that are not piloted by a person on board the craft. One GARDN project involved hybrid UAVs, a technology that was not considered compatible with other clusters.</td>
<td>Hybrid aircraft</td>
<td>NU-21</td>
</tr>
</tbody>
</table>

* No quantifiable environmental benefits could be estimated for those technologies.
### Table 3: Assumptions used for the fleet-level assessment

<table>
<thead>
<tr>
<th>Project</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General assumption</strong></td>
<td>Indirect benefits related to avoided jet fuel production were assumed to happen outside of Canada.</td>
</tr>
<tr>
<td><strong>BA-21</strong></td>
<td>Unconventional configurations will not enter the market before 2035. Bombardier’s 2017–2036 market projections for large regional aircraft (Bombardier 2017) were transposed to the 2035-2050 period. The Bombardier market was assumed to be 35% based on current numbers. Flight distance considered is the Canadian average (675 nmi).</td>
</tr>
<tr>
<td><strong>CMC-21 &amp; 22</strong></td>
<td>The number of aircraft equipped with the technology was provided by the project leaders. Only 7 aircraft in Canada (A310) until 2020.</td>
</tr>
<tr>
<td><strong>HD-21</strong></td>
<td>200 aircraft equipped with the technology by 2030. All abroad.</td>
</tr>
<tr>
<td><strong>NEC-21</strong></td>
<td>7.5% biojet blend by 2030 in Canada is considered. Forest residue biojet production was assumed to start in 2023 and to provide 10% of the biojet in 2030.</td>
</tr>
<tr>
<td><strong>NU-21</strong></td>
<td>Hybrid UAVs are expected to be on the market in three years. According to the Teal Group, civil UAVs are expected to reach more than 4 million units worldwide by 2025 (Geiver 2016). Based on this number and the fact that hybrid UAVs will only represent a fraction of these, it was assumed that the NU-21 technology will be implemented in 100 units by 2030, starting in 2021 and constantly increasing year after year.</td>
</tr>
<tr>
<td><strong>OPT-21</strong></td>
<td>70 gliders converted to electric engines by 2030 in Canada (assumptions provided by project leaders).</td>
</tr>
<tr>
<td><strong>PWC-23</strong></td>
<td>Market projections by ATR indicate 3020 new turboprops by 2038 (Vargas 2018). Projections were transposed to the 2022–2030 period; the technology will begin to be commercialized in 2022.</td>
</tr>
<tr>
<td><strong>PWC-24</strong></td>
<td>Bombardier’s 2017–2036 market projections for large regional aircraft were transposed to the 2024–2030 period (Bombardier 2017). Market penetration was assumed to be 5% until 2027 and 10% until 2030.</td>
</tr>
<tr>
<td><strong>SRS-21 &amp; 22</strong></td>
<td>20 regional airlines by 2030 (linear adoption starting in 2019). Each airline is assumed to have 12 aircraft on average.</td>
</tr>
</tbody>
</table>
### 2.3 Environmental Metrics

For each project, relevant environmental metrics were determined. Metrics were identified based on the nature of the projects, the expected benefits, as well as expert judgment in order for the projects to be aligned with the national indicators and metrics already used by the federal government to monitor the country’s environmental performances. In total, seven metrics were selected to cover the potential environmental benefits of the technologies of the nineteen GARDN projects. Table 4 lists these seven metrics.

