Prospective Life Cycle Assessment in Surface Engineering: Case Studies on a Novel Thermal Spray Coating System and a Novel Coating Removal Method

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ABSTRACT

Prospective Life Cycle Assessment in Surface Engineering: Case Studies on a Novel Thermal Spray Coating System and a Novel Coating Removal Method

Zeynab Yousefzadeh, MASc. Concordia University, 2021

Life Cycle Assessment (LCA) is a framework for quantifying the potential environmental impact of products from raw material extraction through materials processing, manufacturing, distribution, use, and end-of-life. Prospective LCA estimates the future environmental impacts of emerging technologies. It can be used to support eco-design, such as green surface engineering. Prospective LCA is used in this thesis to compare emerging surface engineering and incumbent technologies. The first case study compares a novel thermal sprayed multi-layered alumina-nickel chromium resistive heating coating to heat tracing cables for pipe freeze protection. The coating system's impacts are higher for fabrication but lower for use, making it environmentally preferable in areas with colder climates and non-renewable electricity mixes. Specific life expectancy and efficiency improvements were identified to achieve environmentally preferability in most locations. Alternate strategies include reducing the environmental impact of fabrication by using alternate materials or deposition processes and developing strategies for recovering and recycling coating materials. The second case study compared a novel pulse water jet (PWJ) technology with alkaline electrochemical cleaning for removing hard chromium from aircraft landing gear. If the PWJ system can be designed to remove the coating from workpieces with complex geometry, its environmental impact is expected to be lower due to its lower electricity consumption, chemical use, and waste management. The case studies demonstrate the value of using prospective LCA during early development, adopting a range of techniques for addressing uncertainty, and breaking down the results to provide developers with strategies for reducing environmental impact.

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Contribution of Authors

For the first case study of this thesis (chapter 2), technical inputs of the multi-layered coating system and cable system were provided by Milad Rezvani based on experiments he conducted in the surface engineering lab at the University of Alberta. Chapter 2 is a modified version of a manuscript that will be submitted to the Surface and Coatings Technology Journal. The manuscript is titled "Environmental life cycle assessment of a thermal sprayed multi-layered alumina- nickel chromium resistive heating coating for pipe freeze protection" and is co-authored by Milad Rezvani Rad, André McDonald, and Shannon Lloyd. The research reported in the manuscript and chapter 2 was conducted by the author of this thesis, Zeynab Yousefzadeh, with data and advising provided by the co-authors.

For the second case study of this thesis (chapter 3), the technical data of removal methods was provided by Roger Eybel and Alan Caceres from Safran Group, and Andrew Tieu and William Bloom from VLN Advanced technologies Inc. The third chapter case study will be revised and submitted for publication to a peer-reviewed journal. The resulting manuscript will be co-authored by Roger Eybel, Alan Caceres, Andrew Tieu, William Bloom and Shannon Lloyd. The research reported in chapter 3 was conducted by the author of this thesis, Zeynab Yousefzadeh, with data and advising provided by the co-authors.

As the supervisor of this thesis, Shannon Lloyd revised and advised this work several times, introduced relevant resources, and provided comments and feedback for all chapters of this work.

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1. Introduction

1.1. Life Cycle Assessment as a Tool for Studying Emerging Surface Engineering Technologies

Greenhouse gas emissions are often used as a sole indicator of the environmental sustainability of industrial systems [1]. This is understandable given the rapid increase in CO_2 concentration in the atmosphere [2], the resulting increase in global average temperature [3], and the expected consequences of a warming planet[4]. Although reducing GHG emissions and global warming are commonly used as a proxy for environmental preservation, industrial systems impact the environment and, as a result, humans in many diverse ways. Sustainable production must also consider issues related to resource (e.g. water, mineral and fuel) consumption, releases of toxic materials to environmental media (i.e., air, water, and soil), occupational safety, and other environmental and societal impacts [5]. Failure to do so can result in unintended trade-offs, e.g., where greenhouse gas emissions are reduced while other negative impacts increase[6].

Life cycle oriented environmental assessment methods have been developed to aid industry in identifying, quantifying, and improving environmental impact of their operations since 1960 [7]. Evaluation of these methods led to emerge Resource and Environmental Profile Analysis (REPA) developed by Robert G. Hunt in the United States (US) [8] and Ecobalance was developed by Bernd Wagner and Mark White in Europe [9] to detect and measure environmental performance of industrial activities. By 1990, a new analytical framework inspired by the material flow accounting concepts employed by the REPA and ecobalance frameworks emerged and became known as Life Cycle Assessment (LCA) [7]. This novel analytical framework provided a systematic approach for identifying and quantifying the potential environmental impact of products across the complete product life, from extraction of raw materials through material processing, product manufacturing, distribution, use, and end-of-life, where the product is either disposed of as waste or repurposed (e.g., reuse, remanufacturing, recycling) [7]. In, 1993, the Society of Environmental Toxicology and Chemistry (SETAC) developed an LCA Code of Practice[10]. International Organization for Standardization (ISO) started began developing a set of LCA standards. The first ISO LCA standard, ISO 14040 Environmental management — Life cycle assessment — Principles and framework, was released in 1997 [11]. Over the last three decades the standards have evolved, and now include ISO 14041, ISO 14042, ISO 14043 standards that provide general guidance for LCA[12], as well as specific guidance for performing specific types of LCAs. These standards help industries, companies, and LCA practitioners to conduct the LCA in a standard and systemized way [13].

Surface Engineering (SE) consists of various methods and processes for developing properties in a piece surface independently from the substrate material. Here, the improvement includes a vast range of properties from modifying tribological behaviour or corrosion resistance, creating a particular optical or tactile characteristic, making a hydrophilic or hydrophobic layer, or giving a specific visual appearance to the surface of a part [14]. Nowadays, various industries like aerospace, automotive, electronic, power supply, construction materials, chemical, petrochemical, biomedical, and textile industries benefit from surface engineering added value. In general, surface engineering can help industry achieve a number of objectives, e.g., lowering production expenditure, enhancing durability, increasing recyclability, reducing environmental impact, and adding new functionality to conventional materials [15].

LCA has been used to assess the potential environmental impact of surface engineering processes and products. For example, one of the conventional surface engineering processes that have received many critics because of its high chemical use and hazardous waste is electroplating. Many surface engineering processes and materials developed to be replaced with electroplating and decreasing the impact. Montavon et al. [16] studied alternatives of hard chromium plating, including Atmospheric Plasma Spraying (ASP) and High-Velocity Oxygen Fuel (HVOF) of Cobalt Cermet Tungsten Carbide (WC-Co) and novel hard steel coatings applied with Twin-Wire Electric Arc (TWEA) and ASP, which have similar wear resistance properties. They showed that hard chromium plating has a significantly higher impact considering its need to recycle water and air emissions. Also, hard steel spraying has a better environmental score among alternatives due to the difference in coating material processing impacts. Three years later, in 2009, Moign et al. [17] published an LCA study with opposite results that compared electroplating of nickel with deposition of nickel by thermal spray coating methods including Plasma Spray, TWEA, HVOF, and Cold Spray. The electroplating impact was lower than its alternatives due to the less feed stock impact; however, apart from the difference in the coating, the wastewater treatment impact was not included in this study, which had a large effect on the result in the previous LCA.

Nowadays surface engineering become a vast and dynamic industry and investments in surface engineering research and development have increase substantially. There are about 65 word-wide academic research centers study on and 95 hundred establishments in US engage with surface engineering [15]. Analytical methods, such as LCA, can be used alongside in the development of new surface engineering technologies and materials consider them from an environmental perspective. Instead of comparing existing technologies via ex-post assessments, incumbent systems, processes or materials can be compared with emerging systems, processes or materials even at low technology readiness levels, e.g., during concept development, lab-scale, or benchmarking stages [18]. While ex-post analysis of technologies once they are commercialised provides important data for decision-making, the fast-growing nature of surface engineering requires analyses that can inform decision during research and development via estimations based on the best available information [19]. For example, use of LCA to predict the potential environmental performance of their products during early development stages can help avoid environmental impact, reduce expenditures associated with environmental impacts (e.g., through increased resource efficiency or reduced hazardous waste generation), and ensure compliance with existing and anticipated environmental regulation. [19]. This requires use of ex-ante rather than ex-post LCA.

Prospective LCA is one of the ex-ante study types commonly comparing an emerging technology with an existing matured technology to ensure the new system is developing with environmentally friendly methods [19], [20]. This method has been used to study emerging surface engineering technologies. For example, Gilbertson et al. [21] used LCA to compare two emerging nanowires deposition technologies, including direct growth on a silicon wafer and growth on a native substrate followed by transfer to silicon to fabricate solar cells. This study suggested that technology developers decrease the consumption of gold, decrease the use of the electroplating process, and recycle substrates to minimize potential environmental impact. Moign et al. [22] used LCA to compare two types of plasma sprays, each using different materials for the deposition of yttria-stabilized zirconia. In this work, the potential environmental impact of using a new technology with liquid precursors was compared to a conventional plasma spray that used powder. Based on the results using liquid solution feedstock had lower impact in comparison with powder and suspension.

Despite the benefits of using LCA during the development of emerging technologies [18], there are many challenges associated with prospective LCA of emerging solutions. LCA practitioners tend to rely on a combination of primary and secondary data. For example, a growing number of LCA databases provide life cycle data for commonly used materials and processes. However, these databases rarely include data for emerging processes or materials. Many of these nascent technologies are too novel or are used in niche applications. As such, there is little recorded data about their production, useful life, repair or maintenance. There are also challenges associated with predicting how process with scale up from laboratory to industrial production. Finally, prospective LCA includes several types of uncertainty that must be appropriately communicated in the results [18].

Several efforts have been made to identify and address the lack of collective LCA data for surface engineering applications. For example, Gilbertson et al. [23] reviewed extant LCA studies on engineered nanomaterials conducted prior to 2015 and identified important gaps between LCA models and experiments due to the high level of uncertainty in process emissions, human exposure to these emissions, and end-of-life waste management. In another study data collection methodology were examined in nanomanufacturing to deal with uncertainties including data variation and material choices. Based on the results, the primary source of uncertainty was the effect of material types on final impact, rather than amount of input materials variation [24]. Liu et al. [25] introduced life cycle data sets that can be adapted to a range of plasma spray coatings, to provide a tool for more accurate and consistent data collection for this surface engineering discipline. Additional LCAs for different surface engineering processes, materials, and products are needed to develop a more comprehensive body of life cycle data to be used in future studies and to develop a more comprehensive understanding of the drivers of and key strategies for reducing potential environmental impacts of surface engineering applications.

1.2. Overview of Life Cycle Assessment

LCA principles and frameworks are standardized by International Organization of Standardization (ISO) to use as a global method for environmental assessment [7]. Based on ISO 14040, for conducting a complete LCA study, one should take four essential steps including:

- Goal and scope definition
- Inventory Analysis
- Impact Assessment
- Interpretation of results

Figure (1) shows these four phases linked together by two arrows with opposite directions, represented how each section reflects others [12]. The following paragraphs briefly define each phase of LCA and describe the content that should be reported in each of them.

The first phase, goal and scope definition, concentrates on determining the assessment's goal and the study's boundaries and stating who the audiences are. Two key aspects of the study are defined in this stage: the functional unit and the system boundaries. The Functional Unit (FU) is a basis for comparison and should defined equally for all comparative systems in a study. In other word, Fu is the services or products' unit under survey that should be described quantitatively, and final impact can assign to this unit. The system boundaries identify the activities for providing subjected product or service, which will be considered in the study [12],[26].

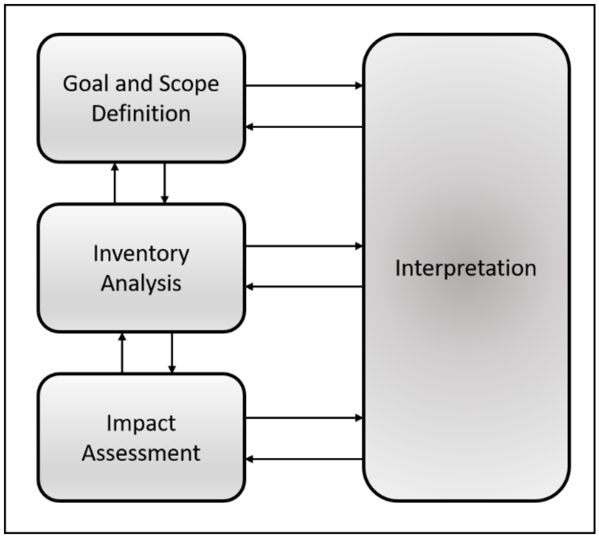

Figure 1 - Life cycle Assessment model

Three terms are commonly used to describe the scope on an LCA: cradle, grave and gate. "Cradle" refers to upstream activities involved with extracting raw materials (e.g., water, land, ore, minerals) to be used in the production of the good and service. Grave" indicates the downstream activities that occur after terminating the usage of a good or service and generally include the management of wasted and the end of a product or service's useful life. "Gate" is commonly considered the assessments starts or ends in the process between cradle and grave. For example, putting the system boundaries after operation stage and exclude end of life or disposal process from study [27].

Although life cycle assessment is a comprehensive review of a product life cycle from cradle-to-grave, the assessment boundary may be adjusted based on the study focus, objectives, or limitations. Consequently, in defining the boundaries of an LCA, one needs to explicitly state which part of the product/service life cycle will be captured in the study. This results in studies that are cradle-to-grave, cradle-to-gate, gate-to-gate, gate-to-grave, or even cradle-to-cradle in the case of circularity (i.e., where strategies such as reuse, remanufacturing, and recycling are used to create a closed-loop system in which waste is eliminated and resources reused) [27],[28]. In defining the scope of the study, it is also important to describe other key aspects of the system boundaries, such as geographical or temporal coverage. A clear definition of goal and scope is essential for ensuring the accuracy of other phases, fulfilling the goal of the study, and providing results in the interpretation phase (last step) with a higher level of validity [26].

LCA's second phase, called inventory analysis, involves collecting data for physical inputs (e.g. materials, fuel, energy and water) and outputs (e.g. products, by-products, waste and emissions). This is generally accomplished by developing a process flow diagram to detail each activity occurring within the system boundaries and collecting input and output data for each of these activities. Based on input flows, all associated intermediary flows included inside the assessment boundaries are calculated. For example, an input to one system requires a specific chemical, then input and output data associated with the production of that chemical must also be collected. Typically a model of all activities is developed in an LCA software application, in which all activities are linked together to insure that all data is scaled according to the functional unit as defined by the study goal and scope [29].

In many cases, based on the absence of experimental or foreground data for specific processes or materials, LCA practitioners may use secondary data, which includes industry average, substitute, and proxy data. Substitute data includes data for the same process or material produced elsewhere. Proxy data includes data for a similar process or material that is expected to have similar inputs and outputs. When alternate data is used, it is essential to document the source of data and any adjustments made to the data inventory analysis data table [26].

There are some studies that focus on providing the inventory data for different disciplines of surface engineering. As an example, Jing Liu et al [25] studied the life cycle inventory of a nickel chromium composite coating applied by the plasma spray to provide complete data set for this coating application method. Conducting experiments, not only they calculated data for process and coating parameters (like similar pervious researches) but also provided detailed list for energy and resource consumption and process emissions in each phase, including cleaning and sandblasting the surface, preheating and plasma spraying.

During Life Cycle Impact Assessment (LCIA), LCA's third step, the physical flows of inputs and outputs are translated to potential environmental impact. This is done using LCIA models that have been developed according to an impact pathway, or cause-effect chain that links the flows to environmental impact. There are several LCIA methods, but the function of all of them is the same. First, all flows that contributed to an environmental impact are assigned to the associated impact category. For example, all toxic releases that contribute to ecotoxicity are assigned to an ecotoxicity impact category. Then LCIA models are used to translate these flows to potential environmental impact, often at a midpoint and endpoint levels. Midpoint impacts are located along the impact pathway, e.g., between toxic releases and damage to ecosystem, and essentially weight each toxic release based on its potential to cause damage to the area of concern. Endpoint impacts are at the end of the impact pathway and represent the potential impact to the are of concern, e.g., the potential impact of the toxic releases to ecosystem. These are commonly referred to as damage categories, which are the areas society aims to protect and generally include Human Health, Ecosystem Quality, Climate Change and Resource Availability [27]. In LCA, the phrase “potential environmental impact” is used because all flows are assigned to all relevant impact categories assessed as if they are occurring instantly, rather than over the life cycle of the product system [28].

In the last step, interpretation, results from inventory and impact should be interpreted to fulfill the goal of study. This is the section that communicates the result with the stakeholders and audiences of research. Accordingly, the weighting and normalisation of result may address here, considering the selected scope (e.g., geographical, technical and temporal assumptions). The results of sensitivity and uncertainty analysis provided in this step help to make better understanding and guide to improvement solutions for future studies [26].

1.3. Prospective LCA of Emerging Technologies

In addition to complying with the ISO standards for LCA, a growing body of literature provides guidance for conducting LCA of emerging technologies, commonly described with the "prospective LCA" phrase. Conducting LCA in early stages serves nascent technology by flexible and low-cost chances for design modifications whether in processes or materials. Also, this method help to avoid predictable environmental expenditure of possible operating scenarios of new technologies [19], [30]. However, due to the novelty of the technology, the assessment process and data collection are challenging. Moni et al. [18] classified this challenges in four groups: 1) uncertainties for defining the basis of comparison (functional unit) and system boundaries for new systems in the Research and Development (R&D) level make challenges in comparability of conducting LCA. 2) Since new system does not have enough recorded data of their operation, in many cases, LCA practitioners face challenges associated with lack of sufficient historic data for their LCA Model. 3) In prospective LCAs, the estimated input/output amounts and calculated impact should be scale up from lab- or portfolio- scale to industrial-scale, however the laboratory parameters typically are not in the same level of complexity as industrial production level. 4) There are many other uncertainties in prospective LCAs that are needed to communicate properly with audiences to avoid misunderstanding and biased interpreting of results[18].

To decrease the impact of these challenges on results, some studies addressed the methodological solutions based on new system's novelty. Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) indicators were first time invented by Gavanka et al. [31] to provide a categorised description of technology maturity level. TRL can be change from 1 to 9 in technologies are still in basic steps of concept development level to fully developed technologies before mass production level [18]. Bergerson et al. [32] detailed another method for determining the novelty level of technology by interfacing two concepts of technology maturity and market maturity each of which can adopt low and high value. Based on this method the emerging technology and its context (market of technology) determine its potential challenges in environmental assessment and required solutions to deal with these challenges. Accordingly, a set of techniques like techno-economic, scenario, sensitivity and uncertainty analyses were introduced to guide LCA practitioners for proper addressing of ambiguities.

1.4. Problem Statement

The current thesis aims to describe the methodology, results, and challenges of two prospective LCA case studies of emerging surface engineering technologies that are anticipated to directly substituted for incumbent technologies in existing markets. In accordance with the International Organization for Standardization (ISO) standards for LCA [33], this study describes the systems to be analyzed, develops an inventory of inputs and outputs associated with each system, and uses an existing impact assessment method to translate the inventory of flows into potential impact on climate change, ecosystem quality, human health, and resource depletion.

The first case study compares a newly developed pipe heating system produced by thermal spray methods with a conventional heat tracing cable technology. The technology has been tested and validated in the laboratory environment (TRL 4) [18]. The study addresses the novel system's advantages in energy efficiency, weak points in production, and uncertainties in the environmental assessment of end of life. The highlighted segment of this assessment is the sensitivity analysis that shows how differences in systems' operation location can affect energy consumption and its associated impact. For sensitivity analysis, the baseline results were expanded to all climate conditions and electricity mix in Canada based on a mathematical method that even can be helpful for LCAs other than assessments conducted specifically for surface engineering. Finally, breakeven analysis was used to identify the level of energy efficiency that must be achieved by the novel system to render it environmentally preferable in each Canadian climate zone. The findings can help inform future research and development to ensure that the new technology has a lower environmental impact than the incumbent technology once commercialized.

In the second case study, a new coating removal technology, Pulse Water Jet (PWJ), was compared with a conventional hard chromium removal method called Alkaline Electrochemical Cleaning (AEC), widely used in aircraft landing gears overhaul sites. While the PWJ technology has been qualified through tests and demonstrations in some operational environments (TRL 8), it is also being further developed for consideration in other operational environments (TRL 6-7) [18]. In this work, the challenges in finding the basis of comparison were discussed, and a three-dimension model was introduced to fulfill the removal methods' dependency on factors like time, mass, and area. This study demonstrates the environmental benefit provided from substituting PWJ for AEC for removing hard chromium from landing gear. The results can be used by engineers to make the case for using PWJ instead of AEC in this application. However, it cannot be concluded that PWJ is environmentally preferable than all other coating removal methods or even for AEC in all applications based on the results of this study. Instead, the framework provided for quantifying the inputs and outputs of different surface removal technologies can be used to help surface engineers determine which surface removal approach has the lowest environmental impact for a specific application.

Each case study has own introduction, methodology description and results, discussion and conclusion. In the last chapter, the potential advantages of new surface engineering technologies, the importance of environmental assessment for them, and the challenges in these studies were discussed and some suggestions were provided for future studies.

2. First case study: Pipe freeze protection systems LCA[1]

2.1. Introduction

In cold climates, steps must be taken to prevent water or other liquids transported in pipelines from freezing, expanding, and ultimately causing pipeline failure and rupture [34]. Some insurance companies limit the coverage for pipe bursting damage when owners neglected to use proper freeze protection for pipelines [35]. Pipe damage from freezing is particularly a concern in countries, such as Canada, where ambient temperatures can reach -30ºC or lower [36]. At these temperatures, thermal insulation is insufficient and more complex freeze protection systems are required. Heat tracing systems are commonly used to maintain the required temperature for freeze protection [37].

There are generally two types of heat tracing systems. Fluid heat tracing systems pass a fluid at an elevated temperature (e.g., steam, glycol, or hot oil) through small tubes attached to the pipeline. Electric heat tracing systems generate and transfer heat via electrical heating cables attached to the pipeline. While steam heat tracing has historically been used in industrial settings [37], the use of electric heat tracing has increased significantly due to lower costs and improved control, monitoring, and reliability [38], [39].

