

SUSTAINABLE PARKING INFRASTRUCTURE: COMPARING BUILDING ENVELOPES ACROSS RENEWABLE ENERGY-INTEGRATED PROTOTYPES

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ABSTRACT: This study evaluates the life cycle environmental and energy performance of two parking structure prototypes in London, Ontario, Canada: (1) an automated steel parking tower with photovoltaic (PV) panels on the roof and south-facing façade, and (2) a ground-level concrete parking structure with rooftop PV. Using Life Cycle Assessment (LCA), the study assesses environmental impacts from material production through the operational phase, considering material inputs, energy consumption, and renewable energy generation. Results indicate that Prototype 2 exhibits a lower overall environmental burden. However, differences between the prototypes remain relatively minor across specific impact categories. The study also finds that Prototype 1 performs better in the production phase, while Prototype 2 performs better in the use phase. Furthermore, when optimized with strategic PV positioning, Prototype 1 shows a 10% improvement in ecosystem quality, outperforming Prototype 2. This study underscores the role of parking structures as active contributors to net-zero developments rather than passive urban elements. Future research should explore the economic feasibility of coupling parking structures with buildings, assess a broader range of prototypes, investigate advancements in PV technology, examine the potential for waste heat recovery, and evaluate various end-of-life scenarios.

1. INTRODUCTION

Over the past century, greenhouse gas (GHG) emissions have experienced a substantial increase, driven predominantly by human activities. This rise is primarily attributed to the combustion of fossil fuels across industrial processes, manufacturing, transportation, and the construction sector. Notably, the construction industry stands out as a major consumer of raw materials and resources, contributing over 36% of global energy consumption and accounting for 39% of energy-related CO₂ emissions. This prominent position within the global energy landscape highlights its significant influence (Seyedabadi et al., 2024; United Nations, 2018). In response to this pressing need, the building sector has undertaken numerous initiatives to develop advanced technologies and environmental assessment methods that promote energy conservation and support sustainability. These efforts include the adoption of Net Zero Buildings, which take a holistic approach to life-cycle carbon emissions. This approach addresses both operational emissions from energy use and embodied carbon emissions resulting from building materials, construction, and renovation processes (Myint et al., 2025). A critical component of achieving these goals is the integration of renewable energy systems in buildings, which enhances energy efficiency and reduces reliance on fossil fuels (Jacobson, 2009; Shehadi, 2020). Several studies have explored strategies to optimize renewable energy use, such as adjusting PV panel tilt angles and incorporating advanced PV

technologies such as Building-Integrated Photovoltaic Thermal (BIPVT) systems to maximize solar energy capture (Al-Shatnawi et al., 2024; Yadav et al., 2020a, 2020b). Life Cycle Assessment (LCA) is a tool used to evaluate the environmental performance of products throughout their entire lifecycle, from raw material extraction and production to use and disposal. Additionally, LCA can account for potential environmental benefits or loads that occur beyond the system boundary, such as those associated with material reuse, recycling, or energy recovery at the end of life. It helps identify key areas of environmental concern and supports sustainable decision-making (Curran, 2013; Popowicz et al., 2024). This makes LCA an ideal tool for evaluating Net Zero Buildings. The infrastructure needed for automobile transportation is vast, encompassing numerous components such as vehicles, roadways, and fuel supply systems (Chester & Horvath, 2009). Parking infrastructure plays a critical role within this system. Assessing the health and environmental costs of parking infrastructure is a key step for comprehensive transportation cost analysis and informed policymaking. (Chester et al., 2010). However, the potential for parking structures to function as integrated or attached systems supporting Net Zero Energy (NZE) goals for adjacent buildings has been largely overlooked in previous research. These structures are well-suited to complement adjacent buildings due to their capacity to incorporate energy solutions, transforming underutilized spaces into active contributors to sustainability (Figure 1). To address this research gap, this study evaluates the life cycle environmental performance of two car parking prototypes, focusing on building envelopes and renewable energy integration. The aim is to identify design strategies that support sustainability objectives in urban development.