**Table 4: Environmental metrics**

<table>
<thead>
<tr>
<th>Clean and sustainable air transportation systems</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Greenhouse gas (GHG) emissions</strong>: Refers to the impact of the global temperature increase on climate patterns (e.g. severe flooding and drought events, accelerated melting of glaciers) caused by the release of GHGs (e.g. carbon dioxide from jet fuel combustion). These emissions are expressed in megatonnes of carbon dioxide equivalents (Mt CO₂ eq.).</td>
<td></td>
</tr>
<tr>
<td><strong>Nitrogen oxides (NOₓ)</strong>: In the presence of sunlight, nitrogen oxides create smog that can affect human health and cause various respiratory problems. NOₓ are also associated with acid rain, which has a negative impact on ecosystems and the built environment. NOₓ emissions are expressed in kilotonnes (kt).</td>
<td></td>
</tr>
<tr>
<td><strong>Particulate matter (PM)</strong>: Fine particles smaller than 100 microns are emitted to air during processes such as incomplete combustion. Exposure to PMs can be harmful and cause respiratory problems. PM emissions are expressed in kilotonnes (kt).</td>
<td></td>
</tr>
<tr>
<td><strong>Sulphur oxides (SOₓ)</strong>: Emitted to air when burning sulphur-containing fuels, these gases dissolve in the atmosphere’s water and are a cause of acid rain. They also contribute to the formation of fine particles that can be harmful to people. SOₓ emissions are expressed in kilotonnes (kt).</td>
<td></td>
</tr>
<tr>
<td><strong>Non-renewable primary energy consumption (NRPEC)</strong>: Refers to the use of energy from non-renewable resources (e.g. jet fuel). The quantity of primary energy used is expressed in petajoules (PJ), on the basis of the resources’ higher heating value (HHV).</td>
<td></td>
</tr>
<tr>
<td><strong>Waste generated</strong>: Corresponds to the dry mass of non-hazardous waste generated.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quiet air transportation systems</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cumulative noise</strong>: Noise around airports is calculated as the cumulative noise from three certification reference measurement points (approach, lateral, take-off/flyover) and expressed in EPNdB (Effective Perceived Noise in decibels), which is a measure of the relative loudness of an individual aircraft pass-by event, as defined by the International Civil Aviation Organization (ICAO). Cumulative noise is not additive from one flight to another. Therefore, it was only evaluated at the flight level.</td>
<td></td>
</tr>
<tr>
<td><strong>Noise footprint</strong>: The noise footprint is defined as the area that experiences noise levels of 70 dB (A) or higher during the take-off and landing events. The noise footprint is not additive from one flight to another. Therefore, it was only evaluated at the flight level.</td>
<td></td>
</tr>
</tbody>
</table>
3. Estimated Environmental Benefits

This section presents the results of the environmental benefits evaluation at the flight level (3.1) and then at the fleet level (3.2) for the technology clusters presented in the previous section.

3.1 Flight-Level Reductions of Clustered Technologies

3.1.1 Clean and Sustainable Air Transportation Systems

Flight-level reductions for clean and sustainable air transportation systems are given in percentages, that is to say, the reduction in environmental metrics for one flight of an aircraft of a given cluster compared to a flight of the same aircraft without the technology. Table 5 includes results for clean air transportation systems and sustainable air transportation systems that reduce air pollutants (GHG, NO$_x$, PM, and SO$_x$) and NRPEC.

<table>
<thead>
<tr>
<th>Clusters</th>
<th>GHG</th>
<th>NO$_x$</th>
<th>PM</th>
<th>SO$_x$</th>
<th>Relative Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAF (30% blend)</td>
<td>18%</td>
<td>-</td>
<td>-</td>
<td>9%</td>
<td>13%</td>
</tr>
<tr>
<td>Greener business jet</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Unconventional configurations</td>
<td>13%</td>
<td>13%</td>
<td>13%</td>
<td>13%</td>
<td>13%</td>
</tr>
<tr>
<td>Greener commercial turbofan</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Electric glider</td>
<td>93%</td>
<td>93%</td>
<td>37%</td>
<td>93%</td>
<td>95%</td>
</tr>
<tr>
<td>Greener large turboprop</td>
<td>-</td>
<td>31%</td>
<td>19%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Greener small turboprop</td>
<td>9%</td>
<td>9%</td>
<td>9%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>Hybrid UAV</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 5: Relative environmental benefits for one flight of clean and sustainable air transportation systems

See Table 4 for legend. Positive numbers mean impact reduction. “-” means no reductions were estimated or attributed to the cluster.