Rezvani Rad and McDonald [40] recently developed a novel coating-based resistive heating system that provides the same function using less energy. A nickel-chromium resistive heating element layer on an alumina coating insulating layer were deposited directly on carbon steel pipes via flame spraying. A copper layer was applied to the ends of the pipe via cold spraying to serve as electrical contacts for a power supply source [40],[41]. A techno-economic assessment (TEA) found that the coating-based heating system used 30% less energy while providing more uniform heating but at a higher life cycle cost [42], [43]. However, it is not clear if the improved use phase energy performance translates into net environmental savings.

Environmental life cycle assessment (LCA) has been used to assess the environmental impacts of cables and thermal spray coatings. For example, Socolof et al. [44] compared standard (leaded) and alternative insulation and jacketing formulations for communication and power cables for all life cycle phases except product use across 14 environmental and human health impact categories. Energy sources used during material production and cable extrusion were important for overall impact but material production and releases during landfilling or incineration were important for determining the differences in environmental impact. Key differences in environmental impact were driven by the lead burden from cables containing lead-based heat stabilizers

Moign et al. [17] compared electroplating to plasma, cold, high velocity oxygen fuel (HVOF), and twin wire arc spraying for nickel coating deposition. Electroplating resulted in the lowest environmental impact for all impact categories when no recycling was considered. The human health and resource impact results were approximately the same for electroplating and the

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[1] This chapter is a modified version of a manuscript that has been submitted to the Journal of Thermal Spray Technology. The manuscript is titled "Environmental life cycle assessment of a novel thermal sprayed resistive heating system" and was co-authored by Milad Rezvani Rad, André McDonald, and Shannon Lloyd. The research reported in the manuscript and in this chapter was conducted by the author of this thesis, Zeynab Yousefzadeh, with data and advising provided by the co-authors.

various thermal spray methods assuming alumina for grit blasting is recycled 50 times and 50% recycled nickel is used for deposition. However, the environmental impacts of chemical production and wastewater treatment for electroplating were not modeled. Taheri et al. [45] assessed the energy and resources efficiency of different thermal spray energy source and feedstock combinations for producing an aluminum oxide coating. High-velocity suspension flame spray was found to be less energy efficient and suspension feedstock to be less resource-efficient. Serres et al. [46] used LCA to assess a NiCrBSi coating applied via thermal spray, using atmospheric plasma spraying and high velocity oxy-fuel (HVOF), and laser cladding (with a diode laser) as an alternative to electrolytic hard chromium plating. The environmental impacts of the APS, HVOF, and laser cladding alternatives were 75 to 80% lower than hard chromium plating, with impacts driven by raw material production and the energy consumption. Follow-up studies further used LCA to assess the environmental impacts of surface preparation methods, including degreasing, laser ablation, sand blasting, cryogenic preparation and laser texturation and post- and in situ treatment methods, including flame remelting, laser remelting, and thermal treatment [47]. Laser ablation and in-situ laser remelting were found to have the lowest environmental impacts of the treatment options, with energy consumption driving impact. Moign et al. [17] compared the overall environmental impact from producing yttria-stabilized zirconia coating via powder and liquid plasma spraying. Suspension of nano powder zirconium in ethanol/glycol solvent had the highest impact, while solution of zirconium salt in water had the lowest environmental impact. Electricity used for spray processes accounted for 70-80% of process impact in all scenarios which can be control by decreasing processing time.

LCA has also been used to study freeze protection applications. For example, Pericault et al. [48] used LCA to compare options for expanding sewer, water and district heating networks in cold climates. Each alternative considered included a different combination of heating, sewer, and freeze protection systems. Freeze protection was provided via deep burial or shallow burial with heat tracing via warm water or an electric cable. The option using electric heat tracing, which also used individual geothermal heat pumps and low-pressure sewer system, performed better on energy efficiency and climate preservation but worse on material efficiency than the other alternatives. This was primarily due to the energy savings and additional equipment required for geothermal heating systems. Given the technology mixes considered, it is not possible to ascertain the environmental impacts attributed to the heat tracing systems [49].

Extant LCAs of cables and thermal spray products find material choice, material consumption, and energy consumption during fabrication to be important drivers of environmental impact. These studies do not consider product use, which can be particularly important for products consuming energy during use [50]. Furthermore, they compared cable options or thermal spray options, rather than comparing thermal spray options to incumbent technologies for a specific application. Extant LCAs of freeze protection show the importance of evaluating integrated systems rather than individual components, with energy sources being an important contributor to overall environmental impact. To better understand the potential environmental impact of novel coating systems, they must be considered in context (e.g., where and how they are produced, as part of an integrated system, and compared to the incumbent technology for achieving the same functionality).

This study uses prospective LCA to compare the expected environmental impact from producing, assembling, and operating the novel coating-based resistive heating system and a conventional electric heat tracing system. In this assessment, it was assumed that the systems are installed in Alberta, Canada where oil and natural gas development, which requires pipe freeze protection, accounts for 30% of the province's economic activity [51]. Sensitivity analysis is used to assess the impact of climate and electricity mix on the systems' environmental performance. Finally, the discussion shows the value of using LCA during research and development to compare the expected environmental performance of the product under development to incumbent products and identify opportunities for reducing the environmental impact of the new product before it goes to market.

2.2. Methods

2.2.1. Systems Considered

The heating systems assessed in this study are based on a recently developed multi-layered alumina-nickel chromium resistive heating coating system [40] and a traditional heat tracing system, both of which have been laboratory tested[41], [42] and compared via a techno-economic analysis [42], [43] for application to pipe freeze protection.

2.2.1.1. Self-Regulating Heating Cables

The baseline system is a conventional self-regulating electric heat tracing system. Most commercial electric heat tracing systems use resistive heating cables comprised of five layers, including a polyolefin outer jacket, tinned copper braid over-shield, radiation cross-linked dielectric insulation inner jacket, radiation cross-linked semi-conductive heating matrix core, and nickel-plated copper bus wires, as illustrated in Figure (2). Materials were assumed based on the product catalogue description [52], [53] of the heating cables used by Rezvani Rad and McDonald [42], [43]. Material mass was estimated by disassembling a one-meter section of cable and weighing the components. The assumed materials and mass are listed in Table (1) in section 2.2.4.1.

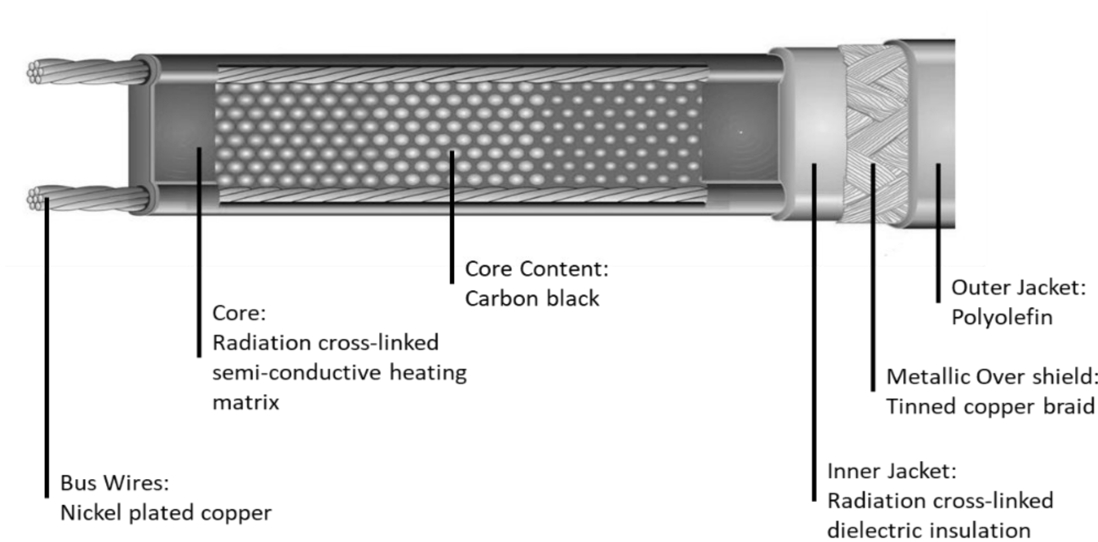


Figure 2 - Schematic picture of heating cable layers
Source: Adopted from [52]

The cable system is attached to a carbon steel pipe via plastic clamps (e.g., wire ties) and tape. These components are assumed to be made of high-density polyethylene, with 50 g assumed per 1-meter pipe section. The cable is connected to a power supply, which is controlled via sensors or controllers. The extruded semi-conductor core surrounds two bus wires connected via a matrix comprised of black carbon particles, which creates heat as electricity passes through it. Energizing the cable system generates heat in the matrix core. As the temperature increases, resistance in the matrix core increases and heat output decreases (and vice versa). This creates a self-regulating effect, in which heat is generated where needed based on the surrounding temperature. [37],[52]. Power connection, end-of-circuit termination, and temperature control components were assumed to be similar in both heating systems and were excluded from the LCA model.

2.2.1.2. Multi-Layered Coating System

The alternative system was a multi-layered coating-based resistive heating system detailed by Rezvani Rad and McDonald [7] and Rezvani et al. [8]. The system comprised of a 51-mm (2-inch) diameter carbon steel pipe (ASTM A333 Grade 6) coated with an aluminum oxide (Al_2O_3) layer, a 50 % nickel - 50% chromium (Ni-50Cr) alloy layer, and copper layered rings at the end of the pipe sections, as illustrated in Figure (3).

The Al_2O_3 and Ni-50Cr layers were applied to the carbon steel pipe via oxy-acetylene flame spraying. Alumina was used as the intermediary layer because of its electrical insulating and heat-conducting properties, which allow heat generated in the top metal layer to transfer easily to the pipe while preventing transfer of free electrons from the top layer to the steel pipe. Nickel-chromium alloy was used for the heating element layer because of its relatively high electrical resistivity. For connection to an electrical power source, a copper coating was deposited onto the Ni-Cr layer at the end of the pipe sections via cold spraying, detailed by Rezvani Rad and McDonald [40] and Rezvani et al. [41]. As with the heating cables, the power connection, end-of-circuit termination, and temperature control components were excluded from the LCA model.

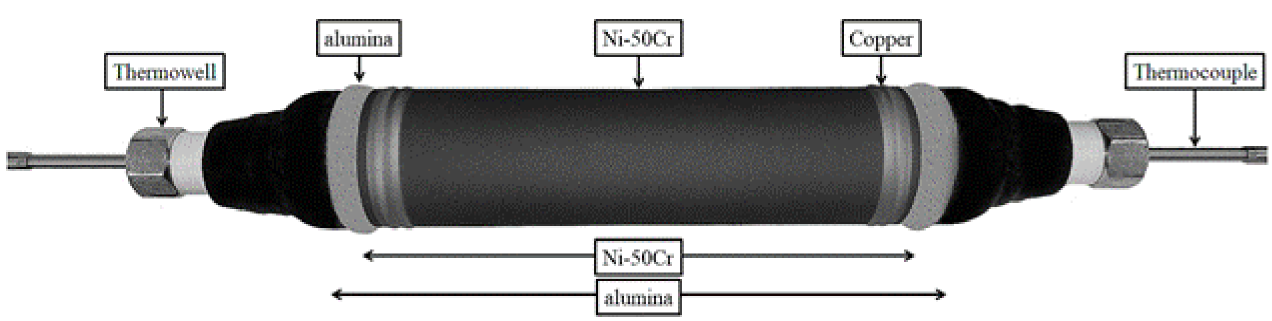


Figure 3 - Schematic of coating system layers
Source: Adopted from [40]

2.2.2. System boundaries

The system boundaries for the study included the life cycle stages and process shown in Figure (4). This is considered a cradle-to-gate (rather than cradle-to-grave) study in that it went from raw material extraction through transport to a waste management site but does not include waste treatment. This cut-off approach for end of life was used because of the lack of practical data and unclarity of waste treatment options, including the possibility of separating and recycling the materials.

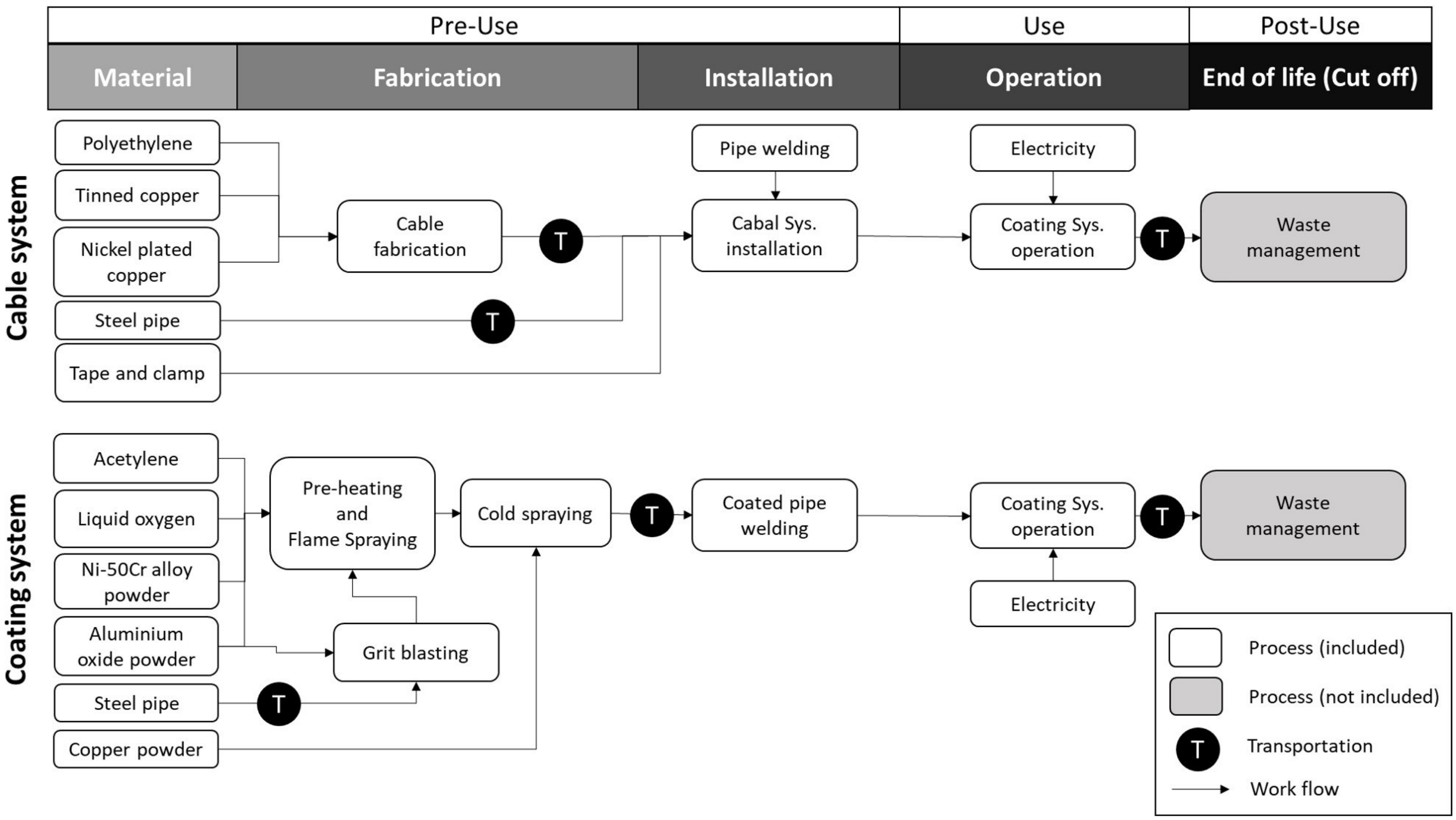


Figure 4 - Life cycle stages of heating systems

2.2.3. Functional Unit

In LCA, a functional unit provides a measurable amount of function by which all alternatives are evaluated. Here, the functional unit is defined as **the protection of a 5-meter aboveground carbon steel water pipe (2-inch diameter) from freezing during the frost days in Alberta for 10 years**. The average annual number of frost days, i.e., days in which the coldest temperature is lower than 0 °C and freeze protection would be needed, was estimated to be 197 days for Alberta based on twenty years (i.e., 1981 to 2010) of climate data for five climate regions in Alberta obtained form the High level Northwestern Forest, Fort McMurray, Calgary, Edmonton, and Medicine Hat weather stations [54], [55].

2.2.4. Life Cycle Inventory (LCI)

Both systems were modeled using the openLCA version 1.9.0 software [56], resulting in a life cycle inventory (LCI) of environmental inputs (e.g., raw materials, energy, water) and outputs (e.g., emissions to air, water, and land) from raw material extraction, material processing, component fabrication and transportation, system installation, electricity generation, and transportation of the decommissioned system for waste management. Both models include the foreground system, i.e., the processes for which the LCA is carried (shown in Fig. 4), as well as the associated background system, i.e., the energy and materials delivered to the foreground system activities[57]. Data for the models were obtained from experimental data [40]–[43], relevant literature and assumptions (detailed below), and the ecoinvent version 3.3 LCI database [58], which provides LCI (i.e., input and output) data for thousands of processes and products and their associated supply chains.

2.2.4.1. Self-Regulating Heating Cable

The materials, masses, and LCI data sources used to model the baseline heating cable system are detailed in Table (1). Material mass was estimated by disassembling a one-meter section of the heating cable used by Rezvani Rad et al. [42] and weighing the components. Assumed heating cable materials include nickel-plated copper for the bus wires [53], high-density polyethylene and carbon black for the semi-conductor core, high-density polyethylene for the inner jacket [59], tinned copper braid for the metallic over shield [53], and low-density polyethylene for the outer jacket [60]. Nickel was assumed to account for 27% of the nickel-plated bus wire mass [61]. For heating cable fabrication, an ecoinvent process for a basic computer cable [62] was modified as follows: the materials identified above were substituted for the materials used in the original ecoinvent process; the copper wire production step was removed (since it is accounted for in the nickel-plated bus wire fabrication process); and the processing inputs (e.g., fuel, electricity, water), and outputs (e.g., air emissions, waste) were adjusted based on the mass of cable produced. Based on the assumption that the materials and cable could come from any market in which they are produced, ecoinvent's global or Rest of world (RoW) datasets were used for these components. These datasets represent the global consumption mixes and average transportation required to produce a Transport of materials to the cable production facility was assumed to be included in the global market datasets.

The system was assumed to be a new installation (e.g., rather than a retrofit or upgrade) located in Alberta, Canada. The transport distance to the installation site was assumed to be 516 km (see Appendix B2) by truck for the steel pipe and heating cables based on the average distance from a heating cable provider in Calgary, Alberta to 15 regions in the province (see Appendix B1). The sections of steel pipe were assumed to be welded together and the heating cable attached to the pipe via polyethylene clamps and tape. The amount of welding required was estimated based on the diameter of the steel pipes. The mass of clamps and tape was assumed based on the average amount used in experiments and transportation was assumed negligible since they would be readily available in any local market.

Table 1 -Assumed inputs and LCI data sources for a one-meter section of the heating cable system

Item	Amount	Units	LCI Data Source
Materials			
Nickel-plated copper (bus wires)	23	g	Based on Moign et al. [17] using the following ecoinvent market datasets: inorganic chemicals[63]; copper [64]; medium voltage electricity (RoW) [65]; nickel, 99.5% [66]; sodium hydroxide without water in 50% solution state [67]; sodium phosphate [68]; sulfuric acid [69]; average wastewater (RoW) [70]; and copper wire drawing[71]
High-density polyethylene (Semi conductive core)	12.04	g	ecoinvent market dataset for high density polyethylene [72]
Carbon black (core content)	1.96	g	ecoinvent market dataset for carbon black [73]
High-density polyethylene (inner jacket)	25	g	ecoinvent market dataset for high density polyethylene, granulate [72]
Tinned copper (metallic over shield)	24	g	ecoinvent market datasets for: copper [64]; tin plating [74]; copper wire drawing[71]; and medium voltage electricity [65]
Low-density polyethylene (outer jacket)	30	g	ecoinvent market dataset for low density polyethylene granulate [75]
Fabrication			
Heat tracing cable fabrication	1	m	Modified ecoinvent dataset for computer connector cable without plug s[62]
Installation			
High-density polyethylene (clamp and tape)	50	g	ecoinvent market dataset for high density polyethylene granulate [72]
Welding	0.0628	m	ecoinvent market dataset for arc welding steel [76]
Operation			
Electricity	1.1234	kWh/day	ecoinvent Alberta market dataset for low voltage electricity [77] and for sensitivity analysis [77]–[89]
End-of-Life			
Transport pipe and cable (to waste facility)	1111	kg·km	ecoinvent market dataset for freight transport via an unspecified lorry [90]

Once in operation, the heating cable would be powered by electricity, which was modeled using the Alberta electricity mix from in the ecoinvent database [77]. Based on experimental data [42], cable system electricity usage per frost day was 1.1 kWh for one meter of pipe section. The amount of electricity required to power a 5-meter section for 197 days/year for 10 years was calculated to be 11065 kWh. For both systems, the transport distance to the waste management centre was assumed to be 200 km. However, waste management processes were not modelled.

2.2.4.2. Multi-Layered Coating System

Surface preparation for the laboratory assemblies included grit blasting and preheating of pipes. Data from a previous LCA [17] was used for grit blasting, assuming alumina grit was used as the abrasive media and can be recycled 50 times. Materials used to fabricate the coatings included aluminum oxide powder, nickel-50 chromium (Ni-50Cr) powder, copper powder, acetylene (for preheating and flame spraying), liquid oxygen (for preheating and flame spraying), and the carbon steel pipe sections. For all but the Ni-50Cr powder, a suitable ecoinvent process was available. For the Ni-50Cr powder, an existing ecoinvent process for iron-nickel-chromium

[91] was modified by removing the iron, adjusting the amount of nickel and chromium based on experimental weights, and adding electricity for gas atomisation, which is used to produce nickel-chromium powder according to the product datasheet. The amount of required electricity was estimated based on a previous LCA of atomisation [92] but adjusted based on the Ni-50Cr melting point. In a commercial setting, a thermal spray booth may require electricity, e.g., for flame ignition, ventilation, or robot movements. Since no data for such electricity requirements were found, the amount of electricity required was estimated based on an ecoinvent dataset for selective coating [93]. This serves as a conservative estimate since the ventilation and process electricity for selective coating is expected to be higher than that for thermal spray. Ecoinvent global or RoW dataset activities were used for all materials except the pipe sections (see section 2.2.4.3).