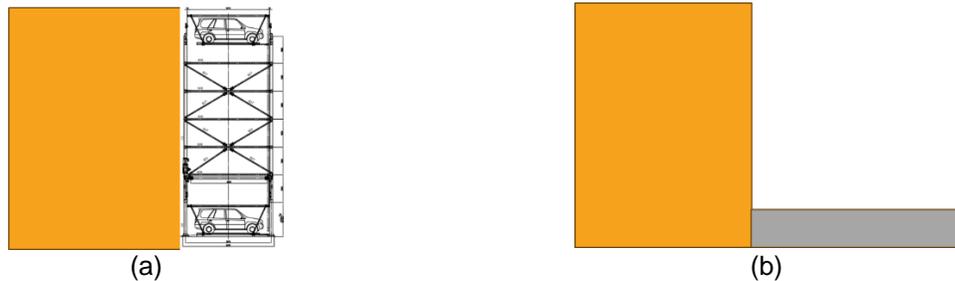


Figure 1: (a) coupling multi story buildings with PV integrated automated parking towers , (b) coupling multi-story buildings with PV integrated horizontal parking structures

2. METHODOLOGY

2.1 Goal and Scope

The goal of this study is to conduct a comprehensive life cycle assessment (LCA) of two real-world parking prototypes located in London, Ontario, Canada, with the aim of evaluating their environmental and energy performance. The scope of the study focuses on assessing the building envelope and energy performance of each prototype from cradle to the end of the operational stage. This includes evaluating their material inputs, energy consumption, and potential renewable energy generation, with the objective of identifying sustainable design strategies that can contribute to net-zero energy goals for urban developments.

2.2 Prototypes

The analyzed prototypes include: (1) an automated steel parking tower equipped with photovoltaic (PV) panels on the roof and south facade, and (2) a ground-level covered concrete parking structure featuring rooftop PV (figure 2).



(a)



(b)

Figure 2: (a) Prototype 1 (under construction), (b) Prototype 2

2.3 Data Collection

The methodology follows a multi-step approach (Figure 3), beginning with the collection of foreground data for the prototypes, primarily sourced from technical drawings and reports provided by the designers. Transportation distances are calculated using Google Maps to assess logistics accurately. Energy generation calculations are performed using the PVWatts calculator from the National Renewable Energy Laboratory (NREL) to estimate the potential energy output of photovoltaic systems. This is complemented by secondary data from literature review and the Ecoinvent database, covering material production, construction, and energy use across the building life cycle. Next, Life Cycle Assessment (LCA) modeling is conducted using Open LCA software (version 2.0.4), followed by a Life Cycle Impact Analysis (LCIA) using both endpoint and midpoint impact categories from the IMPACT WORLD+ methods. Initially, aggregated impacts on ecosystem quality and human health are analyzed. To provide deeper insights, climate change and water scarcity impacts are assessed separately, while fossil and nuclear energy consumption and mineral resource depletion are independently evaluated, as they are not modeled within a specific area of protection. This dual approach ensures a detailed and holistic sustainability evaluation. The environmental performance of the prototypes is analyzed across the production, construction and operational phases. The results are normalized for consistency by setting the prototype with the highest impact as the reference at 100%, and the other prototype is compared relative to this benchmark, and a sensitivity analysis is performed to assess the impact of PV systems on each prototype. The entire LCA framework adheres to the ISO 14044 standard (International Organization for Standardization, 2006) ensuring compliance with internationally recognized environmental impact assessment guidelines.