It was found that technologies reducing fuel consumption (increasing fuel efficiency), namely unconventional configurations, the hybrid UAV, the greener small turboprop, the greener commercial turbofan, and the greener business jet, yield environmental benefits for the five metrics between 0.3% and 13%. Electric gliders offer the highest relative reductions on all environmental metrics. This technology consists in an electric propulsion system for the conversion of existing gliders—which are most often launched with towing aircraft powered by an internal combustion engine—into self-launch electric gliders. Since the NRPEC and air emissions of the converted gliders only result from electricity generation and the production of the electric engine and batteries, the relative

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1 The available data did not allow to differentiate air contaminants affected by fuel burn reductions. Therefore, the same reduction was applied to the four air contaminants in Table 5 (GHG, NO$_x$, PM, and SO$_x$) for these technologies.
environmental benefits are high for one flight. The benefits on PM emissions are not as strong because the towing of conventional gliders produces few of them.

Unconventional configurations greatly reduce drag and consequently also reduces fuel burn. Hence, an average relative reduction of 13% is estimated on the five environmental metrics (between 9% and 17%). The unconventional configurations are followed by hybrid UAVs and small turboprop aircraft that use a flight optimization app. Greener turbofans and business jets are clusters with flight-level reductions representing less than 5%.

The greener large turboprop and the SAF clusters do not affect all environmental metrics related to fuel efficiency. The former cluster includes many different technologies, but only one affected air emissions, that is to say, the low-NO\textsubscript{x} engine enhancement. SAFs are made from renewable plant-based feedstock and therefore reduce NRPEC and fossil CO\textsubscript{2} emissions. A 30% biojet blend (30% biojet mixed with 70% conventional jet fuel) was considered since it was used in one of the SAF projects. Values as high as 43% were tested, but would not constitute a standard value for commercial aircraft operations. Due to the lack of specific information on the impact of SAF use on PM and NO\textsubscript{x} emissions during fuel combustion and production, it was not possible to differentiate between the emissions of the baseline scenario (conventional jet fuel) and the ones of the technology scenario (SAF). Therefore, no reduction could be quantified for these metrics in this cluster.

### 3.1.2 Other Sustainable Air Transportation Systems

Sustainable air transportation systems included waste reduction technologies used during the manufacturing of aircraft in the clusters listed in Table 6. Due to lack of data and the complexity of the aerospace supply chain, the percentages could not be calculated in the same way as the other environmental metrics. For this metric, the quantity of avoided waste for the manufacturing of one specific aircraft part was known. However, the total quantity of waste generated to produce the entire aircraft was not. Therefore, the percentage of waste reduction for the manufacturing of the specific part was calculated, but not as a percentage of waste generated for an aircraft.

<table>
<thead>
<tr>
<th>Clusters</th>
<th>% reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greener business jet</td>
<td>93%</td>
</tr>
<tr>
<td>Greener commercial turbofan</td>
<td>100%</td>
</tr>
<tr>
<td>Greener large turboprop</td>
<td>86%</td>
</tr>
</tbody>
</table>

*See Table 4 for legend. Positive numbers mean impact reduction.*

The greener business jet and large turboprop clusters included additive manufacturing applications. This technique reduces the use of materials and, hence, reduces waste. The greener commercial turbofan cluster consisted in recycling production waste to divert uncured composite waste from landfills.
The SAF and GSCM clusters are also part of this research category (sustainable air transportation systems). However, the former was addressed in the previous section. For the latter, no quantification of benefits was possible.

### 3.1.3 Quiet Air Transportation Systems

Noise reductions for cumulative noise are expressed either in dB SPL (decibels sound pressure level), which is a measure of the change in air pressure due to sound waves, or in EPNdB (Effective Perceived Noise), which is a measure of the relative loudness of an individual aircraft pass-by event. Since decibels represent a variation from a reference value, they have been converted to percentages based on a theoretical formula (see notes in Table 6). Noise footprint reduction represents a decrease in the area exposed to a defined noise level and is expressed in percentages as well. The flight-level environmental benefits are presented in Table 7.

**Table 7: Relative environmental benefits for one flight of quiet air transportation systems**

<table>
<thead>
<tr>
<th>Clusters</th>
<th>EPNdB</th>
<th>% Reduction</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconventional configurations</td>
<td>2.6</td>
<td>16%**</td>
<td>33%</td>
</tr>
<tr>
<td>Greener business jet</td>
<td>2</td>
<td>13%**</td>
<td>31%</td>
</tr>
<tr>
<td>Electric glider</td>
<td>9 dB (SPL)*</td>
<td>65%**</td>
<td>-</td>
</tr>
<tr>
<td>Greener large turboprop</td>
<td>4.7</td>
<td>28%**</td>
<td>11%</td>
</tr>
</tbody>
</table>

See Table 4 for legend. Positive numbers mean impact reduction.