Table 2 - Assumed inputs, outputs and LCI data sources for a one-meter section of the multi-layered coating system

Item	Amount	Units	LCI Data Source
Materials			
Aluminum Oxide powder (for coating)	107	g	ecoinvent dataset market for aluminium oxide [94]
Aluminum Oxide powder (for grit blasting)	157	g	LCA Comparison of Electroplating and Other Thermal Spray Processes [17] and ecoinvent dataset market for aluminium oxide [94]
Nickel-50 Chromium powder	159	g	Modified ecoinvent dataset iron-nickel-chromium alloy production [91]
Acetylene (for preheating)	0.2338	kg	ecoinvent dataset market for acetylene [95]
Liquid oxygen (for flam spraying)	0.452	kg	ecoinvent dataset market for oxygen, liquid [96]
Acetylene (for coating)	0.619	kg	ecoinvent dataset market for acetylene [95]
Liquid oxygen (for flam spraying)	1.243	kg	ecoinvent dataset market for oxygen, liquid [96]
Copper powder (for coating)	31	g	ecoinvent dataset market for copper, cathode [97]
Fabrication			
Electricity (for grit blasting)	0.167	kWh	LCA Comparison of Electroplating and Other Thermal Spray Processes [17] and ecoinvent dataset market group for electricity, low voltage [98]
Electricity (for other activities ventilation, ignite the flame, robot movement)	0.212	kWh	Amount assumed based on ecoinvent dataset selective coating, stainless steel sheet, black chrome[93] and ecoinvent dataset market group for electricity, low voltage [98]
Carbon monoxide emissions	2.566	kg	N/A
Water vapor emissions	0.825	kg	N/A
Electricity (cold spraying copper)	0.0975	kWh	ecoinvent dataset market group for electricity, low voltage [98]
Installation			
Welding	0.0628	m	ecoinvent dataset market for welding, arc, steel [76]
Operation			
Electricity	0.86	kWh/day	ecoinvent Alberta market dataset for low voltage electricity [77] and for sensitivity analysis [77]–[89]
End-of-Life			
Transport coated pipe (to waste facility)	1147	kg·km	ecoinvent dataset market for transport, freight, lorry, unspecified [90]

The coating fabrication steps were modelled based on experimental processes and data [40],[41], with material amounts adjusted based on the specific pipe considered. However, material amounts can vary significantly based on the coating process, pipe type and size, and intended application [43]. The LCI model included the material inputs described above, electricity estimates for each step, and carbon monoxide and water vapour emissions from incomplete acetylene combustion. Transportation distances were assumed to be 15 km between the pipe manufacturer and the coating shop and 352 km between the coating shop and the installation site (for transportation assumptions see section 2.2.4.4). For installation, operation, and end-of-life, the same modeling approach was used as for the baseline system (i.e., welding requirements based on steel pipe length and diameter, electricity from Alberta mix based on experimental data, and 200 km transport distance to the waste management centre, with waste management processes omitted).

2.2.4.3. Steel pipe

While the same uncoated steel pipes were assumed in both systems, the expected life of the coated pipe system is uncertain and different transport distances are assumed for the two systems. For this reason, steel pipes were included in the system boundaries. For both systems, 5-m long ASTM A333 Grade 6 carbon steel pipe sections were assumed [40], with pipe mass calculated via an online calculator [99] and the LCI model developed using the ecoinvent market dataset for steel pipe drawing (Table 3). While the expected life of steel pipe in this application is assumed to be 40 years, the coating system is assumed to have a shorted expected life (i.e., 10 years). At the end of the expected life, it is assumed that the entire coated pipe is decommissioned and transported for waste management (with 10 years life for both pipe and coating).

Table 3 - Assumed LCI inputs, outputs and data sources for a one-meter of steel pipe

Item	Amount	Units	LCI Data Source
Materials			
Unalloyed steel	5.44	kg	ecoinvent market dataset for unalloyed steel [100]
Fabrication			
Drawing of steel pipe	5.44	kg	ecoinvent market dataset for steel pipe drawing [101]

2.2.4.4. Transportation

Transportation assumptions are listed in Table (4). The heat tracing cable was assumed to be transported to the installation site from a distributer located in Calgary, Alberta [102]. Since there is a concentration of coating shops in the greater Edmonton, Alberta area (17 of the 26 shops in the province) [103], coating materials and steel pipe were assumed to be transported to an Edmonton coating shop, with the coated pipe then transported to the installation site. No additional transport was added for coating materials since average transport between supplier and consumer are accounted for in the associated ecoinvent market datasets. Steel pipe was assumed to be transported 15 km from one of the many suppliers in the greater Edmonton, Alberta area [104] to an Edmonton coating shop.

Table 4 - Transportation assumptions for a one-meter section of each heating system

Transported item	Origin	Destination	Distance (km)	Load (kg)	amount	Unit
Heat tracing cable system						
Cable and pipe	Cable supplier (Calgary)	Installation site (Average)	516	5.556	2867	kg.km
Used coated pipe	Installation site (Average)	Waste management site	200	5.44	1147	kg.km
Multi-layered coating system						
Multi-layered coating system	Pipe supplier (Edmonton)	Coating shop (Edmonton)	15	5.44	81.6	kg.km
Coated pipe	Coating shop (Edmonton)	Installation site (Average)	351	5.737	2014	kg.km
Used cable and pipe	Installation site (Average)	Waste management site	200	5.556	1111	kg.km

In estimating transportation from heating system suppliers to the installation site, it was assumed that the heated pipelines are used in oil and gas industry applications. Fifteen cities (i.e., Rainbow lake, Grand prairie, Atikameg, Slave Lake, Fort McMurray, Conklin, Bonnyville, Tawatinaw, Derwent, Coronation, Bassano, Calgary, Saunders, Edson, and Muskeg River) distributed across Alberta's oil wells map [105] were selected as potential installation sites. The distances between each city and Edmonton (i.e., the coating shop) and Calgary (i.e., the heat tracing cable supplier) were calculated by using google maps [106]. The average distances were assumed for transporting the heating systems to the installation site. At the end of their expected life, both heating systems and pipes are assumed to be transported 200 km for waste management. For all transportation, an ecoinvent market dataset for transporting freight via a lorry [90] was used, which represents the average inputs and outputs for transporting 1 metric ton by trucks with more than 3.5 metric ton capacity. It can generally be assumed that heat tracing cables can generally be provided by local distributors and that pipes would be coated by the closest thermal spray shop. While these transportation distances are based on distances between component providers and point-of-use for the Albertan oil and gas industry, transportation distances and modes would likely be similar in other locations.

2.2.4.5. Useful System Life

Due to their high level of safety and reliability, heating cables are usually guaranteed for four decades [37]. While a small percentage of cables are likely damaged and replaced during use, they are assumed to operate maintenance-free for 40 years. Given the novelty of coating-based heating systems for freeze protection, the expected life is not known. A previous life cycle cost analysis of the novel system conservatively assumed useful life of 10 years [42], [43]. Since the functional unit specifies a 10-year period, the comparison of the two systems includes 25% of the impacts from producing, transporting, and installing the heating cable system but all of the impacts from producing, transporting and installing the multi-layer coating system. While this same assumption is used here, it is not unlikely that a longer useful life would be realized once the system is proven in the field.

2.2.5. Life Cycle Impact Assessment

The IMPACT 2002+ life cycle impact assessment (LCIA) method was used to translate the LCI of environment flows into potential impact on human health, ecosystem quality, climate change, and resources [107]. Potential damage to human health from environmental releases is measured in disability-adjusted life years (DALYs), which represents the number of years lost due to ill-health, disability, or early death. Potential damage to ecosystems from environmental releases is measured as the potentially disappeared fraction of surface species in a square meter over a year (PDF×m^2×yr), which represents the loss of biodiversity. Potential damage associated with climate change is measured in carbon dioxide equivalents (kg CO_2 eq.), an indicator of potential damage to life support systems from climate change. Finally, damage to resource availability is measured in MJ primary, which represents the additional amount of primary non-renewable energy required to extract resources due to the consumption of resources.

2.2.6. Sensitivity Analysis

2.2.6.1. Frost Days and Electricity Mix (Based on Geographic Location)

For product systems that consume energy during use, LCA often finds use-phase energy consumption to be an important driver of overall impact [50]. Since climate and electricity mix vary across Canada, sensitivity analysis was used to assess the environmental impact of using the two systems in different regions to determine if there is a universally environmentally preferable freeze protection heating system for Canada.

The average number of frost days for each climate region in Canada was estimated from thirty years (i.e.,1981 to 2010) of climate data from 48 weather stations [54] (see Appendix A). The estimated average number of frost days varied from 41 in Vancouver, British Columbia, to 271 in Baker Lake, Nunavut. The electricity mix for each province and territory was obtained from the provincial and territorial energy profiles published by the Canada Energy Regulator [108]. Figure (5) shows the electricity mix for each province or territory and the corresponding kg CO_2 eq per 1 kWh of electricity from the LCI model. The kg CO_2 eq from electricity production in Nunavut, which relies completely on petroleum, is 120 times higher than in Québec, which uses 99 percent renewable sources.

To estimate the associated environmental impact in each region, two changes were made to the LCI models for the two heating systems: the amount of use-phase electricity was adjusted based on the number of frost days; and the ecoinvent market dataset for electricity generation in the specific province or territory was used for the use-phase electricity [77]–[89]. This approach requires two simplifying assumptions. First, the same amount of electricity is required per frost day regardless of location. Second, electricity consumed at the installation site is generated using the mix of energy sources used in the province or territory. All other phases of the LCI models were left unchanged.

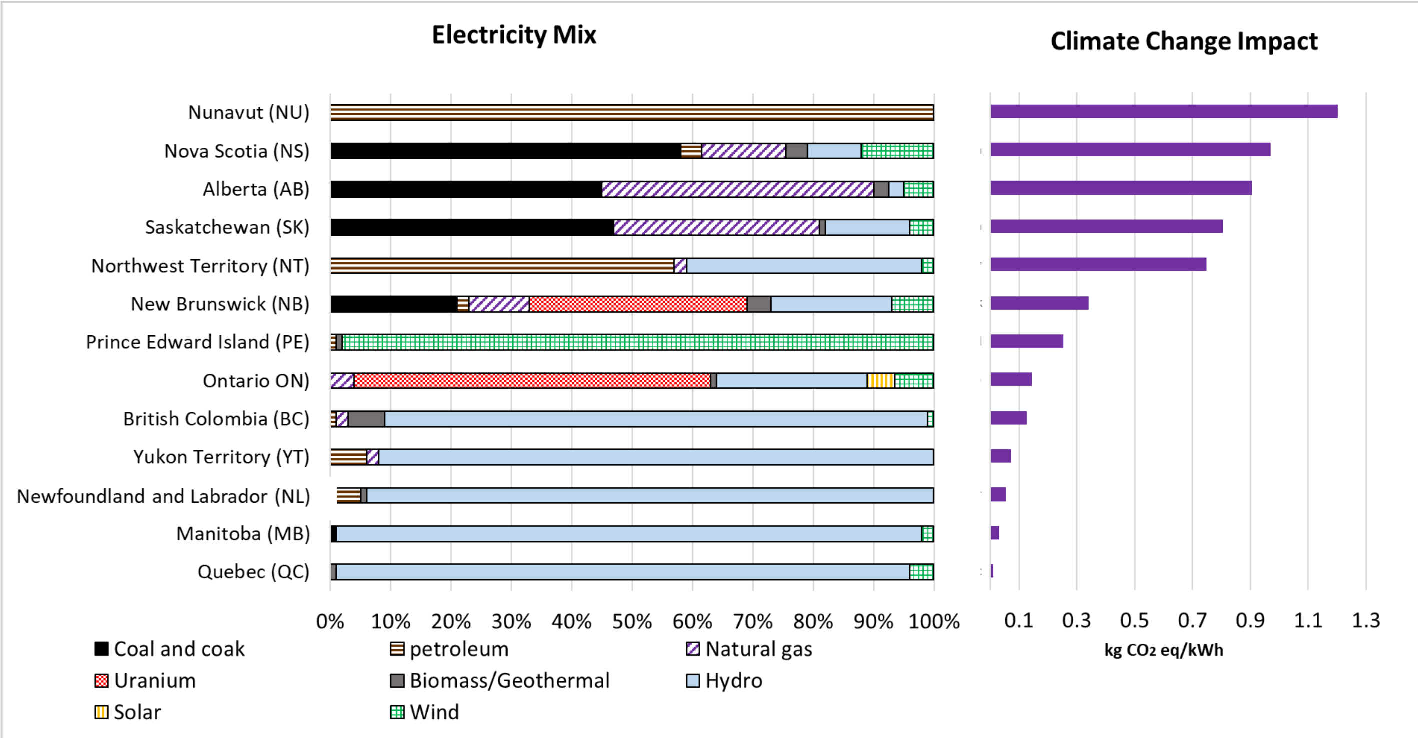


Figure 5 - Electricity mix and climate change impact for each province

2.2.6.2. Expected Useful Life of the Multi-Layered Coating System

Due to the novelty of the multi-layered coating system and its use for freeze protection, a conservative assumption of a 10-year expected life was used (i.e., 25% of the expected life of the heat tracing cable system). Field tests will be required to assess the durability of the coating system and determine a more accurate estimate of expected life. A second sensitivity analysis was conducted to investigate the change in environmental impact if the coating system proves to have a longer expected life, adjusting the model to assume a 20-, 30-, 40- and 50-year expected life for the multi-layered coated pipe.

2.2.6.3. Break even Analysis

Ongoing research and development (e.g., related to using thermal spray processes with higher deposition efficiencies, automating thermal spray production lines, and utilizing different feedstock materials) could significantly change the use-phase energy efficiency of the multi-layered coating system. Break-even analysis was used to determine the level of energy efficiency required for the multi-layered coating system to be environmentally preferable for each region. For each climate region (r), the environmental break-even point [109] was defined as the point at which the environmental impact of the coating system (I_{Coat}) is lower than the impact of the cable system (I_{Cable}) for all impact categories (i). So,

$$I_{Coat,r,i} \leq I_{Cable,r,i} \quad for\ all\ i. \tag{1}$$

Since the focus is on use-phase electricity consumption, the associated impacts for each impact category (i) must be isolated from non-use phase impacts (I'), which includes impacts from materials, fabrication, installation, and end-of-life. For each system, the use-phase impacts for each impact category (i) is the product of the impacts from electricity use (I_{elec}) for region (r), the amount of electricity required per day by the system when operational (e), and the average number of frost days in the region (D_r). Isolation of use-phase impact for both systems gives the environmental break-even point for a given region described by equation (2) as

$$I'_{coat,i} + \left(I_{elec,r,i} \times e_{coat} \times D_r\right) \leq I'_{cable,i} + \left(I_{elec,r,i} \times e_{cable} \times D_r\right) \, for\ all\ i. \qquad (2)$$

For the break-even analysis, the non-use phase impacts for each system were left unchanged. The average number of heating days and impacts per unit electricity consumption were adjusted for each region. A variable (β) was created to reflect the relative electricity savings from using coating system instead of the cable system. Currently, the relative electricity savings for the coating system (β) is 30%. The amount of electricity required per day by the cable is

$$e_{Cable} = (1 + \beta) \times e_{Coat}, \qquad (3)$$

$$\text{thus } \beta = \frac{e_{Cable}}{e_{Coat}} - 1. \qquad (4)$$

Equations (2) and (3) were combined to determine the relative electricity savings required to achieve the environmental break-even point for each impact category (β_i) in a given region. For each region, the global environmental break-even point was taken to be the (highest) value of β_i, i.e., the value at which the coating system would have a lower environmental impact for all four environmental impact categories. Thus,

$$\beta_i \geq \frac{I_{coat',i} - I_{cable',i}}{I_{r,i} \times D_r \times e_{Coat}} \quad for\ all\ i. \qquad (5)$$

2.3. Results

2.3.1. Case Study – Freeze Protection in Alberta

Figure (6) compares the potential environmental impacts from using the novel multi-layered coating system to those from using the conventional heat tracing cable for each life cycle stage and each environmental impact category. The results are provided for the specified functional unit, i.e., protecting a 5-meter aboveground water pipe from freezing for ten years in Alberta. For each environmental impact category, the system with the highest potential environmental impact was assigned a value of 100% with result for the other system scaled accordingly. In addition, the results for the system with the highest potential impact is provided above the column. For example, the potential climate change impacts were highest for the heat tracing cable system (i.e., 10,025 kg CO_2 eq) and the potential impacts for the coating system were estimated to be 78% of (or 22% lower than) that of the cable system. For all impact categories, the potential impact was estimated to be higher for the heat tracing cable system.

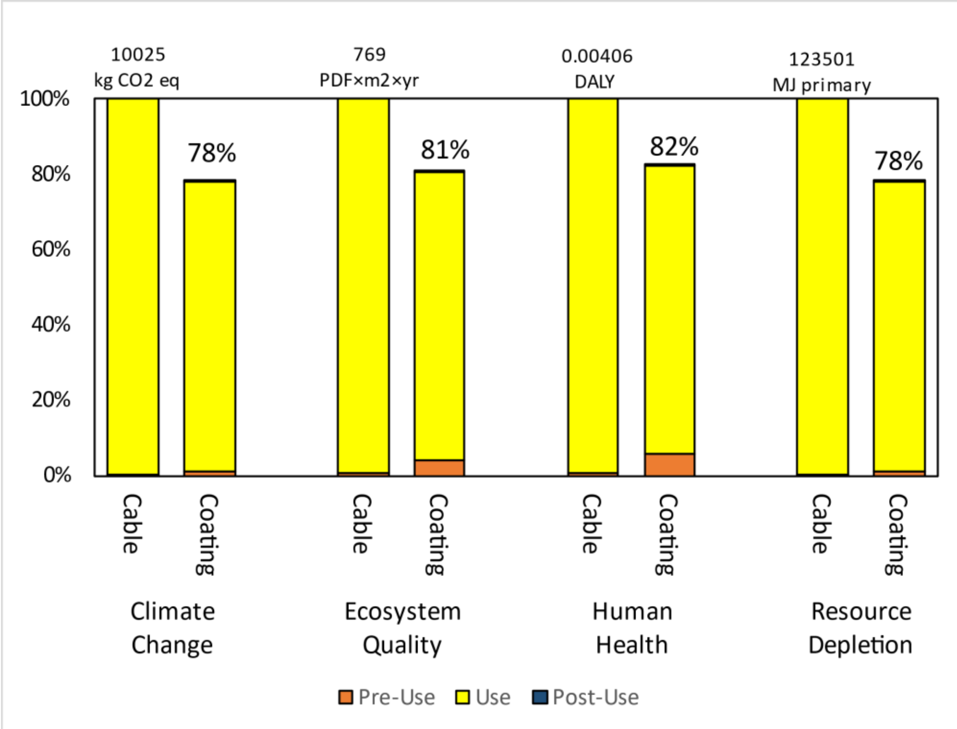


Figure 6 - Comparison of the potential environmental impacts for the two heating systems, with results shown for 5-meters of freeze protection for ten years in Alberta

The pre-use impacts (i.e., from materials, fabrication, and installation) of the coating system are higher than the pre-use impacts form the cable system. In contrast, the use-phase impacts (i.e., from electricity consumption) are higher for the cable system. The post-use impacts (i.e., from transporting components to a waste management site) are negligible compared to the pre-use and use phase impacts. However, this finding could change from consideration of waste management processes. When used in Alberta, use-phase electricity consumption, which includes the extracting and combustion of coal and natural gas, is expected to drive impact for all impact categories. Since the coating system is 30% more energy efficient, it would be expected to have a lower overall environmental impact.

Figures (7) and (8) show the relative contribution of individual components and activities to potential impact for the non-use phases (i.e., production, installation, and transport). For the cable system (Fig. 7), potential impact is driven by steel pipe, tinned copper over shield, and nickel-plated bus wire production. For the coating system (Fig. 8), steel pipe production is an important contributor to all impact categories. Nickel chromium alloy production is an important contributor to potential ecosystem quality and human health impact. The use of acetylene and liquid oxygen as fuels for flame spraying is an important contributor to potential climate change and resource depletion impact. However, as illustrated in Figure (5), these impacts are substantially smaller than those from use-phase electricity consumption.

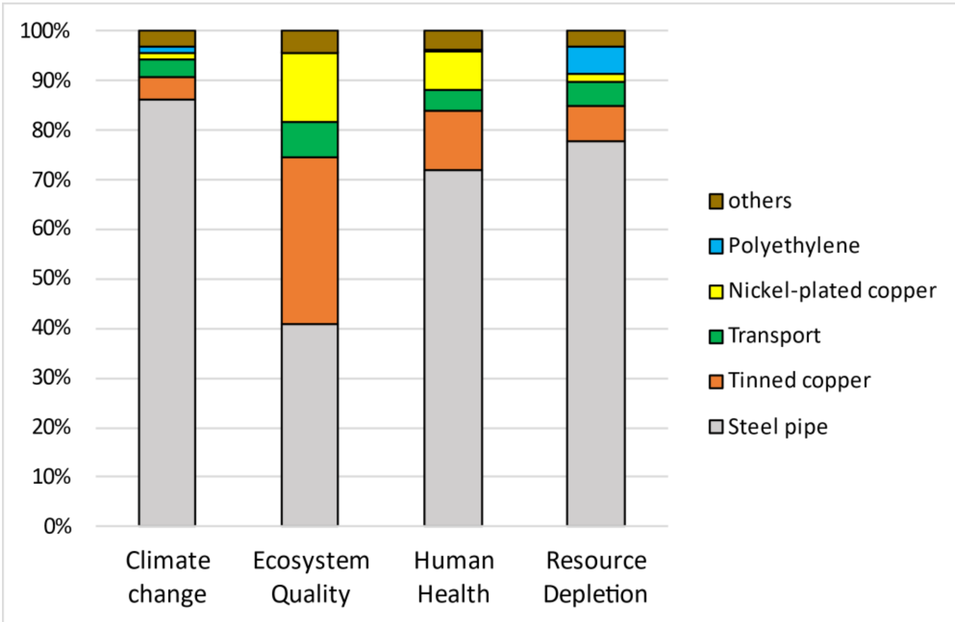


Figure 7 - Cable system impact contribution
in production and installation phases

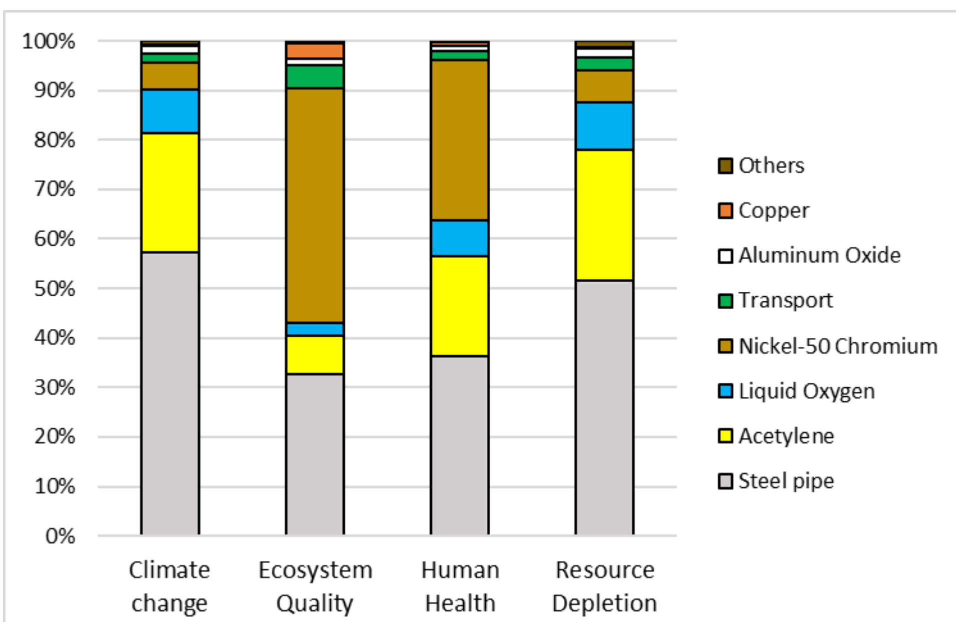


Figure 8 - Coating system impact contribution
in production and installation phases

2.3.2. Sensitivity Analysis

Figure (9) identifies which system is environmentally preferable for each climate region, with differences in impact driven by the electricity mix and number of heating days. The solid black lines represent provincial and territorial borders. An environmental impact grid is provided for each climate region, with each quadrant representing one of the impact categories, as specified by the legend. The quadrants are colored orange or blue when the estimated environmental impact was lower for the cable system or the coating system, respectively. Likewise, the climate regions are colored orange or blue if the cable or coating system resulted in a lower potential impact for all environmental impact categories. Those with mixed results are shaded white. While the shaded areas and grids represent Canada's 48 climate region, similar results were combined, resulting in 19 sets of results.