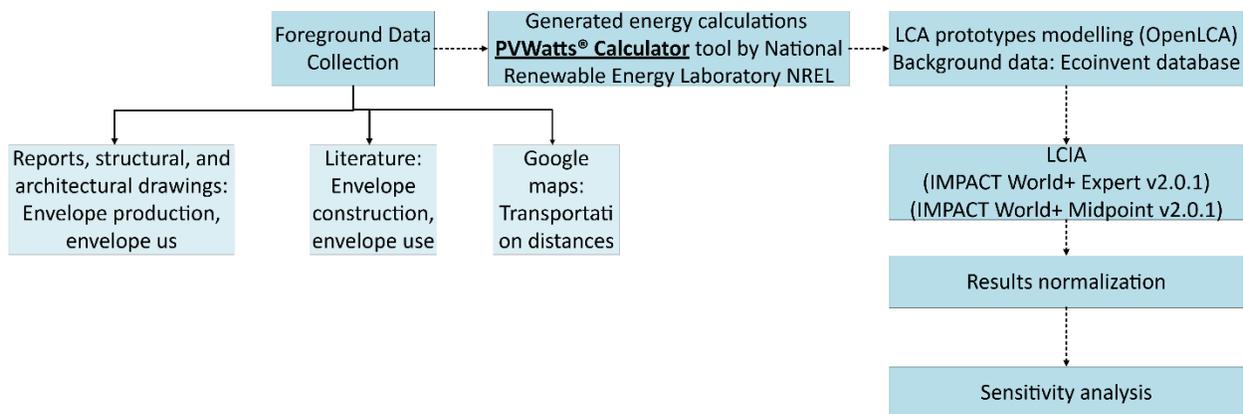


Figure 3: Research methodology

2.4 Functional Unit

In an LCA, the functional unit acts as a benchmark for comparing different products or systems. Selecting an appropriate functional unit is essential for objective comparisons and reliable results. It should be measurable and relevant to the product's intended use and the goals of the LCA (International Organization

for Standardization, 2006). The functional unit in this study is; building envelope designed to accommodate 12 cars in Canada, with a lifespan of 30 years.

2.5 System Boundary

The LCA will include a cradle-to-end-of-use analysis which evaluates the environmental impacts from raw material extraction, manufacturing, construction, operational energy use, and maintenance, up until the point the building is no longer in use. This boundary was selected because the available data for these prototypes is primarily sourced from the industry partners, and the buildings are still in use. As a result, information beyond the operational stage (such as end-of-life or post-use scenarios) is currently unavailable. Figure 4 represents the two prototypes.

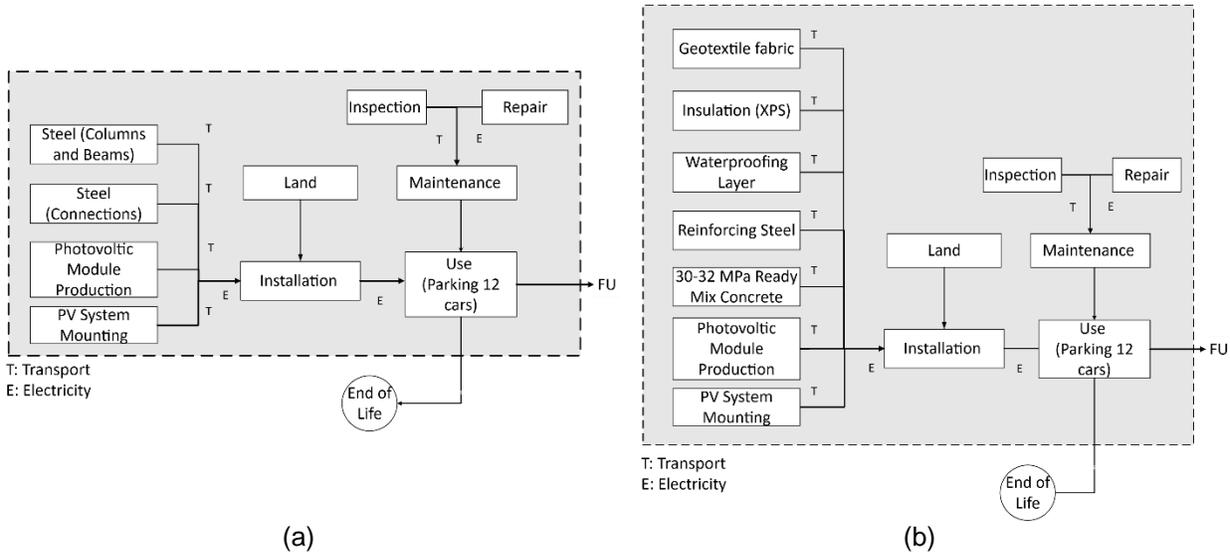


Figure 4: (a) Prototype 1 (automated parking tower), (b) Prototype 2 (ground level covered parking)

2.6 Reference Flows

Reference flows represent the specific amounts of materials, energy, or products required to fulfill the functional unit of the study. They quantify the inputs and outputs needed to achieve the defined function of a system. Tables 1 & 2 present the reference flows for the two prototypes.