* Noise reduction was measured in dB SPL (sound pressure level) for this cluster. This metric differs from the EPNdB in that it corresponds to the change in air pressure due to the sound waves rather than to the perceived loudness of the sound made by an aircraft.

** Conversion of the reduction from dB to % was done using 100% - 2^(-EPNdB/10)*10 for EPNdB and 100% - 10^(-dB (SPL)/20)*100 for dB SPL (http://www.sengpielaudio.com/calculator-levelchange.htm).

Aircraft noise essentially comes from two sources: the airframe and engines. Over the past years, engine noise has considerably improved, and the airframe has become the major contributor of aircraft noise. This is particularly the case during the approach phase (one of the three noise certification reference measurement points for an aircraft) when the engine operates at low or no power. During take-off, engines are the dominant source of noise, as the aircraft uses lower flap settings and quickly retracts its landing gear. Depending on the technology, engine noise is related to several sources: fan, jet, combustion, and turbine and/or compressor (Bertsch et al. 2015).

Focusing on the airframe, the technologies being developed in the unconventional configuration cluster showed significant anticipated noise benefits. The full redesign of business jets’ airframe enables the reconception of its main noise sources and the integration of innovative solutions. For current aircraft, the landing gear, high-lift system (flaps and slats), spoilers, speed brakes, and edge devices are the key contributors to airframe noise (Bertsch et al. 2015). The optimized design of some of these parts and the use of micro-perforated panels (MPP) are two technologies developed under

---

2 The airframe of an aircraft is its mechanical structure. It typically includes fuselage, wings, and undercarriage and excludes the propulsion system.
the GARDN projects that could be applied to current business or commercial aircraft concepts and provide new solutions to reduce noise levels in the near future. The resulting noise benefits are attributed to the greener business jet technology cluster.

As for the engines, a few technologies were tested in the greener large turboprop cluster: a low-noise propeller design as well as an advanced duct and liner technology. Interaction between individual noise reduction solutions was studied to target integrated solutions for regional turboprop aircraft.

The introduction of electric engines is also a very promising technology for the radical reduction of noise associated to aircraft engines. The development of an electric propulsion system for gliders, although very specific to this uncommon type of aircraft, is aligned with the development of such electric technologies in aeronautics. It will help address both local and global issues. At the local level, the frequent landings and take-offs of the towing aircraft powered by a combustion engine during glider training sessions are a source of annoyance for the local population. The development of an electric propulsion system for gliders will help address this local issue. In addition, the developed knowledge for gliders may benefit other types of aircraft.

For all the noise reduction technologies under study, the development of improved models to predict noise at the design phase and to test new solutions is also essential, as this will lower the costs of developing and testing those innovative noise reduction solutions (Bertsch et al. 2015). All GARDN projects related to noise reduction included the development of numerical, semi-analytical, empirical, or semi-empirical models to improve noise prediction.

### 3.2 2018–2030 Fleet-Level Reductions

GARDN II’s research portfolio is directly aligned with the Federal Sustainable Development Strategy for Canada (2016–2019). Indeed, some of the key goals of the Canadian strategy aim to achieve effective action on climate change, clean growth, and safe and healthy communities. The Canadian government has planned to reduce Canada’s total GHG emissions by 30% below 2005 levels by 2030. In this context, the cumulative environmental benefits at the fleet level and for the 2018–2030 period—for most of the environmental metrics presented in section 3.1—have been estimated using the assumptions described in Table 3. Figure 5 shows the results for NRPEC and GHG, NO\textsubscript{x}, PM and SO\textsubscript{x} emissions, which include direct and indirect environmental benefits in Canada and abroad.

Based on the results, three clusters, namely greener commercial turbofan, SAF, and greener large turboprop aircraft, contribute to more than 10% of the cumulative benefits for at least one of the environmental metrics. Although the greener commercial turbofan cluster did not generate the highest environmental benefits at the flight level (3%), the cumulative reductions are the highest due to the large number of aircraft potentially affected by the technologies of this cluster.