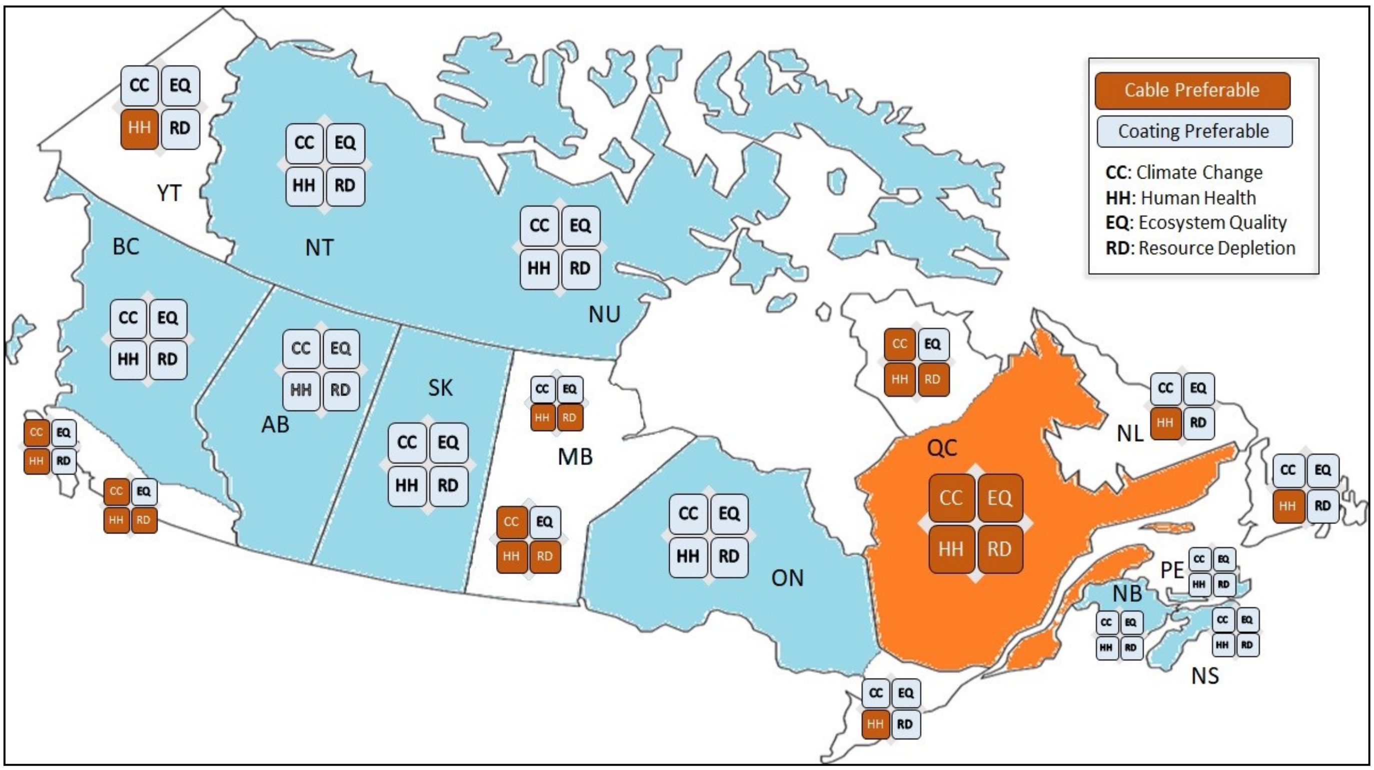


Figure 9 - Identification of the system with the lowest potential environmental impact in each climate region

The coating system is environmentally preferable for all impact categories in nine regions. The cable system is preferable for all impact categories only in lower Québec. The results are mixed in the remaining 9 regions on the map. Due to its higher energy efficiency, the coating system is environmentally preferable in regions that use higher percentage of non-renewable energy sources and have more heating days (i.e., longer or colder winters). In regions using more renewable energy sources (e.g., Québec), the environmental benefit of the energy efficiency is diminished. In those cases, environmental preference is determined primarily by system production and installation.

2.3.3. Break Even Analysis

Figure (10) shows the results of the environmental break-even analysis with the climate regions combined for each province and territory. For provinces with multiple climate regions, the column represents the range of break-even points, with the highest calculated β provided above the range. This value represents the amount of use-phase electricity savings required for the coating system to be environmentally preferable in all regions of a specific province or territory (see equation 5).

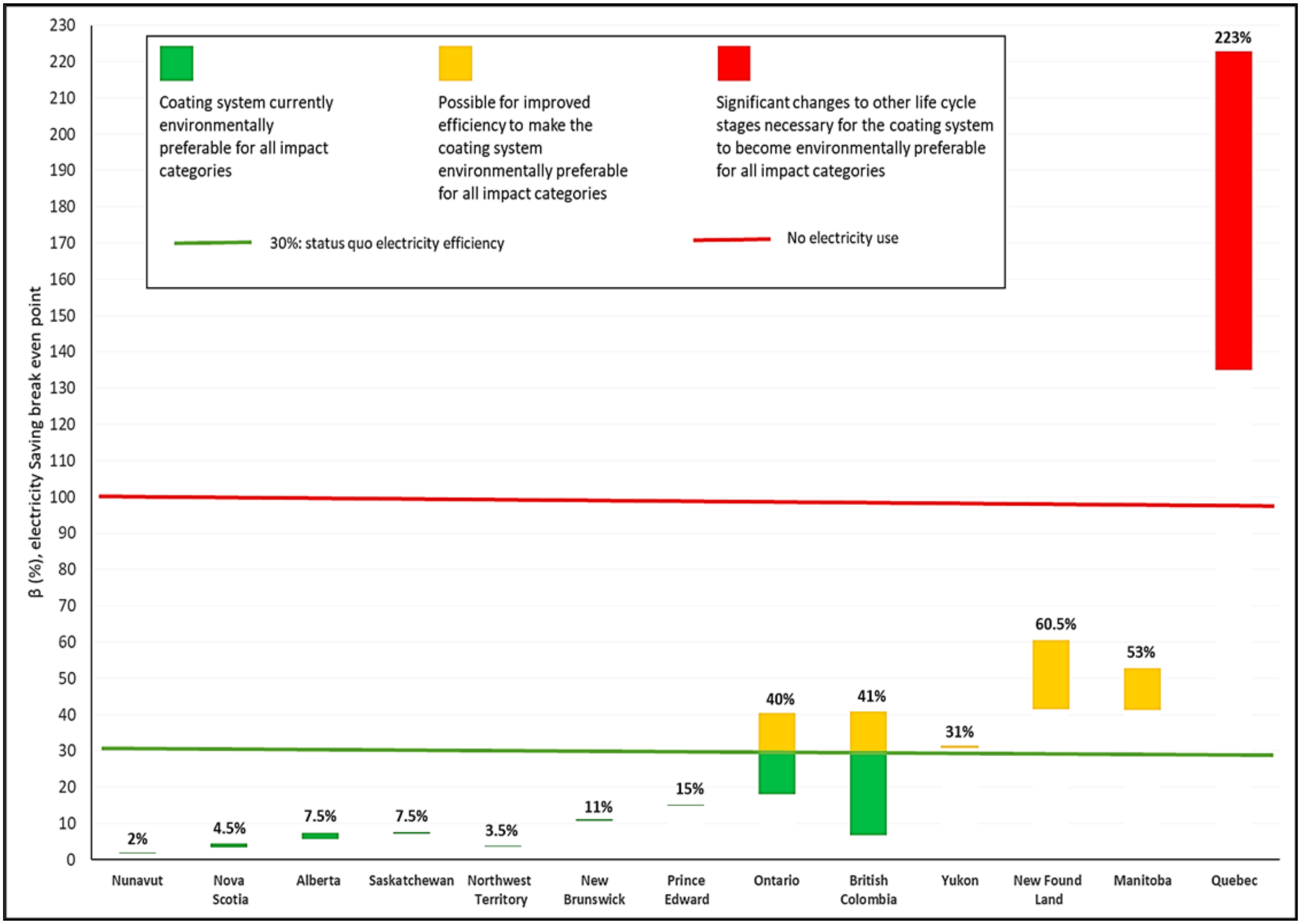


Figure 10 - Electricity savings required for the coating system to be environmental preferable for all impact categories for each Canadian province and territory

Two lines represent two values of β, the 30% electricity savings realized in the experimental study and assumed in this analysis (green line) and a 100% energy savings, which would require no electricity use during operations (red line). The color of the shading represents the level of difficulty in achieving the required electricity savings, with green indicating that the current level of electricity savings is sufficient for the coating system to be environmentally preferable for all impact categories and red indicating that environmental preferability cannot be achieved via electricity savings since a relative efficiency greater than 100% is not possible. In this case, significant changes in other life cycle stages would be necessary for the coating system to become environmentally preferable for all impact categories.

2.3.4. Lifespan scenarios and Break Even point

To investigate the sensitivity of results to coating system lifespan, the variation of β value was calculated for all 49 climate regions (48 climate regions plus baseline scenario indicated by red box) and plotted in Figure (11) assuming an expected life of 10, 20, 30, 40 and 50. For each province and territory, the climate regions are represented by the number frost days, which are presented in descending order from left to right.

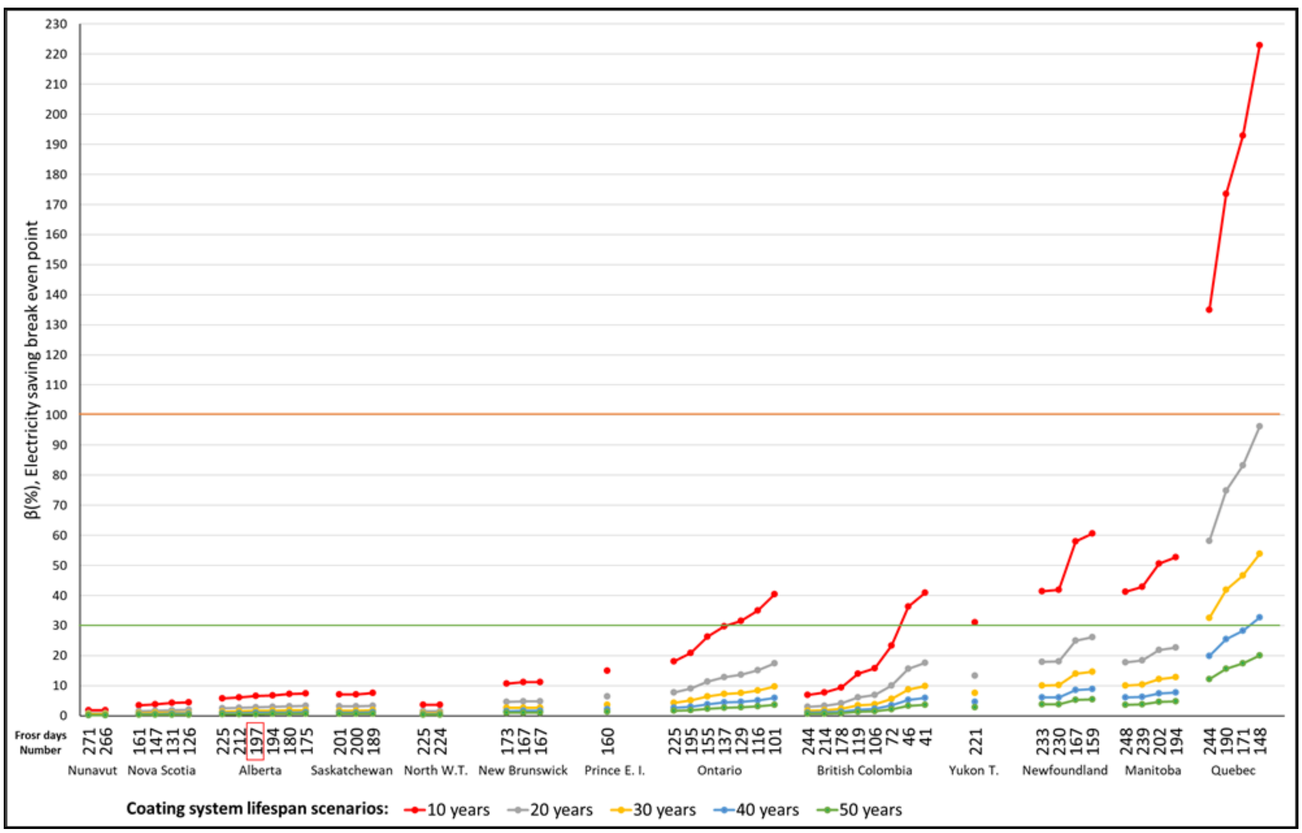


Figure 11 - Electricity saving break-even point of coating system sensitivity to coating system lifespan

As the expected life of the coating system increases, the required electricity savings for achieving environmentally preferable decrease significantly. At a 20-year expected life, the coating system would be environmentally preferable at the current energy efficiency level in all provinces and territories except Québec. At a 40-year expected life, the coating system would be environmentally preferable in all but one Quebec climate region. At 50-year expected life, it would be environmentally preferable in all Canadian climate regions. Increasing the durability (expected life) of the coating system would reduce the amount of impact associated with production, installation and transport allocated to the functional until, thereby rendering it environmentally preferable even in locations that use more renewable energy.

2.4. Discussion

A previous TEA found the multi-layered coating system considered herein to perform better but cost more than electric heat tracing systems for protecting pipes against freezing [43]. The coating system offered higher thermal efficiency and produced uniform temperature distribution over a large surface. However, the 10-year cost for the coating systems was roughly nine times higher than that of the cable system. The authors concluded that efforts to reduce fabrication and maintenance costs would be key to reducing the cost of the coating system. Otherwise, their applicability may be limited to situations requiring high performance, even if at higher cost.

This study finds that the environmentally preferability of the coating system depends on where it will be installed, based on energy sources and climate at the locations. The fabrication of the coating system was found to have a larger environmental footprint than that of the cable system, assuming a 10-year expected life. However, the higher energy efficiency of the coating system would reduce use-phase energy consumption by 30% [42]. The resulting environmental savings is sufficient to make the cable system environmentally preferable in provinces and territories with longer, colder winters and electricity generated from non-renewable energy sources. However, in regions that have milder, shorter winters or use more renewable energy sources, the use-phase energy savings is insufficient for offsetting the higher environmental impact from fabrication. In these cases, the cable system is environmental preferable for some or all environmental impact categories.

The results of this study are quite sensitive to the assumption of a 10-year expected life for the coating system. In contrast, a 40-year expected life was assumed for the cable system based on historic performance and manufacturer product guarantees. As a result, all environmental impacts from fabricating, installing, and transporting the coating system were assigned to the functional unit (i.e., freeze protection for 10 years), whereas only 25% of these environmental impacts were assigned to the functional unit from cable system. If the coating systems proves to have a comparable expected life as the cable system, the coating system would be expected to be environmentally preferable in 47 of 48 climate regions for all four impact categories. Depending on industry practice, it more be appropriate to use useful life instead of expected life. The previous TEA [42] was based on a useful life of 10 years for both systems based on an average heating equipment discard age of 11 ± 4 years in Canada [110]. Basing the LCA on the same useful life would have a similar effect as assuming the same expected life for both systems, i.e., the coating system would be environmentally preferable in most climate regions.

In assessing emerging technologies, it is also important to consider broader trends that could influence the results. Two ongoing trends would likely reduce the use-phase impacts of Canadian pipe freeze protection systems. First, Canada’s annual mean temperature has been increasing at twice the rate observed globally [111]. Warmer winters may reduce the amount of electricity required for pipe freeze protection. Second, Canada's plan to address climate change includes policies and investments to increase the amount of electricity generated from renewable and low-emitting sources [112]. This could reduce the environmental impacts associated with use-phase electricity consumption. These trends are not unique to Canada and could reduce the apparent environmental benefits from use-phase electricity savings when assessing the environmental burdens strictly associated with the product systems. While these trends would diminish the use-phase environmental savings from the coating system under the assumptions used in this study, the coating system would still be environmentally preferable if the same useful or expected life were used.

Several important limitations should be considered when interpreting the results of this study. First, there are several important sources of data and model uncertainty. For example, cable materials were assumed based on published information, electricity consumption was based on experimental rather than operational performance, and LCI data was primarily obtained from the ecoinvent market-type data rather than actual producers of components used in Canadian pipe freeze protection systems. Second, the nascent multi-layered coating system is an unproven technology for which there is no operational data. The system was modeled based on laboratory-scale production, an experimental heating test, and conservative assumptions. Third, several aspects of the system life cycle were omitted from the study, including system maintenance, repair, or replacement and end-of-life waste management. While many of the materials used in both systems can be recycled, the likelihood and impacts of separating and recycling these materials is not well understood. Occupational health and safety impacts were also omitted from this study. Given the emerging knowledge about the occupational hazards from thermal spraying [113], this could be an important limitation. While methods for considering occupational impacts in LCA have been proposed [114], additional research is needed to understand and model the potential impacts from specific industrial processes. Finally, the study takes an attributional approach, i.e., it assesses the environmental burdens associated with the product systems. For this reason, renewable electricity savings result in relatively small environmental savings. However, such savings may allow renewable electricity producers to sell more electricity to other markets, thereby displacing fossil fuel-based electricity and reducing global GHG emissions. Consequential LCA could be used to consider indirect implications for widescale adoption of the more efficient coating system.

Taken holistically, studies on the proposed multi-layered coating system for pipe freeze protection present a problem of competing objectives, contingencies, and trade-offs under uncertainty. The conventional heat tracing cable option is cost effective, proven, and performs sufficiently well in most applications. The multi-layered coating system improved performance most likely with a lower environmental impact but currently at a higher cost.

2.5. Conclusion

LCA was employed to compare the cradle-to-gate environmental performance of two heating systems for protecting industrial pipes against freezing and bursting. Due to its lower operational energy consumption, the experimental multi-layered coating-based resistive heating system was found to be environmentally preferable when installed in areas with longer, colder winters and electricity generated from non-renewable energy sources. However, in areas with a milder or shorter winter or where electricity is generated from renewable energy, the use-phase savings is insufficient for offsetting higher environmental impact from fabricating, installing, and transporting the coating system. Several realistic scenarios could render the coating system environmentally preferable in most climate regions; the coating and cable system have a comparable expected or useful life; savings in electricity from renewable sources reduces the use of electricity from non-renewable sources elsewhere; industrial scale fabrication of the multi-layered coating system has a lower environmental impact than laboratory scale fabrication; or changes are made to the coating process (e.g., alternate coating materials or deposition methods) to reduce the environmental impact of coating system fabrication.

The limitations identified in this study underscore research needs for more accurately assessing and ultimately reducing the life cycle environmental and human health impacts of emerging thermal spray technologies, both for freeze protection applications and more generally. Future research should focus on validating the performance of the coating system for freeze protection applications, determining a relevant and accurate useful or expected life to use in comparing freeze protection systems, incorporating occupational impacts in LCA thermal spray technologies, analyzing material, geometry, and thermal spraying process options for fabricating multi-layered coated pipes, and investigating the likelihood and impacts of separating and recycling coating materials.

While the multi-layered coating-based resistive heating system offers significant potential for improved operational and environmental performance in freeze protection applications, the primary challenge to widescale adoption is its higher cost. Future work should focus on reducing both the cost and environmental impact of coating materials and deposition processes, ensuring worker safety during coating deposition, field testing the system for durability and reliability, and recovering and recycling coating materials after decommissioning. The TEA (presented in an earlier study) and LCA (presented here), can be updated to assess the business-environmental case of future developments.

3. Second case study: Hard Chromium removal methods LCA[2]

3.1. Introduction

Coatings, which are applied to protect or enhance the properties of surfaces, must sometimes be removed. For example, coatings may be removed to repair or replace a damaged or degraded coating, inspect or repair the substrate, eliminate environmental hazards to enable component disposal, and enable material recycling [115], [116]. Removal methods in industry are divided into three main categories: molecular disassociation or chemical methods, impact or mechanical methods, and thermal methods[115].