Since aircraft with unconventional configurations are not expected to enter the market before 2035, this cluster does not contribute to the environmental benefits presented on Figure 5. However, over a 13-year period of time starting in 2035 instead of 2018, if this type of aircraft is widely adopted, the estimated cumulative environmental benefits (direct and indirect) due to fuel burn reduction from reduced drag could be 23 PJ of NRPEC, 1 Mt CO\textsubscript{2} eq., 6 kt of NO\textsubscript{x}, 0.3 kt of PM, and 2 kt of SO\textsubscript{x} worldwide (rough estimates). Considering these numbers represent between 15% and 48% of the
GHG
Total: 6.5 Mt CO₂ eq.
- SAF: 2.9 Mt CO₂ eq.
- Greener commercial turbofan: 3.4 Mt CO₂ eq.

NOₓ
Total: 16 kt
- Greener commercial turbofan: 13 kt

PM
Total: 0.63 kt
- Greener commercial turbofan: 0.58 kt

SOₓ
Total: 8.2 kt
- SAF: 2.4 kt

NRPEC
Total: 90 PJ
- SAF: 35 PJ
- Greener commercial turbofan: 52 PJ

Legend:
- Greener commercial turbofan
- Greener business jet
- Greener large turboprop
- Electric glider
- Hybrid UAV

Figure 5: Worldwide 2018–2030 cumulative direct and indirect reductions
cumulative 2018–2030 benefits for all other clusters presented on Figure 5, unconventional configurations have a significant potential to reduce the environmental impacts of aviation.

The previously presented results aggregated direct and indirect environmental benefits. The former occur as a result of the operation of an aircraft, while the latter represent upstream benefits (e.g. avoided impacts related to jet fuel production). Figure 6 below shows worldwide direct and indirect fossil GHG emission reductions over time for the greener commercial turbofan, SAF, and the remaining clusters grouped together. Between 2018 and 2030, net GHG emission reductions on an annual basis are predicted to increase from 0.2 to 1.0 Mt CO₂ eq.

Fuel efficiency technologies for turbofan aircraft generate both direct and indirect fossil GHG emission reductions. The above figure shows that indirect emission reductions related to avoided jet fuel production (light blue) account for 16% of the projected direct emission reductions every year for that cluster. On the other hand, the current production of SAF generates more fossil GHG emissions than the production of conventional jet fuel (approx. 1.2-1.8 vs. 0.5 kg CO₂ eq./kg of fuel) according to the data used in this study from Canada’s Biojet Supply Chain Initiative (de Jong 2017) and SCLCI (2018). Therefore, there are no indirect fossil GHG emission reductions for that cluster, but rather an increase represented by the pale purple area in the negative part of the graph. Since direct emissions from SAF combustion do not contribute to climate change and replace emissions from conventional jet fuel, direct reductions are much more important than the increase in fossil GHG emissions resulting from SAF production; the SAF cluster thus has net environmental benefits on climate change.

3.3 GARDN II’S CONTRIBUTION TO A GREENER CANADA

The following sections focus on the contribution of these estimated environmental benefits to Canadian environmental targets.
3.3.1 Greenhouse Gases (GHGs)

ICAO members, including Canada, have the aspirational goals of improving its annual fuel efficiency and carbon neutral growth by 2% from 2020 onwards (ICAO 2018). In 2017, domestic aviation accounted for approximately 7 Mt CO₂ eq. (Government of Canada 2018). This target is represented by the purple line in Figure 7. According to historical data, domestic aviation GHG emissions grew by 3% annually between 2012 and 2017. Assuming a similar growth based on a business-as-usual scenario (BAU), domestic aviation GHG emissions should reach nearly 10 Mt CO₂ eq. by 2030. The BAU emissions are represented by the blue line in Figure 7. The distance between the blue and purple lines is therefore the annual reduction target, that is to say, 2.6 Mt CO₂ eq. by 2030.

To evaluate the GARDN program’s contribution to the achievement of this target, only the GHG reductions from Figure 6 happening in Canada were taken into account. They represent approximately 0.7 Mt CO₂ eq. for the year 2030. By subtracting them from the business-as-usual projections, they contribute to 27% of the reductions required to reach the neutral growth target (7 Mt CO₂ eq./year). In 2030, SAFs will account for 98% of the annual and cumulative GARDN GHG reductions happening in Canada.

This assessment demonstrates the importance of investing in the research and development of greener technologies in the aerospace sector to achieve the international and national climate change targets. It indicates that the benefits of greener technologies tend to grow over time and consequently stresses the relevance of investing early in their development.
3.3.2 Other Air Contaminants

In Canada, the national emissions of several air contaminants are evaluated annually and recorded in the Air Pollutant Emission Inventory (APEI). Emissions from the transportation sector and the air transportation subsector in 2016 show that aviation is an important source of lead (97% of the transportation sector), SO\textsubscript{x} (29%), NO\textsubscript{x} (8%), and polycyclic aromatic hydrocarbons (PAHs; 8%) emitted to air (ECCC 2018a). As a comparison, aviation contributed to 11% of transportation GHG emissions that year (ECCC 2018b). Moreover, while SO\textsubscript{x}, NO\textsubscript{x}, and PAH emissions have decreased in the Canadian transportation sector since 2011, they have increased in the aviation sector according to APEI data (see Appendix A).

Aviation lead emissions are generated by the combustion of aviation gasoline (avgas) by piston engine aircraft. It is the second leading source of airborne lead in the country (Canteenwalla et al. 2017). Health problems such as neurological effects in children as well as high blood pressure and heart diseases in adults can be caused by lead exposure (US EPA, n.d.). Therefore, technological innovations that reduce avgas consumption are relevant to address this environmental concern. In this regard, the hybrid UAV technology developed with the support of the GARDN II program will help limit avgas consumption by this type of aircraft and, hence, limit lead emissions. Although lead emissions are significant, they were not investigated further in this study, as only the UAV cluster is concerned by this environmental issue.

Due to the sulphur content of jet fuel, SO\textsubscript{x} emissions from aviation also represent a significant part of the Canadian transportation sector emissions. In 2012, the average jet fuel sulphur content in the country was 539 mg/kg of fuel, compared to 21 mg/kg for gasoline (EC 2015). SO\textsubscript{x} are partly responsible for acid rain and smog formation. The development of fuel-efficient aircraft helps to reduce SO\textsubscript{x} emissions resulting from the combustion of sulphur-containing jet fuel. All technology clusters covered in this study, except SAFs and GSCM, included such fuel-efficient technologies, and thus contribute to reducing SO\textsubscript{x} emissions. Moreover, SAFs, as opposed to fossil fuels, do not contain sulphur (Kharina and Pavlenko 2017; USDOE 2017). Therefore, their development has benefits not only on the climate, but also on direct SO\textsubscript{x} emissions (during flight). Indirect (upstream) SO\textsubscript{x} emissions related to jet fuel and SAF production were taken into account.

NO\textsubscript{x} and PAH are related to how fuel is burned. NO\textsubscript{x} contribute to acid rain and smog, while PAHs are highly toxic substances. Again, fuel-efficient technologies reduce these airborne emissions by decreasing fuel burn for equivalent travelled distance and mass. In addition to these initiatives, the GARDN II program has supported research for the implementation of a low-NO\textsubscript{x} turboprop engine technology that aims to reduce direct NO\textsubscript{x} emissions by 31%.

PM emissions are recognized as a public health concern, as they are linked to cardiac and respiratory diseases. For that reason, they were included as an environmental metric in the benefits evaluation of green technologies. This study has revealed that, while still relevant because of their impact on human health, PM emissions in aviation may not be as important as other air contaminants due to their limited contribution to the transportation sector (2% or less). A comparison of the health impacts caused by airborne contaminants emitted by the aviation sector could lead to a different conclusion.
3.3.3 **Non-Renewable Primary Energy Consumption (NRPEC)**

The NRPEC environmental metric is closely linked to GHG emissions. Although there is no Canadian target for this environmental metric, GARDN II technologies have the potential to generate major NRPEC reductions for the aviation sector. Based on the BAU jet fuel consumption projection used for GHG emissions, NRPEC of domestic aviation could go from 98 PJ to 141 PJ between 2018 and 2030, which represents an increase of 43 PJ. The GARDN II technologies could limit this increase by 25%, in other words, to 32 PJ in 2030.