With chemical methods, the workpiece is immersed in a solution with a specific pH and a chemical reaction between the coating and solution breaks the bond between the coating and the substrate[117], [118]. With mechanical methods, mechanical power is used to strip the coating from the substrate. This includes the use of traditional (manual) methods (e.g., scuff paper, sanding, and grinding)[119] as well as industrial abrasive blasting methods, which includes wet blasting methods (e.g., water jet stripping [120] and ultrasonic cleaning[121]) and dry blasting methods[122], [123] (e.g., propelling blasting media against the surface using compressed air, centrifugal force [124], or negative pressure produced via a vacuum[125]). Thermal methods utilize controlled heat and localized penetration created by laser or heat lamps for abrading or decomposing the coating from the substrate. [116], [126] The most effective removal method depends on a number of factors, including coating type, substrate type, work environment, part dimensions, desired surface finish, work environment, environmental and occupational safety regulations, and operational budget.[115], [123], [126]

Over the last three decades, a novel wet blasting method Pulse Water Jet (PWJ), also called Forced Pulse Water Jet, has been developed[127] that uses the kinetic energy produced by a high-pressure water jet combined with the hammering effect of pulses generated in the water stream to remove coatings from a substrate [128]. The pulse are generated by installed prob ,called microtip, inside the water jet nozzle which is manipulated with a piezoelectric transducer[127].

PWJ is currently used to remove Aluminized Epoxy Enamel, SermeTel Type “W”, Plasma sprayed Thermal Barrier Coating (TBC) and Tungsten Carbide HVOF coating from in the renewal process of aircraft gas turbine engines [129], [130]. It has been tested for removal of hard coating like International Intertuf KTE, Alkyd Marine Enamel and Amercoat 68HS from the interior surface of ships[131] decontamination of steel piping in nuclear industry[132], [133], modifying surface in medical grade alloy of titanium[134], steel container surface preparation for cold spraying of copper [135], cleaning of delaminated concrete and rust from parking ceiling [136] aircraft overhaul applications, including the removal of hard chromium, Tungsten Cobalt HVOF, and epoxy coating and other coatings in aircraft components [137], [138]. In addition, PWJ is introduced as an environmentally preferably to other coating removal methods because of the lower chemical usage and water recycling system[139] .

[2] This chapter will be revised and submitted for publication to a peer reviewed journal. The resulting manuscript will be co-authored by Shannon Lloyd, Roger Eybel, Alan Caceres, Andrew Tieu and William Bloom. The research reported in this chapter was conducted by the author of this thesis, Zeynab Yousefzadeh, with data and advising provided by the co-authors.

A rigorous method for comparing the environmental impact of PWJ to incumbent coating removal methods is needed. In this study, a framework using life cycle assessment (LCA) to conduct such as comparison is proposed. The framework is developed to compare PWJ to electrochemical cleaning from removing hard chromium from aircraft landing gear. Since PWJ has not yet been used in such an application, a prospective LCA approach is used in which a number of techniques are used to anticipate the performance and PWJ in this application[18], [32]. To develop a process-level understanding of each method, VLN Advanced Technologies' research and development facility in Ottawa, Canada and Safran's landing gear manufacturing and maintenance, repair and overhaul (MRO) site in Mirabel, Canada were visited.

Hard chromium coating is widely used in aerospace, automotive, petrochemical, agricultural, marine, decorative and other industrial applications[140], [141] due to its hardness, low coefficient of friction, and wear, corrosion, and heat resistance properties[142] Chromium is commonly deposited on the substrate through the electroplating process of hexavalent chrome (Cr(VI)). Due to its high risk of cancerogenic emission of Cr(VI) in this method[143], alternatives[144] like trivalent chromium electro deposition [145], thermal spray methods [16], [17], [146]and different coating with similar properties like Tungsten Cobalt Chromium (WC-Co-Cr) are developed[147], but still they could not totally replaced with all applications of hard chromium plating.

The landing gear has an essential role in the safety and configuration of aircraft, and their design and production are costly. Therefore, in the case of failure or periodic maintenance, there is an attempt to renovate and recycle landing gears [148]. Based on the vast application of hard chromium plating for landing gears in the Maintenance, Repair and Overhaul (MRO) of these components, removing the old hard chromium coating from the workpiece is frequently required. The appropriate removal method should provide a clean surface without significant damage to the substrate. This damage can be hydrogen embrittlement, rusting, microcrack, etching, filiform, exfoliation, or other over-exposure and impact damages on the workpiece that make it improper for future use [115].

Among methods applied for hard chromium removal, electrochemical cleaning is a commonly used [149]. In electrochemical cleaning, the workpiece is immersed in an electrolytic system and connected to one of the poles of a rectifier. Then, the electrical current increases the removal efficiency. The solution in this system can be chromate acid, and the process is similar to electrodeposition with a reverse current that is led to chromium removal. The high risk of cancerogenic chromium hexavalent ions emission [150] caused the developing of alkaline solutions with lower hazards. Chemical strippers in Alkaline Electrochemical Cleaning (AEC) are water-soluble materials like Sodium Hydroxide, Potassium Hydroxide or the combination of these two Alkalis. Alkaline electrochemical cleaning is the standard method of hard chromium removal used in Safran's MRO department [151].

For selecting a feasible coating removal method, it is needed to consider coating and substrate materials, the purpose of de-coating, cost efficiency, environmental limitations, and waste management regulations. Several companies and experts that provide coating removal services compare removal methods from mentioned aspect [123], [125], [152]–[158]. Some academic papers address technical aspects of removal methods and compare them with other systems. Menini et al. [159] compared five electrochemical stripping solutions of WC-Co-Cr coating in four criteria, including the level of substrate integrity preservation, stripe rate, uniformity of coating removal and final damage level to the substrate. The results showed that two of them did not fulfill the standard removal process requirement for landing gears, and among the rest, the cyanide-based solution was more efficient with potentially higher risk to the environment [159]. For the same coating, Ruusuvuori et al. [160] compared the replacement of aluminum oxide powder water jetting with conventional chemical stripping. They concluded that with accurate coating thickness measurements and controlling the blasting parameters, the new technology could be used for WC-Co-Cr and Cr3C2-NiCr coatings instead of the chemical method.

Some studies investigated the environmental impact of metal workpiece cleaning. McCrabb et al. [161] tested different stripping solutions, comparing common concentrations of sodium hydroxide and sodium carbonate with mineral salt and acid solutions to minimize the hexavalent chromium formation in cleaning baths. Determining the functional unit in these studies was a key challenge. Ruhland et al. [162] investigated a method for defining a reference unit for LCA degreasing a workpiece in a bath and tried to cover the differences in part geometry, impurities mass, working hours and load volume per cleaning practice. Based on this study, after estimating the reference flows, some experiments should be conducted to obtain a specific coefficient that is unique for a particular machine, material, or energy efficiency. In another study, Peng et al. [163] conducted an LCA to compare two cleaning methods for removing rust, paint, carbon impurities, and grease. The novel system was a combination of Supercritical CO_2 and liquid blasting compared with the conventional thermal decomposition combined with shot blasting. The results showed that the new system has less impact in five specific impact categories defined in this study. In some LCA studies, the removal processes were discussed briefly as the surface preparation stage in the renew, repair and maintenance processes. Montavon et al. [16] studied the environmental impact of hard chromium electroplating in comparison with thermal spray methods, and they addressed the impact of alkaline cleaning in electroplating and grit blasting in the thermal spray method [151]. In another LCA, Moign et al. [17] included the impact of alkaline cleaning in the nickel electroplating and the grit blasting in thermal spray coating LCA models. Lopes de Almeida [164] conducted environmental life cycle and cost analysis of electroplating, HVOF and cold spray, and he referred to material and energy input of alkaline electro-cleaning and sandblasting as a part of coating processes. However, the focus of mentioned studies is the coating process, and they did not address the complexity and critical details of LCA modelling of removal methods. The current analysis concentrates on two feasible industrial hard chromium coating removal methods, including conventional Alkaline Electrochemical Cleaning (AEC) and a novel Pulse Water Jet (PWJ). This study uses a system based LCA to compare the expected environmental impact from the chromium stripping process and waste management of these two cleaning methods in landing gears overhaul. For collecting data in this study, we were working directly with two industrial coating removal experts and the source of data collection includes experiments, expert elicitation, recorded historic practical data, site visiting, technical guidelines, literature review, and assumptions.

3.2. Methods

3.2.1. Systems Considered

3.2.1.1. Alkaline Electrochemical Cleaning (AEC)

Alkaline electrochemical Cleaning (AEC), Reverse Electroplating, or Anodic Cleaning are synonym phrases for describing a surface preparation process in an electroplating plant. This process aims to remove the soil and old inorganic coating from the substrate to prepare it for applying new coating [149], [165] . In this study, hard chromium removal in an AEC bath with sodium hydroxide and water solution at ambient temperature is modeled.

After receiving the workpiece for cleaning, it is transferred to the degreasing bath. Degreasing bath contains water with a portion of cleaning agent for removing oil and grease from the surface of workpiece. Also, a degreasing bath is commonly equipped with ultrasonic cleaning technology. Immersing duration in the degreasing bath and exposing the workpiece to the ultrasonic cleaning process differs based on the part and its coatings [151]. In the next step, if it is required, the areas that need to be protected from chemicals are masked. Commonly, for masking, specific consumable tapes are used, but sometimes durable metallic tools are fitted to protecting area and can be used unlimitedly. After masking, the workpiece goes to the alkaline cleaning process. In this stage, the electrolytic system uses electrical power to strip unwanted inorganic layers from the workpiece. Figure (12) shows the simplified electrolytic system in an alkaline cleaning process. The fundamental components of this electrolytic system are as follow:

- A bath containing a certain amount of sodium hydroxide solution with controlled concentration, PH and temperature.
- A rectifier converting the electrical current from AC to DC
- The cathode: a piece of metal (commonly steel) connected to the negative leg of the rectifier.
- The anode: the workpiece connected to the positive leg of the rectifier.

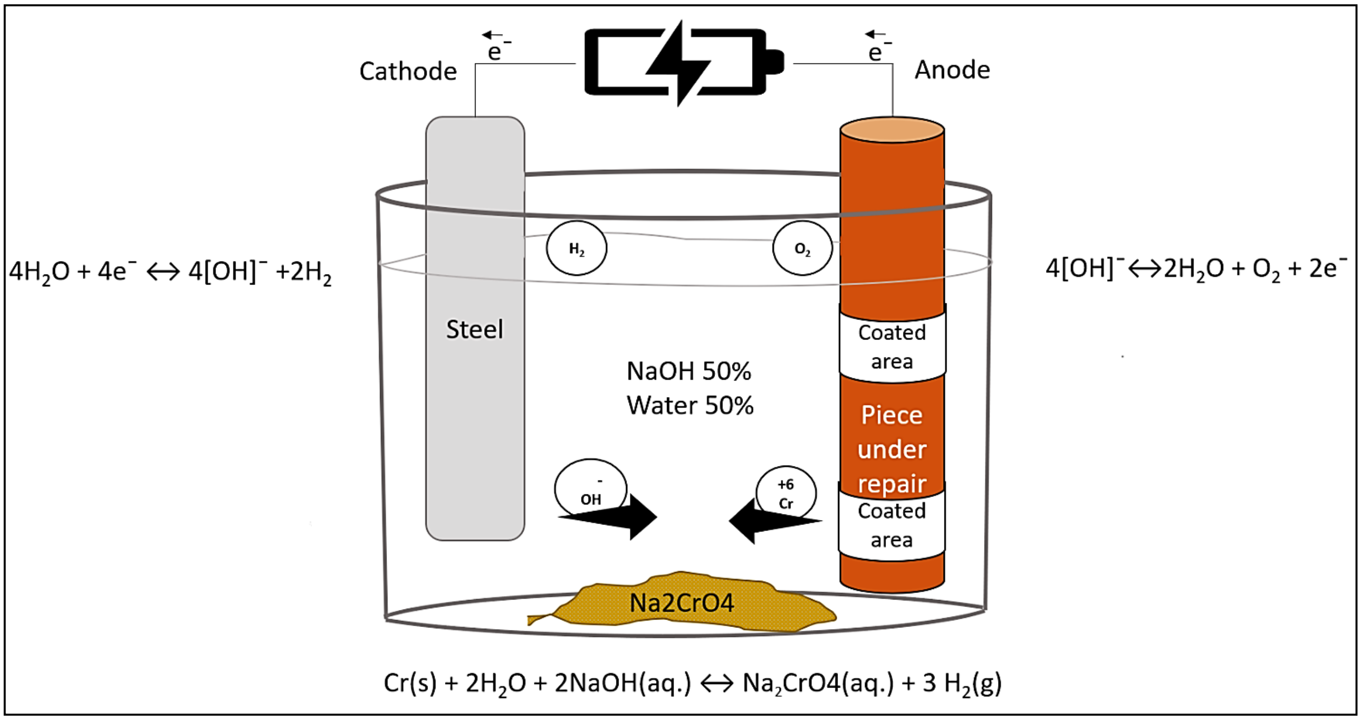


Figure 12 - Alkaline Electrochemical Cleaning, schematic electrolytic system

Sodium hydroxide in an aquatic environment decomposes to its radicals based on the following reaction:

$$NaOH \leftrightarrow Na^{1+} + OH^{1-}$$

After running the electricity, two mechanisms help coating removal on the surface of the workpiece. First, the current triggers the chromium molecules to lose their valance electrons in the anode and become positive ions. Released cations (Cr+6) travel toward the cathode and inside the solution react with negative radical (OH^-), as following reaction:

$$Cr\,(OH)3(s)+OH-(aq) \leftrightarrow Cr(OH)-4(aq)$$ [166]

The second mechanism is the formation and bursting of gas bubbles generated through the chemical reactions at the cathode and anode surface. The oxygen and hydrogen bubbles form respectively at the surface of anode (workpiece) and cathode, based on the following reactions:

- *Anode Reaction: 2H2O → O2 + 4H+ + 4e−*
- *Cathode Reaction: 4H2O + 4e− → 2H2 + 4OH−*

Although the bursting of hydrogen bubbles in the cathode side releases more energy, bursting oxygen bubbles in the anode side and on the workpiece's surface also help accelerate coating removal [167], [168]. Overall alkaline electrochemical cleaning reaction can be described as follow:

$$Cr(s) + 2H2O + 2NaOH(aq.) \leftrightarrow Na2CrO4(aq.) + 3H2(g)$$ [169]

The theoretical amount of time (t) required to remove chromium via electrochemical stripping can be calculated using Faraday's law [170]. Here, the formula is adjusted to allow for use of current density (i):

$$t = (F \cdot m \cdot z) / (i \cdot a \cdot M)$$

where F is Faraday's constant (96,485 °C mol-1), m is the mass of coating to be removed, z is the valence number of ions of the substance (6 for Cr), i the current density, a is the area of coated surface exposed to the electrolyte, and M is the molar mass of the coating. Actual stripping time depends on the system's current efficiency, which may be reduced by secondary electrochemical reactions, metal deposits on the work rack, the pH of the solution, and other characteristics. For example, small amounts of carbon dioxide in the air can react with the sodium hydroxide solution to form sodium carbonate, reduce sodium hydroxide in the solution, and lower the Cr stripping rate [169]. The theoretical and actual stripping times for 13 components processed by the electroplating site were compared. Calculations were performed using the average of that sites specified current density of 20-30 A/dm² [151]. The calculated process efficiency ranged from 11% to 30%, with an average of 18%. While reported current efficiency Cr stripping was not found, Hard chrome plating solutions have a very limited cathodic plating efficiency (ranging from 10 to 30 % in industrial baths), cathodic plating efficiency is reported to be between 10 and 30 % in industrial hard chrome plating baths [171]. For parts in which the actual time is not known, Cr stripping time can be estimated assuming an 18% current efficiency (see appendix C).

Operators observe the cleaning process to make sure the stripping is complete. After accomplishing the coating removal, the workpiece is brought out of the bath and rinsed in the water for about one minute. This is the final stripping step for the workpiece, and it will go for other required treatment sections[151].

This waste of the process are the wastewater and sludge both are considered as hazardous wastes because of containing hexavalent chromium [172]. Therefore, they should be treated based on the specific protocols and guidelines [173]. The wastewater from all bathes in an electroplating plant is brought to treatment facilities. For reduction of toxic Cr (IV) to Cr (III) sulfuric oxide and for sedimentation of Cr (III), agents like soda, calcium hydroxide or magnesium hydroxide are used [174].

3.2.1.2. Pulse Water Jet (PWJ)

The alternative system is pulse water jet technology which was invented by VLN Advanced Technologies, located in Ontario, Canada [175]. This system is comprised of six subsystems, including a water filtration system, water pump, robot system, pulse generator machine, ventilator and cooling air compressor. The process occurs in a closed booth. A robot inside the booth holds and controls the water jet gun, and the after-use water is collected in a bath embedded in the booth’s floor. Figure (13) displays the schematic configuration of the subsystems together

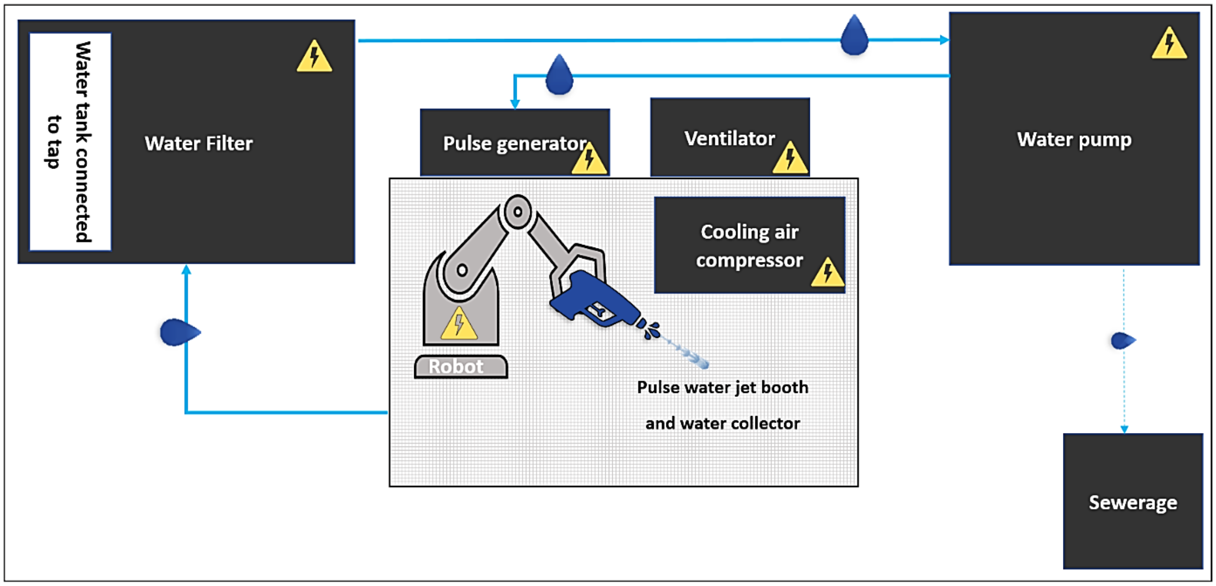


Figure 13 - Pulse Water Jet technology schematic sub-systems' layout

The arrows in the picture indicate the water flow in the system. High-pressure water combined with frequent pulses acts as abrasive media, which is circulated in the system unlimitedly. The small amount of water lost during pump cleaning or through ambient evaporation is refilled by tap water. Due to the presence of the water, the risk of bare substrate rusting is high; therefore, the specific organic solvent is used as a solution in the water to avoid rusting.

A computer outside the booth controls the robot. The robot operator adjusts the system based on the determined parameters like the pressure of the jet, gun speed and the removal width before operating the system. These parameters are dependent on the type, thickness, area and other technical aspects of the coating and substrate.

3.2.2. System boundaries

The system boundaries for the study include the processes shown in Figure (14). This is considered a cradle-to-grave study that goes from raw material extraction to waste treatment. However, in this study, only the inputs and outputs of removal processes were considered, and the material and fabrication of landing gears or other treatment processes were not included.

In Figure (14), solid gray rectangles represent the steps of the removal processes, solid white boxes display the inputs, and the dashed white rectangles show the output of each step. Solid and dashed arrows respectively display the workflow inside and to/from outside of the system boundaries. Due to the high risk of Cr (IV) emission to air, in AEC (Fig. 14a), ventilation constantly works for all sections shown as a box connected to all processes with gray arrows. In PWJ (Fig. 14b), the after-use water is recirculated unlimitedly from the water collector (at the floor of the robot booth) to the system shown with gray arrows and highlighted triangles.

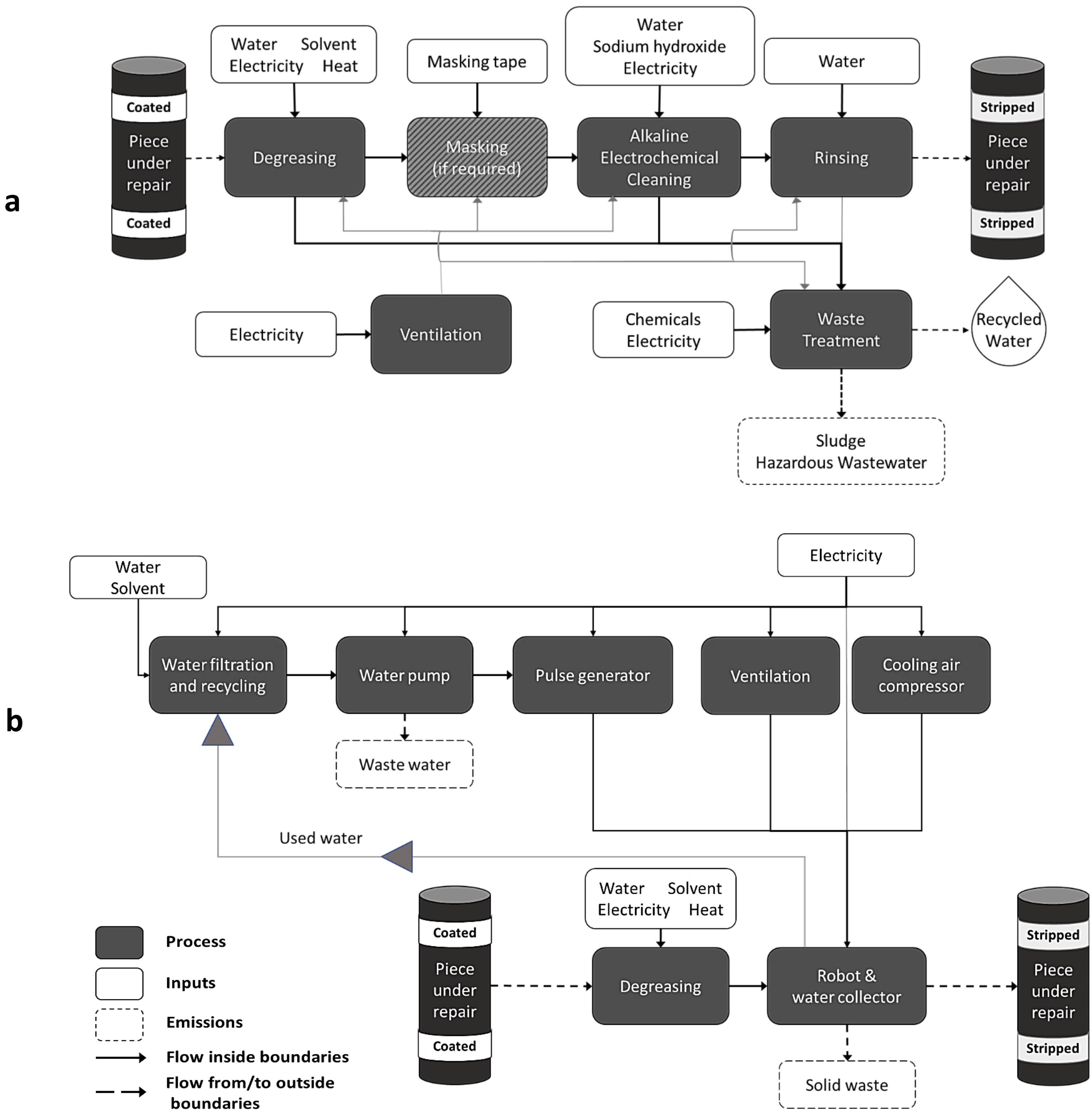


Figure 14 - Removal process flow a) Alkaline electrochemical cleaning, b) Pulse water jet

3.2.3. Functional Unit

In LCA, a functional unit provides a measurable amount of function by which all alternatives are evaluated. Here, the functional unit is defined as ***removing of hard chromium coating from landing gear component A340 with three hard chromium coated zones in Quebec.*** Table (5) shows characteristics of part number A340 estimated based on provided data from the landing gear overhaul department.

Table 5 - Characteristics of landing gear component A340 as the basis of comparison

Item	Amount	Unit
Total chromium coated area	2.25	m^2
Total chromium coating mass	815.3	g
Part total length	3.134	m

3.2.4. Life Cycle Inventory (LCI)

Removal method parameters can vary with several coated piece properties, including substrate composition, substrate hardness, coated area, coating thickness, coating mass, process time, part geometry, and coating method efficiency. Accordingly, the inputs and outputs of removal methods can be sensitive to area, mass and time. The total impact of the removal process (I_{Total}) for a workpiece with n coated zones, is equal to the summation of area-sensitive impact (I_A) multiply in the coated area (A_i), mass-sensitive impact (I_M) multiply in coating mass (M_i), and time-sensitive impact (I_T) multiply in process time (T_i) as follow (equation 6):

$$I_{Total} = \sum_{i=1}^{n} (A_i \times I_A) + (M_i \times I_M) + (T_i \times I_T) \tag{6}$$

Both systems were modelled using openLCA version 1.9.0 [56], resulting in a life cycle inventory (LCI) of environmental inputs (e.g., raw materials, energy, water) and outputs (e.g., emissions to air, water and land) required from raw material extraction, material processing, energy generation, system fabrication, installation, use and decommissioning. Each model included the foreground activities shown in Figure (14) as well as the associated background (supply chain) activities, including natural resource extraction, materials processing, material and part transportation, and electricity generation. Data for the models were obtained from two industrial metal finishing units in Canada based on practical data [176], [177], relevant literature and assumptions (as detailed below), the ecoinvent version 3.3 LCI database [58], which provides LCI process data for thousands of products. It should be noted that the ecoinvent processes include all of the material and energy inputs and resulting outputs (e.g., emissions, waste) associated with the modelled activity.

3.2.4.1. Alkaline Electrochemical Cleaning (AEC)

The data sources for AEC included expert's input, provided information based on recorded historic practical data, site visiting, technical guidelines, literature review and assumptions. However, literature that studied alkaline cleaning was rare; the electroplating studies with alkaline cleaning as a part of their processes were reviewed to model this process. Determinging a reference unit (e.g. coated area or coating mass) for allocating inputs and outputs has specific challenges due to the variety of variables that affect the system's proficiency.

Montavon et al. [16] modelled the hard chromium electroplating per square meter of coated area; however, they calculated input/outputs based on a specific thickness of the coating (140 µm), which resulted in approximately 1 kg coating per m^2 based on density of chromium (7.20 g/cm3). Choosing a specific thickness to obtain the coating per unit of area and mass at the same time proved to be a clever way to solve the multifaced nature functional unit problem. In the current study, the parameters were divided into three groups: time-sensitive, area-sensitive, and mass-sensitive parameters to have a more accurate calculation and create a model that can work with different thicknesses and areas.

For the first process, degreasing, the existing unit process in ecoinvent database was used. Since this process inputs were allocated based on the area, it was considered as an area-sensitive parameter. The second step is masking. Since specific tools in the overhaul department have already been replaced with consumable masking tapes, no input was considered for this step. The third and main process is immersing the workpiece in the alkaline bath to remove coating via coating and solution electrochemical reactions. Since the removal process occurs at the molecular level, all parameters, including required processing electricity, sodium hydroxide and water, and amount of sludge, were considered mass-sensitive parameters and allocated based on the coating mass.

Process electricity was calculated based on the recorded data in the overhaul department. Data included the voltage of the rectifier (4-6 V) and the average amount of current density (20-30 A/dm^2), and area and processing time for per coated zone. Since electricity is used at the molecular level and each ion transfer consumes some, it is more realistic to calculate processing electricity based on the mass rather than the area. This approach can be more reasonable since there are coated sections with a similar coated area but different thicknesses, which probably needs more immersing time. Accordingly, the required electricity (Watt) for the electrochemical process for 13 coated sections was calculated; it was multiplied in time and divided into coating mass (kWh/g). The average electricity per mass was considered the required electricity for one gram of chromium to be stripped. More accurate measurements during the process can resolve the uncertainty related to this calculation in future studies.

The consumption of sodium hydroxide, water and sludge (Na2CrO4) were estimated based on the electrochemical stripping reactions [169], [178], which includes the reduction of water to hydrogen gas and hydroxide ions (cathode reaction), oxidation of metallic chrome plating to hexavalent chromium (anode reaction), and formation of soluble sodium chromate (hydroxide reaction). Based on the assumed overall reaction shown below, the removal of 1 g of chromium requires 1.54 g of sodium hydroxide and generates 3.11 g of sodium chromate.

$$Cr(s) + 2H2O + 2NaOH(aq.) \leftrightarrow Na2CrO4(aq.) + 3H2(g)$$

The final process is rinsing. The water consumption through rinsing was estimated based on the ecoinvent hard chromium electroplating unit process. In this process, the amount of water used for rinsing is considered 8 kg per coated area [16],[151].

The ventilation electricity and amount of wastewater treatment were estimated based on the time that facilities are working in the overhaul department. The ventilator purifies 32,571 m^3 per hour. The average power needed for a wet scrubber with 1000 cfm (cubic foot per minute), which is common scrubbers in electroplating sites[143], is 3.41 hp [180]. Having these, ventilation power per hour was calculated to be 48 kWh.

The average annual electroplating wastewater in the overhaul department is 1271 m^3. By dividing the number of parts processed in the alkaline cleaning bath into the number of parts processed in other chemical bathes of the overhaul department, the portion of AEC from the overall waste stream was estimated at about one percent. It was considered that the wastewater facility works 20 hr per day, and the amount of alkaline bath wastewater was calculated to be 0.0017 m^3 per hour. The amount of sulfuric acid and sulfur dioxide needed for wastewater treatment was estimated by ecoinvent unit process for electroplating [179]. In that unit process amount of sulfuric acid and sulfur dioxide was calculated for 1 kg coating, and in this study, it was calculated for 1 g of coating. The final amount was multiplied in 1% (the contribution of alkaline cleaning in overall wastewater) to achieve the needed chemicals for alkaline cleaning wastewater treatment. The inputs and outputs of AEC are listed in the Table (6).

Table 6 -Assumed inputs and LCI data sources for Alkaline Electrochemical Cleaning

Item	**Amount**	**Units**	**LCI Data Source**
Time sensitive			
Electricity (Ventilation)	48.72	kWh/hr	ecoinvent dataset market for electricity, medium voltage [181], [182]
Wastewater treatment (Waste treatment)	0.0017	m^3/hr	ecoinvent dataset market for wastewater from black chrome coating [183]
Area sensitive			
Degreasing	1	m^2/ m^2	ecoinvent dataset market for degreasing, metal part in alkaline bath[184]
Water (for rinsing)	8	kg/ m^2	LCA of Thermal-Sprayed and Chromium Electroplated Coatings [16] and ecoinvent datasets: market group for tap water[185], [186]
Mass sensitive			
Electricity (Alkaline bath)	0.11	kWh/g	Practical data and ecoinvent datasets: market for electricity, low voltage [78], [98] (Appendix D)
Water (for alkaline bath)	0.35	g/g	Mass calculation of alkaline cleaning reaction and ecoinvent datasets:market group for tap water [185], [186]
Sodium Hydroxide (for alkaline bath)	1.54	g/g	Mass calculation of alkaline cleaning reaction and ecoinvent dataset market for sodium hydroxide, without water, in 50% solution state [67]
Sulfur dioxide (for waste treatment)	0.035	g/g	LCA of Thermal-Sprayed and Chromium Electroplated Coatings [16] and ecoinvent datasets: market for sulfur dioxide, liquid [187], [188]
Sulfur acid (for waste treatment)	1.2E-8	g/g	LCA of Thermal-Sprayed and Chromium Electroplated Coatings [16] and ecoinvent datases:market for sulfuric acid [69]
Sludge treatment (for hazardous waste treatment)	3.11	g/g	Mass calculation of alkaline cleaning reaction and ecoinvent dataset market for sludge from steel rolling [189]

An average processing time was mentioned for each coated zone in the technical overhaul guideline. For the first, second and third coated section in A340, the processing time, respectively, were 2.5, 4 and 3.75 hr. It was assumed that all sections were stripped simultaneously, and therefore instead of summing up the mentioned amount, the max time (4 hr) was considered as a required time for immersing the part in the alkaline bath [151] and with 0.5 hr for degreasing required time for calculating ventilation and wastewater was estimated to be 4.5 hr.

3.2.4.2. Pulse Water Jet (PWJ)

Data sources for pulse water jet inventory included expert's input, technology developer's white papers, site visit, provided data from experiments, previous experimental results, and assumptions. Since the real samples were not available, the experiments were conducted on 8 inches long × 1.5 inches wide × 0.4 inches height flat 300M steel coupons. The approach of this study was considering conservative assumptions for PWJ in scale-up emerging systems experimental inventory to amounts that can be compared with AEC on a practical level. PWJ removal effectiveness has been already approved for hard chromium and Tungsten Carbide Cobalt Chrome (WC-Co-Cr) coating in a previous study [137], [138]. WC-Co-Cr coating applied by HVOF is an alternative for hard chromium electroplating in landing gears. There is a lack of empirical data on PWJ processing time. A previous study showed that the time required to remove coatings via PWJ was approximately two times greater to remove WC-Co-Cr than to remove hard chromium [138]. For this study, it was decided to observe and collect process time data for PWJ coating removal. Safran was able to provide a test coupon that was coated with WC-Co-Cr. The PWJ coating removal process was observed at VLN on date and process time was documented. The process time was extrapolated to estimate the process time (and associated inputs) to remove hard chromium from the specified landing gear component. This approach can decrease uncertainties generated from the lack of empirical data for the new system. Also, there is a strong trend to replace hard chromium plating with WC-Co-Cr HVOF coating with fewer hazards [146], and in many landing gear components, both coatings are present. Accordingly, these measurements can be more compatible with the real and future trends of the aircraft industry. However, experiments can reconduct on hard chromium samples to validate the result of this study.

The degreasing process for PWJ was considered an area-sensitive parameter, and similar to AEC, the existing process in the ecoinvent database was used to model it. The electricity consumption for PWJ subsystems considered as a time-sensitive parameter. However, it is obvious that for scanning bigger coated area more time is required and the effect of coated area size is hidden in the required processing time. Processing time is dependent on various factors. First of all, based on the approximate hardness and thickness of the coating, coating application method and vulnerability of substrate, it is needed to calculate pump pressure, the standing distance of the gun from the workpiece surface and the effective width that water stream removes in each pass (nozzle index) [137]. These parameters are obtained by a series of experiments and checking the quality of the final surface. Figure (15) shows a coupon (15a) was processed by different adjustments to reach best practice (15b). The specifications of the best practice for this study are detailed in Table (7).

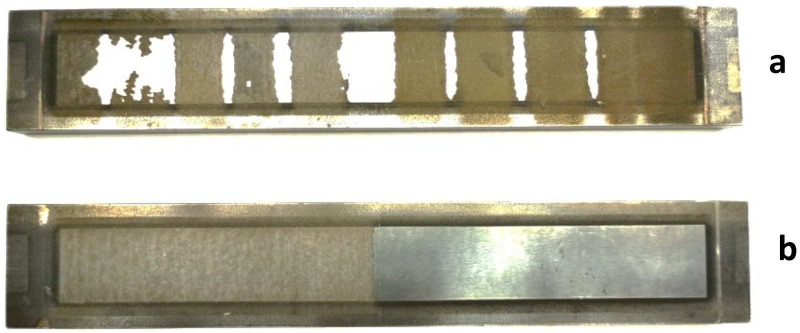


Figure 15 - Coupons processed in PWJ experiments:
a) attempts for adjustment, b) best practice

Table 7 -Specifications of best practice

Item	Amount	Unit
Standing Distance	2	inch
Nozzle index	0.055	inch
Water pressure	15000	Psi
Gun speed	800	mm/s

The geometry of the workpiece is a key factor for programming the robot movement and processing time. By increasing the number of robot turns, the processing time is increased. To obtain total time ($T_{Process}$), the required time for each pass (T_{Pass}) based on gun speed and average robot turn time in each pass (T_{Turn}) was summed up and multiplied by the number of passes (N_{Pass}) required to scan a specific coated area (Equation 7).

$$T_{Process} = N_{Pass} \times (T_{Pass} + T_{Turn}) \tag{7}$$

Figure (16) schematically illustrates the robot's movement. Increasing the length of each pass decreases the number of turns for the same coated zone, consequently decreasing total processing time. Based on calculations, the probable processing time for A340 was estimated to be 1.2 hr.

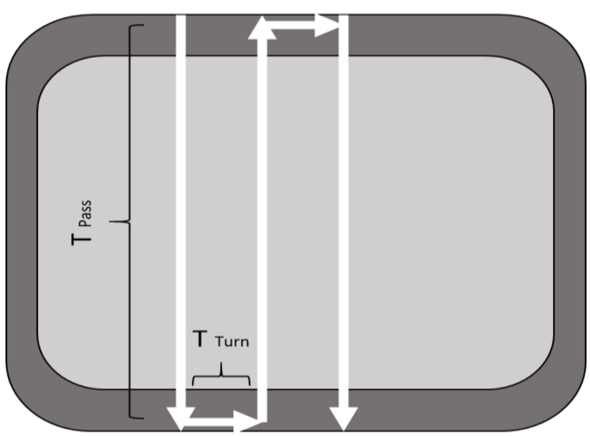


Figure 16 - Illustration of the time needed
for pass and turn in PWJ

Since all subsystems are operational during the entire processing time, the power ratings of each component multiplied by the processing time to estimate electricity required for coating removal. Water with rust inhibitor is recirculated in a close loop in the system. Accordingly, the consumption of them were considered equal to the amount their losses through evaporation or pump cleaning. Water losses were estimated to be 2 lit/hr and rust inhibitor solvent losses estimated to be 10% of this volume.

Table 8 - Assumed inputs, outputs and LCI data sources for Pulse Water Jet

Item	Amount	Units	LCI Data Source
Time sensitive			
Electricity (For filter machine)	3.73	kWh/hr	PWJ supplier and ecoinvent datasets: market for electricity, low voltage [78], [98]
Electricity (For high pressure pump)	63.35	kWh/hr	PWJ supplier and ecoinvent datasets: market for electricity, low voltage [78], [98]
Electricity (For pulse generator)	0.25	kWh/hr	PWJ supplier and ecoinvent datasets: market for electricity, low voltage [78], [98]
Electricity (For robot)	2.5	kWh/hr	PWJ supplier and ecoinvent datasets: market for electricity, low voltage [78], [98]
Electricity (For booth air cooler)	2.98	kWh/hr	PWJ supplier and ecoinvent datasets: market for electricity, low voltage [78], [98]
Electricity (For ventilator)	3.73	kWh/hr	PWJ supplier and ecoinvent datasets: market for electricity, low voltage [78], [98]
Water	2	kg/hr	Estimation based on expert input and ecoinvent datasets: market for tap water [185], [186]
Solvent (For rust inhabitation)	0.22	kg/hr	Estimation based on expert input and ecoinvent dataset market for solvent, organic[190]
Wastewater	2.2	l/hr	Estimation based on expert input and ecoinvent dataset market for wastewater, unpolluted[191]
Area sensitive			
Degreasing	1	m^2/m^2	ecoinvent dataset market for degreasing, metal part in alkaline bath [184]
Mass sensitive			
Solid waste	1	g/g	ecoinvent datasets: treatment of municipal solid waste, sanitary landfill [192], [193]
Chromium (output)	1	g/g	N/A

After removal, the metallic chromium coating sediments pass with the after-use water to the water collector embedded in the booth's floor and are removed via gravity settling. This sedimentation, which is considered nonhazardous, is vacuumed out of the booth and disposed of as municipal solid waste. The amount of solid waste and chromium releases to landfill were estimated as the mass of the removed coating. Table (8) details PWJ removal process inputs and outputs.

3.2.5. Life Cycle Impact Assessment

As in the first case study, the IMPACT 2002+ life cycle impact assessment (LCIA) method was used to translate the LCI of environment flows into potential impact on human health, ecosystem quality, climate change, and resources [61] described in section 2.2.5.

3.2.6. Sensitivity Analysis

3.2.6.1. Electricity Mix

In this study, the baseline scenario was defined as operating removal systems in Quebec. Regarding primary impact results and the essential role of electricity, we decided to recalculate results again by considering Canada's average electricity mix. The water and municipal waste source was also changed from Quebec to RoW (Rest of the World). With more than 95% renewable sources of electricity generation, Quebec is representative of Canada's movement toward cleaner electricity production and Canada's average electricity is representative of the overall status quo. In this analysis, the changes of mass-, time- and area-sensitive parameters contribution were discussed by comparing electricity source alteration from Quebec to average Canada electricity mix.

3.2.6.2. Ventilation uncertainty

As mentioned in the system boundaries (section 3.2.2), the ventilation systems run continuously to control workplace air contamination for all electroplating operations. For AEC, it is difficult to estimate the amount of ventilation electricity required solely for the hard chromium removal. If ventilation is used only for the alkaline bath, replacing AEC with PWJ would reduce ventilation operations and energy consumption. On the other hand, if the ventilation system is used for multiple electrochemical baths, it may not change significantly with the adoption of PWJ. The LCA model allocates the full amount of electricity consumed by the electrochemical bath ventilation system during the time required for coating removal, indicating a reduction in ventilation electricity consumption with AEC replacement. The second sensitivity analysis omits ventilation AEC, indicating no change to ventilation electricity consumption with AEC replacement.

3.3. Results

3.3.1. Baseline – Coating removal in Quebec

Figure (17) compares the potential environmental impacts from removing hard chromium with the emerging PWJ technology and incumbent AEC for the four environmental impact categories, i.e., climate change, ecosystem quality, human health, and resource depletion. The results are shown for the specified functional unit, i.e., removing hard chromium from three zones on landing gear component A340 Québec, Canada. For each environmental impact category, the results are scaled relative to the system with the highest impact for each impact category. For example, the potential climate change impact for AEC was estimated to be 5.54 kg CO_2 eq, which was 75% higher than the impacts from PWJ. The estimated potential impact from using PWJ is lower for all impact categories, ranging from 24-42% of that from using AEC.