3.3.4 **Noise**

Noise is one of the main environmental issues the aerospace sector faces. Aircraft noise is the main cause of adverse reactions to the operation of airports, and reducing the number of people affected by it is one of ICAO’s main environmental priorities (ICAO 2016). Aircraft noise could also be related to several effects on ecosystems and human populations, ranging from annoyance to effects on sleep and children’s cognitive skills (ICAO 2016). Since the 1970s, aircraft noise has been controlled by setting limits (ICAO, n.d.), which are defined in Annex 16 of the Convention on International Civil Aviation entitled “Environmental Protection,” Volume I, “Aircraft Noise”. The following figure illustrates the evolution of the ICAO noise standards over time (note how noise limits vary with maximum take-off mass [MTOM], as heavier aircraft produce more noise). The current standard of reference for a new aircraft is the one defined in Chapter 14 of Annex 16.

As illustrated in Figure 9, ICAO noise regulations are increasingly stringent, and since every aircraft must be certified under these regulations, the aeronautic industry must constantly improve to meet current regulations and to anticipate upcoming ones. The impact of noise standards on effective aircraft noise is constantly monitored by ICAO, and Annex 16 will be reviewed and updated in the upcoming years. New types of aircraft also lead to the development of new standards to reflect their specific reality, which in turn could affect current Canadian research projects on this type of aircraft. The noise reductions presented in section 3.1.3 could not, however, be compared to ICAO targets, as future targets are not known and depend on several parameters (such as the MTOM). Most recent aircraft already comply with Chapter 14 of Annex 16.

![Figure 8: Evolution of ICAO Noise Standards](Image taken from ICAO [n.d.])
In Canada, ICAO noise standards are included into the Canadian Aviation Regulations, which require that all aircraft operating in Canada obtain a Certificate of Noise Compliance. The regulations state that noise emission standards and noise evaluation methods for the certification of aircraft in Canada are those defined by the ICAO’s Annex 16 (Transport Canada 2018). Noise operating restrictions and noise abatement procedures are also published by NAV CANADA, the company that owns and operates Canada’s civil air navigation service, to reduce aircraft noise by changing aircraft operational procedures. At the airport level, noise management committees, which include representatives of all stakeholders, develop specific noise abatement proposals relative to its specific context.

More stringent restrictions than those developed by the ICAO also exist. Some airports can, for instance, develop specific regulations regarding the types of noise and the noise emission levels of the aircraft they accept. London’s Heathrow Airport developed its own restrictions for night flights, forbidding the noisiest aircraft to land or take off between 11:30 p.m. and 6:00 a.m. and using a system of quotas based on the noise level of the aircraft (Heathrow Community Relations Team, n.d.). Other airports, such as the San Francisco International Airport and the Toronto International Pearson Airport, are using or planning to implement a Fly Quiet Program that scores and ranks airlines based on measures, such as the type of aircraft operated and the flight schedule (Toronto Pearson 2018).

All these regulations could significantly affect aircraft production in Canada, as airline companies or private clients would not buy aircraft that do not comply with these regulations if they are to be used at such airports. It is also expected that more and more airports and countries will be developing similar stringent regulations or incentives regarding noise levels. Noise reduction then becomes a competitiveness issue for the Canadian aerospace industry and could affect airlines’ licences to operate.

It is expected that the technologies developed in the projects under study will be implemented in the next generation of aircraft and/or engines developed in Canada and that they will be used in a portion of the Canadian fleet in operation in 2030. However, the number of affected aircraft was not available for the noise reduction technologies, except for electric gliders, for which 80 aircraft are expected to be converted in Canada.