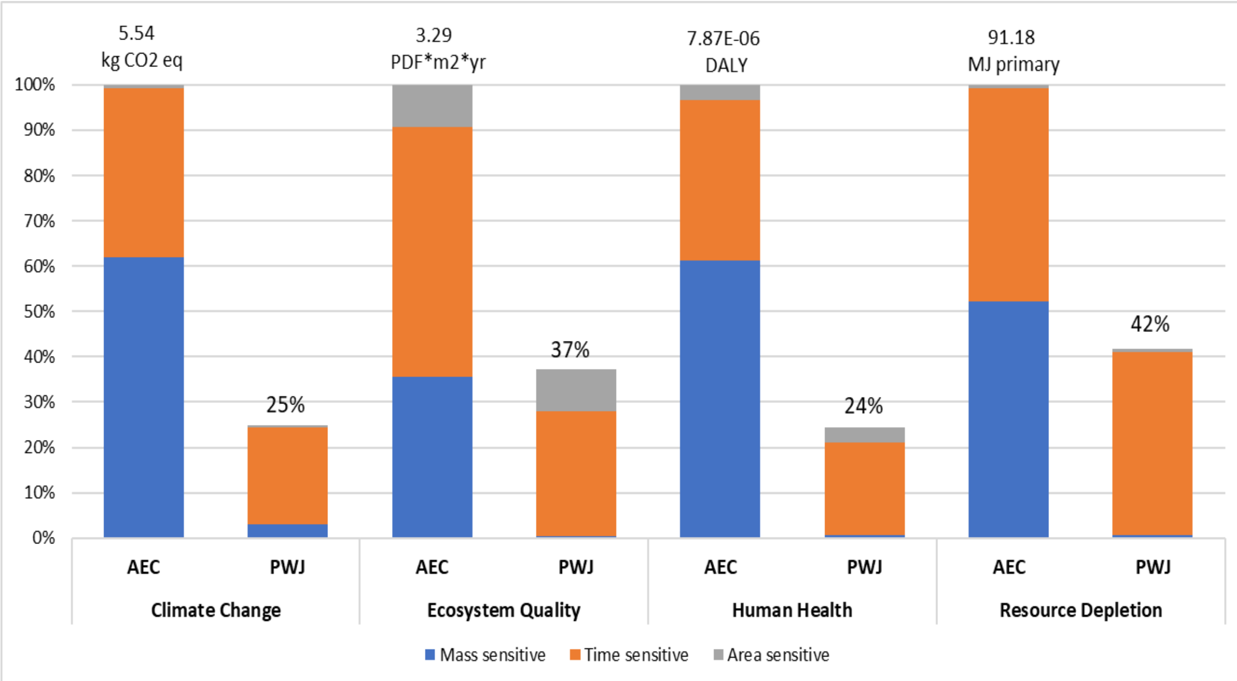
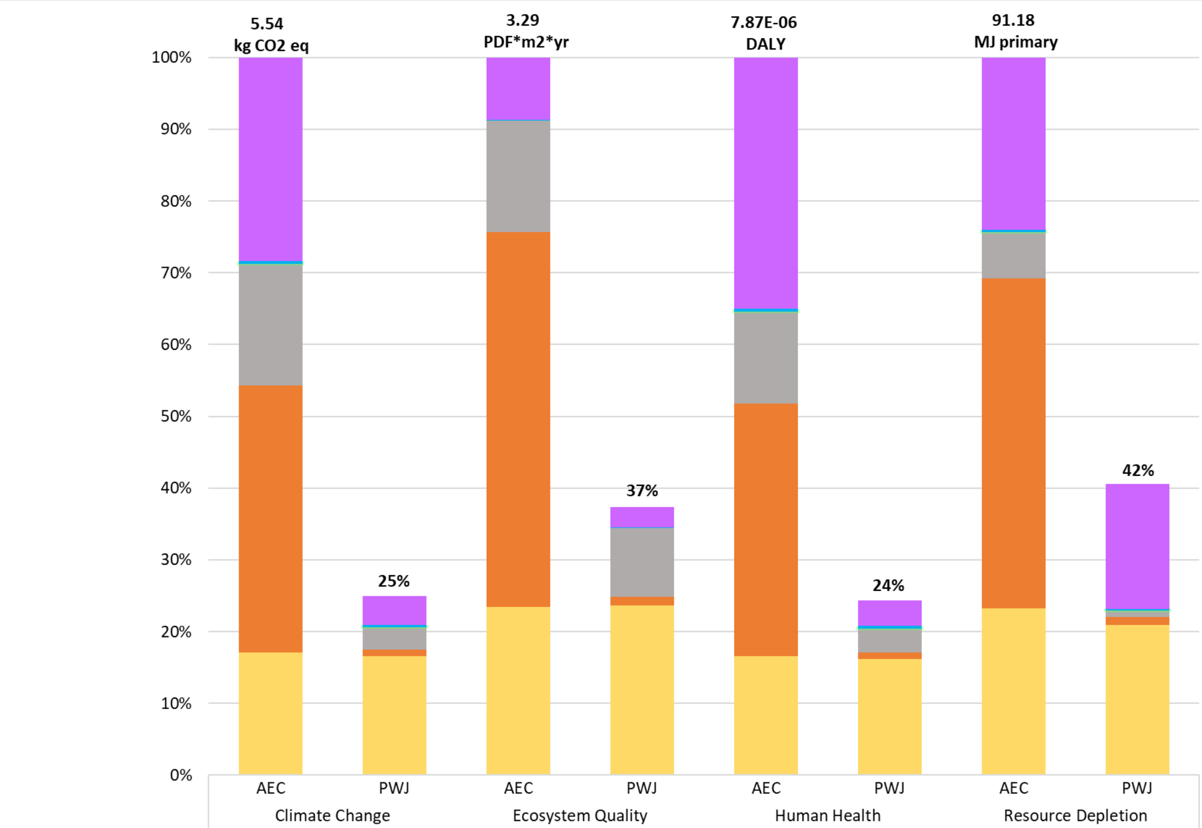


Figure 17 - Impact results in Quebec with determining
the mass-, time- and area-sensitive parameters contribution

The results in Figure 17 are divided into three groups, which include the impacts related to mass-, time- and area-sensitive parameters. Environmental impact from AEC is driven by mass- and time sensitive parameters. Mass-sensitive parameters include process electricity, water and sodium hydroxide, sludge disposal, and wastewater sulfur dioxide emissions. Time-sensitive parameters include ventilation electricity and wastewater treatment. Environmental impact from PWJ is driven by time-sensitive parameters, which include process electricity water, and rust inhibitor and municipal wastewater treatment.

Figure (18) shows the same results as Figure (17), but instead broken out into several input and output categories for each system. Electricity is categorized as process or ventilation. Waste includes wastewater and hazardous waste treatment for EAC and wastewater and solid waste treatment for PWJ. includes energy for heating water during degreasing for both systems. Water includes the provision of water that ultimately lost during rinsing for AEC and from ambient evaporation and during pump cleaning for PWJ. Chemicals include sodium hydroxide, sulfur dioxide, sulfur acid, and degreasing chemical production for AEC, and rust inhibitor and degreasing chemical production for in PWJ.

Potential environmental impacts from processing electricity and water consumption are similar for both systems for all impact categories, but with process electricity accounting for 16-23% of potential impact for AEC and 50-67% for PWJ depending on the impact category. In contrast, the potential environmental impacts from ventilation electricity, waste, and chemicals are much higher for AEC, with ventilation electricity being the most important driver of environmental impact for all environmental impact categories (i.e., accounting for 35-52% of potential impact depending on the impact category). The potential environmental impacts from



	Climate Change AEC	Climate Change PWJ	Ecosystem Quality AEC	Ecosystem Quality PWJ	Human Health AEC	Human Health PWJ	Resource Depletion AEC	Resource Depletion PWJ
Chemicals	28.40%	4.05%	8.67%	2.81%	34.97%	3.51%	24.05%	17.44%
Water	0.35%	0.30%	0.10%	0.08%	0.42%	0.36%	0.30%	0.27%
Heat	0.01%	0.01%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%
Waste	16.93%	3.18%	15.53%	9.60%	12.84%	3.41%	6.40%	0.91%
Electricity(ventilation)	37.25%	0.86%	52.29%	1.22%	35.20%	0.84%	46.04%	1.08%
Electricity (process)	17.05%	16.61%	23.40%	23.62%	16.57%	16.21%	23.20%	20.91%

Figure 18 - Impact results with determining the physical inputs contribution

heat and water are relatively small compared to that of the other input and output categories.

3.3.2. Sensitivity Analysis

3.3.2.1. Operating systems locations other than Quebec

Since electricity consumption is the main driver of potential environmental impact for both systems, it is important to consider the implications of performing coating removal in locations using a different is electricity mix, particularly since Québec generates 99% of its electricity from renewable sources, namely wind and hydropower (Fig. 5), the results from using the Canadian electricity mix and global market datasets for water distribution and municipal waste management are shown in Figures (19) and (20). Since they are more important drivers of potential environmental impact, process and ventilation electricity account for most of the changes to model output from this sensitivity analysis.

Figure (19) shows the portion of potential environmental impact attributed to mass-, time-, and area- sensitive parameters. The results can be compared by location and impact category (vertically) or by system and impact category for each location (side by side). Performing coatings removal in a location that uses less renewable energy sources (Average Canada) increases the contribution of time-sensitive parameters to potential impact for all environmental impact categories. This is particularly the case for PWJ since most of the impacts is due to electricity consumption, which is sensitive to process time.

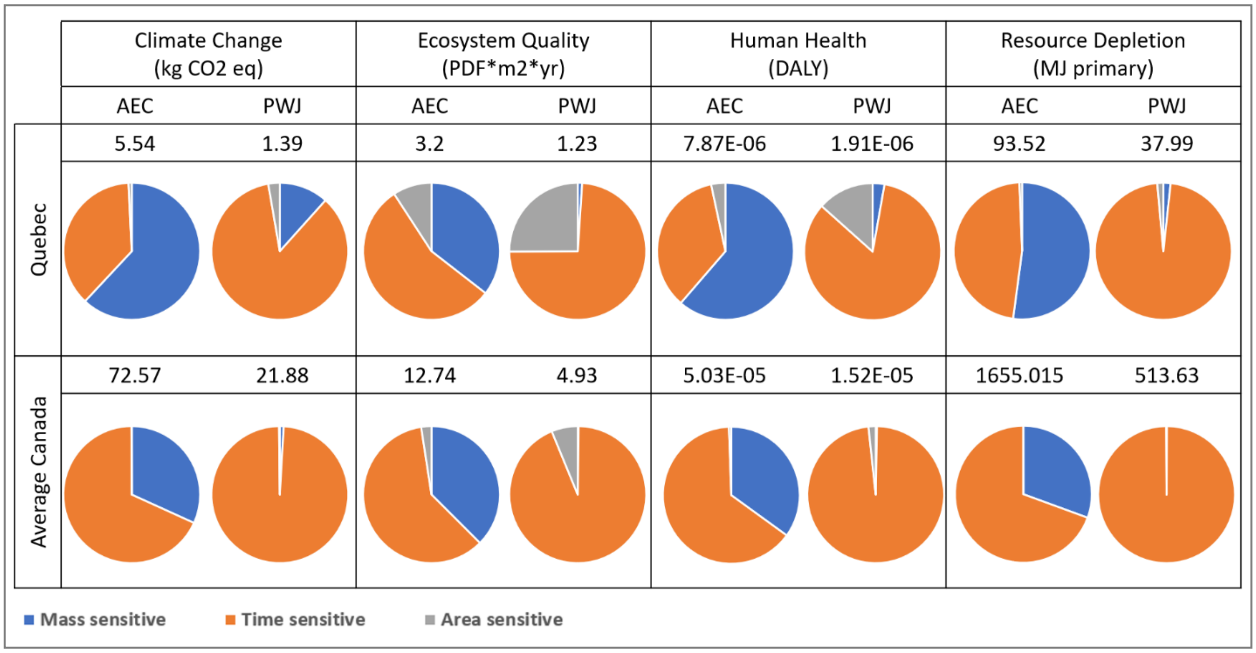


Figure 19 - Portion of impacts related to mass-, time-, and area-sensitive parameters for coating removal using dataset for Québec and Canadian/global electricity mix, water distribution, and waste management

Figure (20) compares the potential impacts for each technology-location scenario relative to the system with the highest total impact broken out by input and output category. Primarily due to the transition from 99% renewable to 68% non-renewable energy sources [108], total potential environmental impact and the contribution of electricity to impact increased.

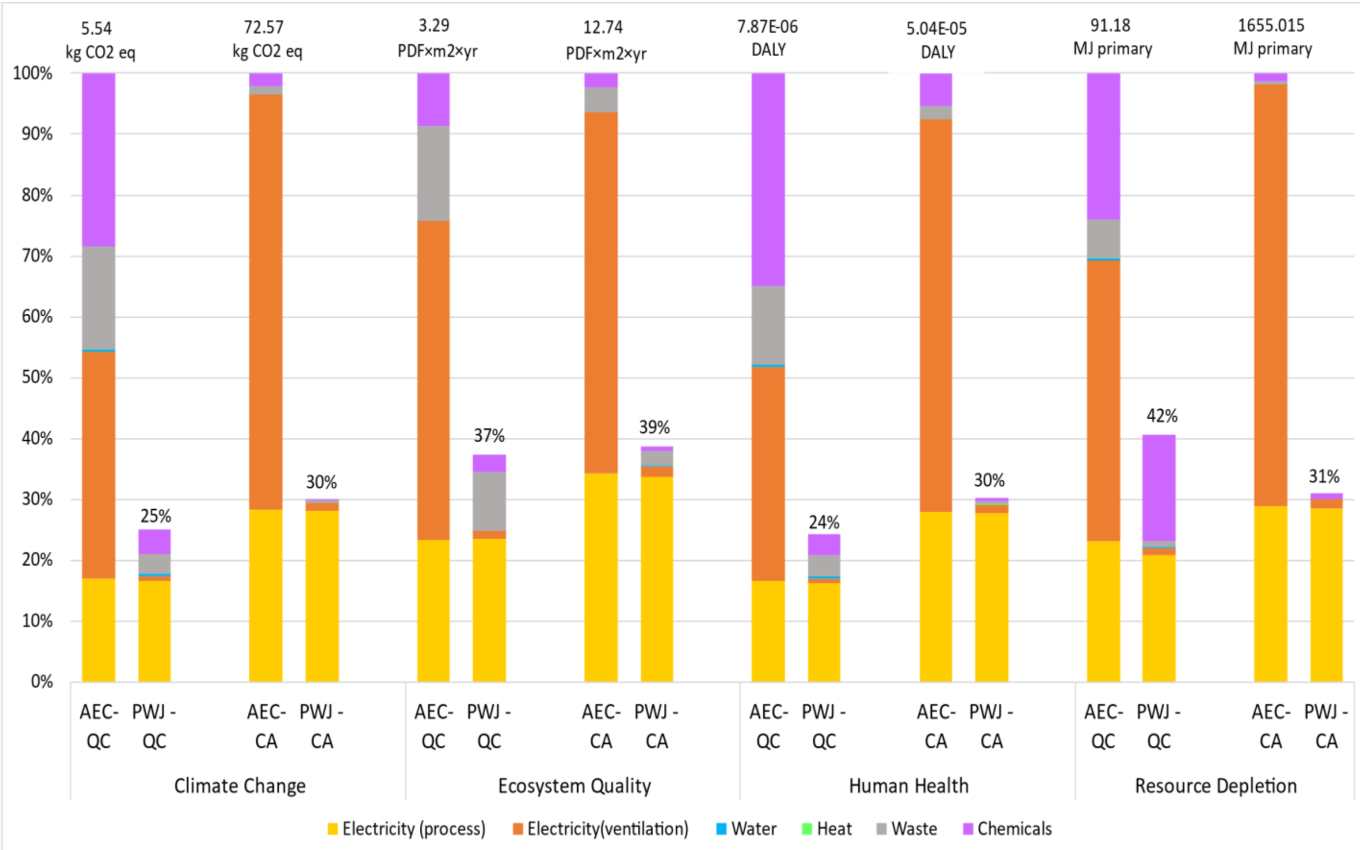


Figure 20 - Impact results with determining the input and output contribution for Québec and Canadian electricity mix

In Table (9) a factor for impact increase was calculated based on percentage increase relative to Quebec. In PWJ potential impact increased from a factor of 301% for ecosystem quality to a factor of 1252% for resource depletion and in AEC potential impact increased from a factor of 298% ecosystem quality to a factor of 1670% for resource depletion for AEC. Climate change and human health impacts went up more for PWJ, resource depletion impacts went up more for AEC, and ecosystem quality impacts went up the same for both.

Table 9 - Impact of location change scenario for coating removal using dataset for Québec and Canadian electricity mix

Location	Climate Change (kg CO2 eq)		Ecosystem Quality (PDF×m2×yr)		Human Health (DALY)		Resource Depletion (MJ primary)	
	AEC	PWJ	AEC	PWJ	AEC	PWJ	AEC	PWJ
Quebec	5.54	1.39	3.2	1.23	7.87E-06	1.91E-06	93.52	37.99
Average Canada	72.57	21.88	12.74	4.93	5.03E-05	1.52E-05	1655.01	513.63
Increase Factor (Basis of Quebec)	1210%	1474%	298%	301%	539%	696%	1670%	1252%

3.3.2.2. Ventilation uncertainty

The results from excluding AEC ventilation are provided in Figure (21) for coating removal based on Québec and Figure (22) in Canadian/global market condition. When located in an area that predominantly uses renewable energy sources, the potential environmental impact is still 22-60% lower for PWJ when AEC ventilation electricity is excluded.

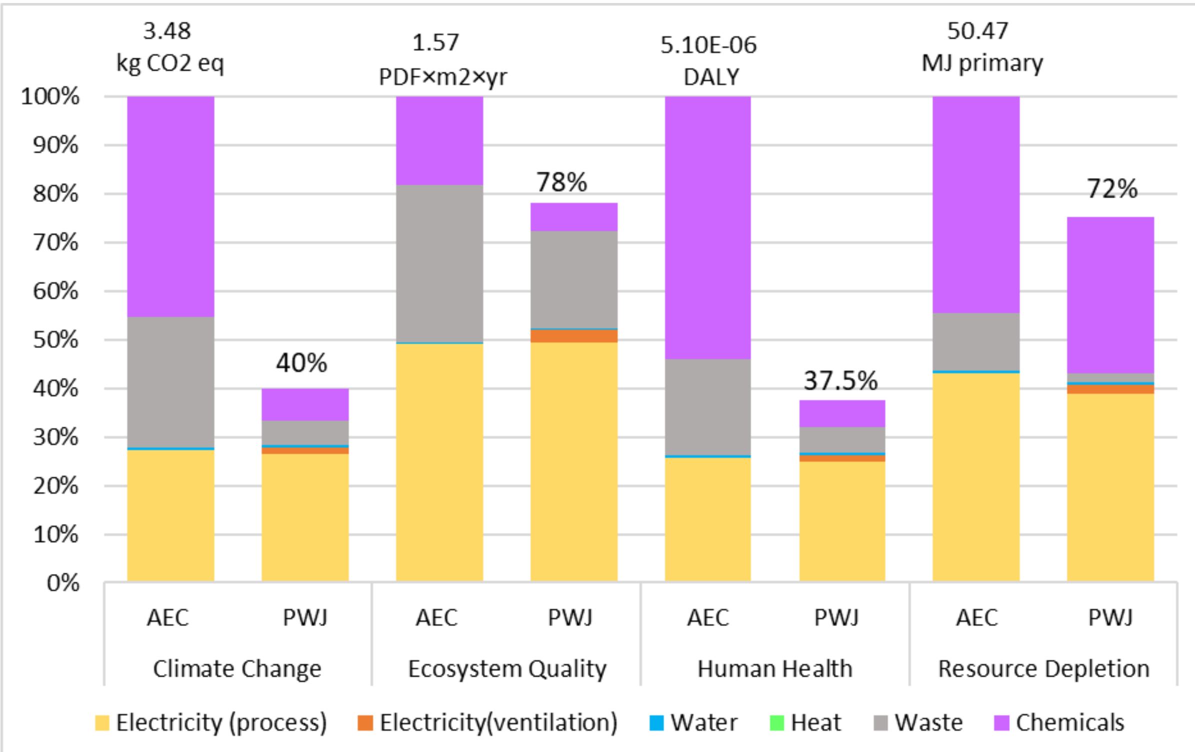


Figure 21 - Comparison of impact results of removal method for scenario of excluding ventilation with Quebec electricity mix

However, when located in an area that relies more heavily on non-renewable sources and excluding AEC ventilation electricity, the potential environmental impact is 5-15% lower for PWJ for all impact categories except for resource depletion, which is 1% higher. As the potential impact from electricity consumption increases, the relative contribution of the other input and output components (namely chemicals and waste) decrease and therefore play a less important role in distinguishing between the two technologies.

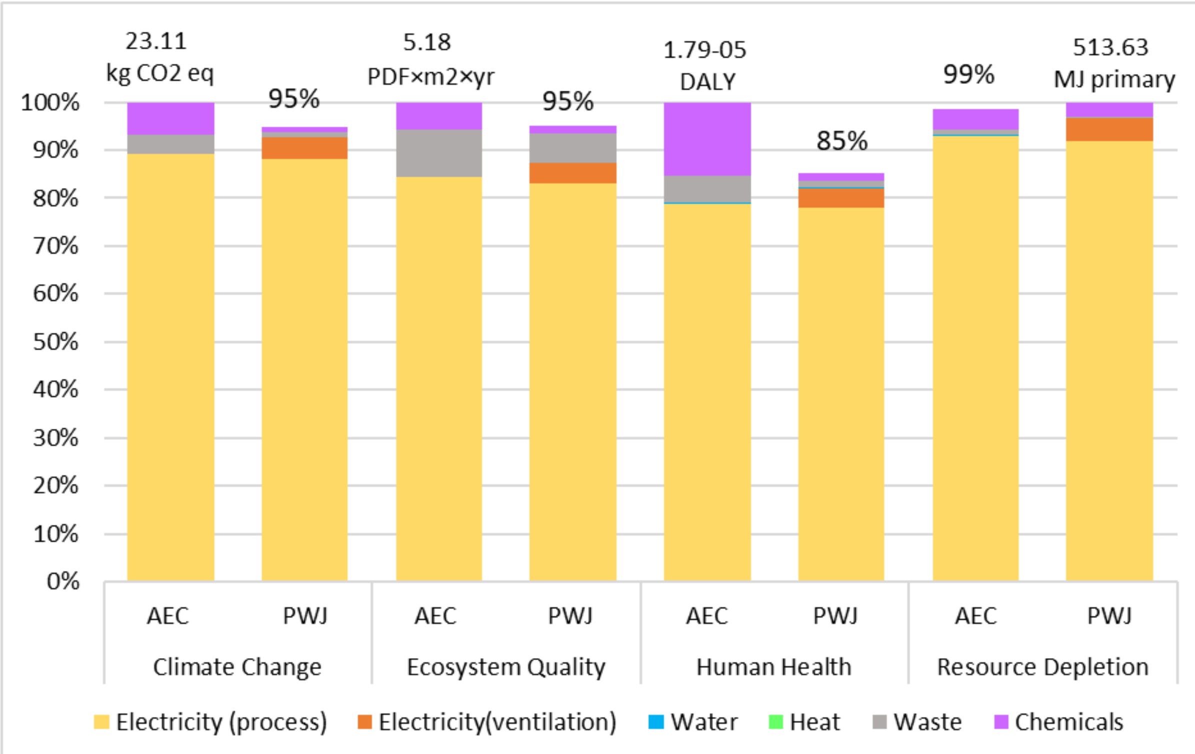


Figure 22 - Comparison of impact results of removal method for scenario of excluding ventilation with Canada group electricity mix

3.4. Discussion and Conclusion

Due to the high risk of toxic emissions and occupational hazards of electrochemical processes, industry owners are mandated to use strong ventilation and waste treatment facilities and obey specific pollutant controlling regulations. For fulfilling these regulations, in electrochemical activities like alkaline electrochemical cleaning, it is needed to use a huge amount of electricity for ventilation, various types of chemicals, and complicated waste management methods. These protecting activities themselves are drivers of electrochemical activities' environmental impact because of extra electricity and chemicals. Replacing the conventional electrochemical methods with less pollutant processes seems a rational solution for decreasing these activities' risk and environmental footprint.

Pulse water jet with more efficiency in electricity use, less chemical consumption, and limited level of waste generation is an appropriate alternative for alkaline cleaning. The key controller of impact in PWJ is processing time that determines the amount of required electricity. This parameter in PWJ can be decreased by optimization, robot programming and designing the removal process with fewer turns.

However, PWJ technology still needs many improvements. Machinery, gun and nozzle design should be adapted with the complex geometry of different industrial components like landing gears. Till now, among hard inorganic coatings which can be comparable with hard chromium, the effectiveness and feasibility of PWJ coating removal have been proven in experimental stages[128], [137]. These experiments were conducted on flat coupons and the external surface of cylindrical samples, but the landing gears' hard chromium coatings are mostly applied inside the pipe shape area of these components. In addition, the size of workpieces is important to design water jet booth, install enough guns and provide proper supporting facilities for a feasible and efficient removal process. Landing gears components are mostly made in big sizes about 3 meters in height, and an accurate R&D (Research and Development) process is needed to make PWJ compatible for aircraft overhaul sites.

Although we did not compare the technologies' operation cost in this study, it is predicted that the extra electricity and chemicals in AEC are drivers of expenditure as well [194]. Having this prediction, investigating on R&D for adapting new technology with landing gear overhaul requirements can benefit this industry with decreasing impact and cost simultaneously. In this case, based on the last sensitivity analysis (excluding ventilation from AEC impact), PWJ needs hard work to minimize its processing time to preserve its environmental advantages in Canada.

For interpretation of results, like other prospective LCAs, potential audiences should consider uncertainties and limitations. First of all, the new system's data were collected from experiments conducted in the laboratory rather than practical situation. When developing and testing the system in actual circumstances, inputs and outputs can be changed and cause significant alteration in results. Secondly, although this study adopted a conservative approach (favouring incumbent system) to tackle some uncertainties that emerged from the novelty of PWJ, simplifying assumptions, attributional allocations, using proxy data and estimations make the results indecisive. Finally, the incumbent technology input data are not certain and need more precise measurements to be validated.

Removal methods as a part of the repair, maintenance and recycling processes merit more attention in evaluating surface engineering environmental efficiency. Based on the author's viewpoint, this work should be considered a preliminary study to show the optimistic perspective of emerging technology's utilization in aircraft overhaul sites. This study needs to become more robust and complete in the future by updating the results with more accurate data, integrating with cost analysis, validating results in real situation, and expanding the model to address the recyclability of removal waste.

4. Conclusion

This thesis included two separate life cycle analyses in the surface engineering area. In both case studies, in the framework of prospective LCA, a new technology was compared with a matured incumbent technology.

The first case study compared a novel pipe heating system lab-scale portfolio with a conventional heating cable technology used for about 100 years. The new system is developed with thermal spray methods and is made from three coting layers, including aluminum oxide and nickel-chromium alloy applied by flame spray and copper applied by cold spray. Both systems work with electricity; however, the new system is 30% more efficient in electricity usage. The environmental assessment results in the baseline scenario, Alberta, showed that the multi-layered coating system has a better environmental score in all impact categories, including climate change, ecosystem quality, human health, and resource depletion. The critical driver of impact in both systems is use-phase electricity, which depends on frost days and regional electricity mix. The model was recalculated for all provinces in Canada to compare the environmental proficiency of systems across the country. This analysis shows that environmental assessment results could be changed significantly based on the geographical location. In regions with renewable electricity sources like Quebec, the conventional heating cable had a better score as it had less of an environmental impact in the production stage. A sensitivity analysis was conducted to determine the break-even point of electricity for the new system to make it environmentally preferable in each province.

Many uncertainties accompanied the coating system's modelling due to its novelty and lack of historical data in practical scale. Accordingly, in another sensitivity analysis, the coating system's best efficiency was recalculated by considering 20-, 30-, 40- and 50- year lifespans. Results show that the coating system is environmentally preferable in all provinces except Quebec when the lifespan increases by ten-year increments. Having a 50-year or more lifespan makes the new system preferable in Quebec as well. Quebec represents the future of Canadian electricity impact, and, predictably, other provinces in the future will close the gap with Quebec. Therefore, finally, it was concluded that although the electricity efficiency is a significant advantage for the new system, developers of the coating system need to conduct improvements for decreasing the production impact in order to maintain their environmental advantage at present and in future.

The second case study compared two hard chromium removal methods, including a pulse water jet technology, which is still in its benchmarking stage, and an alkaline electrochemical cleaning method, which is a popular hard chromium removal technique in landing gear overhaul departments. The conventional system is an electrolytic bath that contains a sodium hydroxide solution, steel anode, rectifier and a workpiece (as the cathode). After running the electricity, coating removal occurs based on the electrochemical reactions of coating ions (chrome hexavalent) with the alkaline solution. In comparison, the pulse water jet uses a high-pressure water force combined with the hammering effect of the generated pulse (in the water stream) to remove the coating. The water jet gun is held and manipulated with a programmed robotic system. Other subsystems include a water filtration machine, water pump, pulse generator, ventilator, and cooler.

The main challenge of the study was finding a proper basis for comparison. For example, some parameters change based on the area, but others in the same area change based on the coating mass or removal time. Therefore, the inputs were divided into three groups: mass -, area-, and time-sensitive parameters. The results show that the new system has environmental preferability in all impact categories, operating with Quebec electricity mix. The processing electricity in both systems was the same, but alkaline cleaning had a significant electricity consumption in the ventilation process. Since electricity was the key driver of impact, the results were calculated again considering the average Canadian electricity mix. The impact trends were the same; however, after changing the electricity source, the contribution of the time-sensitive parameters increased in environmental impact.

Both case studies were prospective LCAs. In the first study, emerging technology was lab-scale, whereas the second was in the benchmarking stage. In both studies, LCA suggested ways for new system developers to reduce their product's impact. In heating systems' LCA, multi-layered coating technology will achieve better environmental proficiency by increasing the coating materials' efficiency and the product's durability. In the removal methods study, the researchers suggest that the pulse water jet impact can be decreased by programming the robot to obtain less processing time.

The LCA modelling of the new systems has many uncertainties linked to the novelty of the technologies. Bergerson et al. [32] defined emerging technologies as a range of innovative products and processes from potentially disruptive technologies to those that make marginal modifications in existing technologies. However, they believed that the emerging technology could not be assessed without considering the market in which any new system attempts to enter. Accordingly, they divided the potential positions of a technology advent in a market into four categories, including emerging technology in an emerging market, emerging technology in a mature market, mature technology in an emerging market, and mature technology in a mature market. Based on these classifications, they provide some suggestions for LCA practitioners to tackle the uncertainties of environmental assessment modeling.

According to Bergerson et al.[32], both new technologies assessed in this work (i.e. multi-layered coating system and pulse water jet technology) are emerging technologies and aim to enter a mature market (i.e. the pipe heating systems and the coating removal methods markets). They compete with well-stabilized incumbent technologies (i.e. self-regulating heating cables and alkaline electrochemical cleaning technologies). Identified challenges for this group of LCAs include: 1) the emerging technology's expected environmental performance compared with the more realistic performance of an incumbent technology, 2) a probability of skewing the results in favour of incumbent or emerging technologies, and 3) uncertainties in extrapolating new technology's lab-scale results to practical results. In order to tackle these issues, Bergerson et al. [32] suggest integrating other analytical methods like techno-economic analysis, process-design techniques, scenario analysis, estimation models, and break-even analysis to the LCA study.

The lack of recorded data was an important source of uncertainty in both case studies. In the first case study, the multi-layered coating system's lifespan, the maintenance/repair process, and the end-of-life phase were uncertain. In the removal methods research, the pulse water jet's flexibility to remove the coating from complex geometries and its compatibility with the landing gear overhaul department were uncertain.

In addition, based on this studies processes uncertainties of emerging technologies LCAs are not limited only to obtaining input for the new system or its market. In some cases, finding the data for incumbent technologies of these studies is also challenging. For example, in the first case study, analysts did not have access to cable system input data because of the competitive atmosphere and trade secrets. As a result, much data for existing technology were also estimated or assumed based on proxy data. In the second case study, sometimes, incumbent technology experts did not have relevant data which can be allocated to the basis of comparison. A range of cumulative data was not precise or validated, and most of the available data had been translated to cost or time instead of physical inputs and outputs. These uncertainties, alongside of those associated with the novelty of emerging technologies, increase the complexity of prospective LCAs.

For tackling these uncertainties, a set of suggested solutions was used in both case studies to handle the uncertainties. In the first case study, the environmental assessment was built upon a techno-economic analysis conducted for the same pipe heating systems. In conclusion, the techno-economic and environmental analyses results were compared to understand better two aspects of the new technology (see section 2.4). Next, the results were recalculated by considering different scenarios for operating systems in regions with various winter lengths and electricity mixes to study the nascent system's environmental proficiency in Canada's other provinces (see section 2.3.2). Finally, the break-even analysis was conducted to quantify the contribution of electricity efficiency in the coating technology's environmental advantage. The results were calculated again for different climate, electricity mix scenarios and lifespan scenarios; suggestions were provided for developers to improve this advantage across the country by increasing the material and process efficiency and durability (see section 2.3.3 and 2.3.4).

In the second case study, we calculated impact in two scenarios, including Quebec and Canada's average electricity mix, to investigate the sensitivity of the impact results to the most important driver of impact (i.e., electricity). In addition, by considering the market that this new technology is attempting to enter (i.e. landing gear overhaul sites), another sensitivity analysis was conducted on ventilation electricity. This analysis shows the potential trade-off that decreases the new system's environmental advantage in this particular market (see section 3.3.2.2). In the next step of this ongoing research, we plan to do a cost analysis and integrate it with this environmental assessment.

These case studies are examples of the new technologies' capacity to reduce environmental impact in the surface engineering field. Developers of these systems have introduced their products mentioning their environmental advantages (i.e., more energy efficiency for multi-layered coating system [42] and less chemical use for pulse water jet [130]). However, to avoid biased results, we considered the conservative assumptions favouring the incumbent technology, like minimum lifespan for multi-layered coating system and turning time for pulse water jet.

Future studies need to concentrate on the limitations of developing LCAs in surface engineering. Lack of cumulative data is one of those hot spots. For example, inventory data of several existing thermal spray processes are absent in LCA databases. In addition, the surface engineering products' end-of-life scenarios have not been studied sufficiently. Many studies investigate the reusing of the substrate, but they rarely discuss coating recycling, while many metallic coatings are made with precious materials that can be upcycled several times. Therefore, coating material and process design for increasing recyclability can be interesting subjects for future studies. Since these studies and many recent LCAs in surface engineering are prospective LCAs, their results need to be validated by practical data. The author of this thesis hopes the output of this work serves to help future studies progress toward more innovative and clean development in surface engineering.

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Appendix

A. The basis of frost days in Canada climate regions

Yearly temperature averages for selected locations in Canada[45]

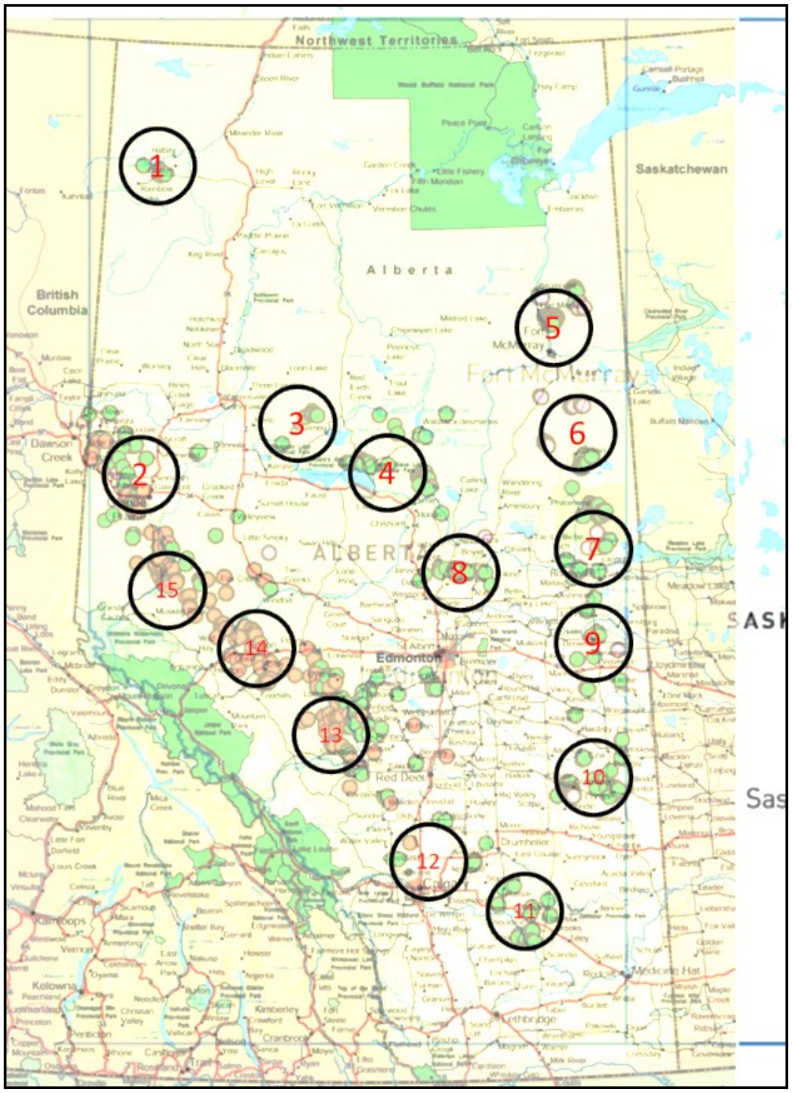
Location	Region	Days >30°	Days >20°	Frosts	Max temp <0°	Days <-10°	Days <–20°	First frost	Last frost	Frost-free
Baker Lake	NU	0.21	13.1	270.5	225.5	206.3	158.2	Aug 30	Jun 25	65 days
Brandon	MB	15.9	109.8	202.3	110.0	108.6	52.6	Sep 14	May 24	112 days
Calgary	AB	5.1	87.2	194.4	59.3	71.3	21.7	Sep 16	May 21	117 days
Charlottetown	PE	0.9	79.3	160.2	72.6	54.6	6.5	Oct 17	May 16	153 days
Churchill	MB	1.1	28.0	247.5	193.7	171.0	117.2	Sep 15	Jun 19	87 days
Corner Brook	NL	0.7	58.5	159.3	79.0	43.0	3.4	Oct 13	May 19	146 days
Dawson Creek	BC	2.6	62.1	243.7	156.9	162.4	104.1	Aug 13	Jun 3	70 days
Edmonton	AB	4.0	88.4	179.7	82.6	75.3	24.6	Sep 22	May 9	135 days
Fort Frances	ON	6.9	100.4	195.4	106.6	90.8	44.2	Sep 17	May 27	108 days
Fort McMurray	AB	5.9	84.2	212.1	115.8	119.5	57.5	Sep 6	May 30	97 days
Fort Nelson	BC	3.3	78.1	214.2	133.6	139.1	79.8	Sep 11	May 16	117 days
Fort Simpson	NT	4.2	73.8	224.3	159.3	157.3	101.1	Sep 1	May 26	97 days
Fredericton	NB	9.0	104.4	172.9	69.1	72.6	20.0	Sep 25	May 17	130 days
Halifax (city)	NS	1.0	78.2	131.0	47.0	29.8	0.8	Oct 31	May 1	182 days
Hamilton	ON	18.5	119.8	129.0	48.6	32.6	2.5	Oct 16	Apr 21	177 days
High Level	AB	2.7	76.5	224.8	136.3	138.9	79.9	Sep 1	Jun 1	91 days
Iqaluit	NU	0.0	2.1	265.8	212.2	182.4	130.6	Sep 3	Jun 20	74 days
Kamloops	BC	32.8	132.0	119.2	34.5	19.9	3.4	Oct 10	Apr 24	169 days
Kuujjuaq	QC	0.3	21.7	244.0	177.1	155.6	104.5	Sep 9	Jun 18	82 days
Labrador City	NL	0.4	33.1	232.8	155.3	144.5	90.6	Sep 14	Jun 9	95 days
Liverpool	NS	3.3	102.7	146.8	42.0	34.6	3.6	Oct 5	May 15	142 days
Medicine Hat	AB	26.5	120.4	174.6	58.4	64.4	22.8	Sep 25	May 13	134 days
Moose Jaw	SK	21.7	115.1	188.7	86.7	87.7	37.7	Sep 17	May 17	121 days
Moncton	NB	6.8	99.1	166.9	70.0	58.9	14.0	Oct 2	May 23	131 days
Montreal	QC	9.3	117.1	147.7	74.0	62.9	14.3	Oct 12	Apr 29	165 days
Moosonee	ON	6.1	66.3	224.9	129.1	125.6	78.4	Aug 25	Jun 26	58 days
Nain	NL	0.5	16.4	230.1	148.1	126.7	62.4	Sep 24	Jun 18	96 days
Nanaimo	BC	6.7	96.9	71.5	2.6	1.8	0.0	Oct 26	Apr 14	194 days
Osoyoos (west)	BC	36.0	142.4	105.5	25.3	10.7	0.3	Oct 9	Apr 22	169 days
Ottawa	ON	13.0	116.4	154.9	77.5	67.9	16.3	Oct 7	Apr 30	157 days
Princeton	BC	24.2	107.6	177.8	50.6	33.6	6.4	Sep 17	May 23	116 Days
Quebec City	QC	5.1	94.1	170.7	94.9	84.8	31.1	Oct 4	May 11	145 days
Regina	SK	16.2	108.1	201.2	103.0	102.3	43.1	Sep 12	May 20	115 days
Saguenay	QC	7.7	86.8	189.7	104.9	99.2	46.6	Sep 23	May 22	123 days
Saint John	NB	0.9	74.3	167.2	60.7	65.7	14.1	Oct 2	May 16	138 days
Saskatoon	SK	13.1	103.1	200.4	108.0	105.6	47.1	Sep 15	May 21	117 days
St. John's	NL	0.1	52.6	166.6	65.9	34.9	0.6	Oct 17	May 30	139 days
Sydney	NS	2.3	74.9	160.8	60.0	43.2	2.7	Oct 17	May 21	149 days
Thompson	MB	3.8	66.9	238.6	152.5	150.0	100.0	Aug 27	Jun 14	74 days
Toronto	ON	11.5	117.2	100.8	45.9	21.9	1.2	Nov 3	Apr 13	203 days
Toronto Airport	ON	15.8	122.3	136.5	52.8	38.9	3.9	Oct 16	Apr 30	168 days
Vancouver	BC	0.3	76.5	40.9	3.4	1.6	0.0	Nov 10	Mar 18	237 days
Victoria	BC	2.1	78.9	46.0	2.0	0.4	0.0	Nov 5	Apr 7	211 days
Windsor	ON	23.5	138.9	116.3	44.3	24.1	1.2	Oct 30	Apr 17	195 days
Winnipeg	MB	13.3	109.7	193.7	113.0	102.2	50.1	Sep 22	May 23	121 days
Whitehorse	YT	0.9	41.5	221.3	118.7	106.4	48.7	Aug 25	Jun 5	80 days
Yarmouth	NS	0.0	56.7	126.1	36.0	21.7	0.1	Oct 21	Apr 27	176 days
Yellowknife	NT	0.4	42.8	224.5	175.2	160.9	105.2	Sep 18	May 25	115 days

"National Climate Data and Information Archive". Environment Canada. Retrieved April 30, 2016.

https://en.wikipedia.org/wiki/Temperature_in_Canada#cite_note-Canadian_Climate_Normals_1981-2010-45

B. Transportation assumptions in first case study

B1: Potential locations for installation site



Number on map	Name
1	Rainbow lake
2	Grand prairie
3	Atikameg
4	Slave lake
5	Fort McMurray
6	Conklin
7	Bonnyville
8	Tawatinaw
9	Derwent
10	Coronation
11	Bassano
12	Calgary
13	Saunders
14	Edson
15	Muskeg river

B2: Calculations of average distance for cables and pipes transportation from Calgary and coated pipe transportation from Edmonton

Number on map	Name	Distance from Calgary (km)	Distance from Edmonton (km)
1	Rainbow lake	1168	876
2	Grand prairie	711	458
3	Atikameg	686	394
4	Slave lake	547	380
5	Fort McMurray	736	434
6	Conklin	660	358
7	Bonnyville	543	240
8	Tawatinaw	398	97
9	Derwent	480	188
10	Coronation	302	265
11	Bassano	143	405
12	Calgary	15	299
13	Saunders	279	279
14	Edson	439	201
15	Muskeg river	637	399
Average distance		516.2667	351.5333333

C. Comparison of processing time from practical data and Faraday law

No.	Part	Zone	Practical time (hr)	Estimated time by Faraday law (hr)	Alkaline bath efficiency %
1	Main fitting A340	Pintle Bore	2.5	0.454256	18%
2		Mid bores	4	0.454256	11%
3		Lower bore	3.75	0.454256	12%
4	Main fitting A320	Mid bores	0.75	0.133605	18%
5		lower bore	2	0.445349	22%
6	Boeing 787	Int -1	1.75	0.454256	26%
7		Int -2	2	0.454256	23%
8		Int -3	2	0.454256	23%
9		Int -4	3	0.454256	15%
10		Int -5	3	0.454256	15%
11		lower bore	3.75	0.454256	12%
12		Ext	5.75	0.904058	16%
13	A380	Int-1	2	0.106884	5%
Average electricity efficiency in alkaline bath					18%

D. Calculations of average electricity per mass in alkaline electrochemical cleaning

No.	Part	Zone	Estimated electricity (kWh)	Estimated coating mass (g)	Required electricity per mass (kWh/g)
1	Main fitting A340	Pintle Bore	2.175	21.2976	0.10
2		Mid bores	113.4	694.008	0.16
3		Lower bore	15.32813	100.062	0.15
4	Main fitting A320	Mid bores	0.2925	2.808	0.10
5		lower bore	3.849	46.188	0.08
6	Boeing 787	Int -1	2.205	30.8448	0.07
7		Int -2	0.3	3.672	0.08
8		Int -3	0.48	5.8752	0.08
9		Int -4	2.547	20.78352	0.12
10		Int -5	2.9475	24.0516	0.12
11		lower bore	13.67438	89.26632	0.15
12		Ext	4.05375	34.3476	0.12
13	A380	Int-1	2.175	33.12	0.10
Average required power for 1g hard chromium coating					0.11