Unlike other environmental metrics, noise benefits cannot be evaluated at the fleet level, as aircraft noise is essentially locally perceived (around airports), and the entire fleet will not be using only one airport. To be able to assess the impact of the noise reductions associated with the new technologies at the airport level, it would be necessary to know the forecasted number of flights and their schedule, the types of aircraft and the airports they will be using; however, this information could not be obtained. Therefore, noise reductions were evaluated only at the flight level (see section 3.1.3).
3.4 Result Limitations

The environmental benefits evaluation of GARDN II technologies in this study relied on assumptions, both at the flight and fleet levels. Here is a list of assumptions that could limit the validity of the results:

- **SAFs:**
  - Market forecasts of SAF or biofuel production capacity in Canada are scarce.
  - The direct and indirect environmental benefits of SAFs were attributed to a GARDN project that is developing a way to integrate SAFs in the current jet fuel distribution systems, since this is required to ensure significant market penetration.
  - Only GHG, NRPEC, and SOx were considered during SAF production. NOx and PM were not due to lack of data.
  - At the fleet level, it was considered that the GARDN projects’ SAF, that is to say, made from forest residues and cooking oil, would provide all projected biojet fuel in Canada. Other types of biofuels are likely to appear on the market by 2030.

- **End-of-life:** This life cycle stage was not included in this study. Therefore, the environmental benefits of the GARDN technologies at the aircraft’s end-of-life, if any, are not included in the results.

- **Non-quantifiable reductions:** The benefits of some technologies could not be quantified, as no data could be used. It is the case for green supply chain management, aircraft contrail formation using SAFs, and the measurement of non-volatile particulate matter from the engine exhaust. The estimated environmental benefits related to these innovations were not included in the results and are therefore underestimated in that sense.

- **Unconventional configurations:** This technology has a low readiness level (TRL), and there is high uncertainty as to when and if it will be marketed.
4. **CONCLUSIONS AND RECOMMENDATIONS**

The overall contribution of GARDN II projects to reduce the environmental footprint of the Canadian aerospace industry is significant. Manufacturing greener aircraft will contribute to ensuring the competitiveness of Canadian aerospace companies in an industry where regulations on environmental performance are increasingly stringent. More specifically, this study found that the technologies under study have the potential to:

- Contribute to 27% of the Canadian aviation GHG target of neutral growth in 2030. 98% of this reduction is attributed to SAFs.
- Address important environmental issues related to the aviation sector: GHG, NOx, and SOx emissions, non-renewable energy consumption, and noise, as well as emissions of other air contaminants, such as PAH and lead.
- Help the industry meet ICAO’s noise regulations, which must be met to operate for an aircraft to enter service, and therefore contribute to the competitiveness of the sector.

At the flight level, the GARDN II projects demonstrate greater benefits for gliders, small and large turboprops, and UAVs. However, when benefits are scaled up to a fleet level and extrapolated over time, commercial turbofans are found to have the greatest potential. This illustrates the importance of considering the potential benefits on both assessment levels.

With a view to achieving the national and international GHG reduction targets, the study also identified the development of the SAF industry as a key component of success. GARDN II projects have addressed different issues at the manufacturing, distribution, and operation levels that need to be solved to unleash the potential benefits of this technology. It is therefore important to continue the work to ensure that benefits calculated in this study materialize.

This study established a methodology that will allow the standardization of the environmental assessment of potential benefits of past and future technology development projects in the aerospace sector. This approach proposes different assessment levels and several impact indicators and includes direct and indirect potential environmental impacts or benefits. All these dimensions are essential to capture the actual potential benefits in a consistent and comparable approach. Using this methodology, it will be possible for future GARDN programs to:

- Select projects that have the potential to be implemented in a large fleet of aircraft. Technologies achieving the highest environmental benefits at the flight level do not necessarily end up contributing the most to cumulative fleet-level benefits.
- Focus on technologies applicable to aircraft that are operated or that will be operated in the country to increase GARDN’s contribution to Canada’s neutral growth target in aviation.

Environmental benefits related to the end-of-life of aircraft and to SAF air emissions (NOx and PM) were not included in this study due to a lack of data, which constitutes a limitation of the developed methodology. Therefore, it is recommended to increase efforts in future programs to collect data for the assessment these potential environmental benefits.
Finally, this assessment demonstrated the importance of investing in the research and development of greener technologies in the aerospace sector to achieve the international and national climate change targets. It also shows that the benefits of greener technologies tend to grow over time and consequently stresses the relevance of programs like GARDN to invest early in their development.
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Figure 9: Canadian emissions of air contaminants for the entire transportation sector (left) and for air transportation (right). Source: APEI.