Table 1: Reference flows for prototype 1

Unit process	Flow type	Flow	Flow Quantity	Unit
	IF- O	Building envelope	1	Item
	IF-I	Columns and beams steel (low alloyed)	6596	kg
	IF-I	Connections steel (low alloyed)	132	kg
	IF-I	Photovoltaic module production	109	m ²
Envelope production	IF-I	PV panel mounts	109	m ²
	IF-O	Constructed envelope	1	Item
	EF-I	Land (area)	30.7	m ²
	IF-I	Transport (steel, marine)	53,824	ton.km
	IF-I	Transport (steel, train)	26,720	ton.km
Envelope construction	IF-I	Transport (steel, truck)	67	ton.km
	IF-I	Transport (PV module)	14	ton.km

	IF-I	Transport (PV mounts)	7	ton.km
	IF-I	Electricity for welding and installation (Manual arc welding)	7,986	kWh
	IF-O	Building envelope use	1	Item
	IF-O	Electricity generation	693090	kWh
	IF-I	Electricity consumption	511590	kWh
	IF-I	Installation inspection transport	300	km
	IF-I	Repair energy welding	160	kWh
	IF-I	Steel replacement	200	kg
	IF-I	PV replacement	22	m ²
	IF-I	Steel replacement transport	2	ton.km
Envelope Use	IF-I	PV replacement transport	1.34	ton.km

Table 2: Reference flows for prototype 2

Unit process	Flow type	Flow	Flow Quantity	Unit
	IF- O	Building envelope	1	Item
	IF-I	30-32 MPa Ready Mix Concrete	66	m ³
	IF-I	Reinforcing steel	779.25	kg
	IF-I	Water proof layer (EPDM)	288	kg
	IF-I	Insulation (XPS)	384	kg
	IF-I	Geotextile fabric (Polyester)	312	kg
	IF-I	30-32 MPa Ready Mix Concrete (side walk)	24	m ³
Envelope production	IF-I	Photovoltaic module production	216	m ²
	IF-I	PV panel mount	216	m ²
	IF-O	Constructed envelope	1	Item
	EF-I	Land (area)	240	m ²
	IF-I	Transport (ready mix concrete)	1152	ton.km
	IF-I	Transport (reinforcing steel)	7.79	ton.km
	IF-I	Transport (waterproof layer)	1.44	ton.km
	IF-I	Transport (insulation)	2.69	ton.km
	IF-I	Transport (PV module)	27.5	ton.km
	IF-I	Transport (PV mount)	11.52	ton.km
Envelope construction	IF-I	Transport (geotextile fabric)	3.12	ton.km
	IF-I	Electricity for installation	7064	kWh
	IF-O	Building envelope use	1	Item
	IF-O	Electricity generation	1531560	kWh
	IF-O	Electricity consumption	727380	kWh
	IF-O	PV replacement	43	m ²
	IF-O	PV replacement transport	5.5	ton.km
	IF-O	Installation inspection transport	300	km
Envelope use	IF-O	Repair energy consumption	2119	kWh

2.7 Assumptions

For construction, manual arc welding is assumed with a speed of 5 mm/s. Additionally, annual inspections are considered, with 20% of the PV panels and 3% of the steel being replaced over the structure's lifespan. While the original steel was sourced from South Korea, as indicated by the design team, the replacement steel was assumed to be supplied locally due to the impracticality of importing small quantities from such a distant location. To ensure accurate calculations for PV energy generation, the inputs outlined in Tables 3 and 4 were entered into the calculation tool. These inputs were carefully selected to reflect the specific characteristics and conditions of the photovoltaic systems being analyzed, ensuring reliable and precise energy performance results.

Table 3: Location and station identification

Requested Location	Location	Elevation (m)
2100 Lumen Drive, London Ontario, Canada	Lat, Lng: 42.97, -81.38	255.4400024

Table 4: PV system specifications for the prototypes

Prototype	Prototype 1		Prototype 2
Envelope component	Roof	South facade	Roof
DC System Size (kW)	6.75	19.34	46.64
Module Type	Standard	Standard	Standard
Array Type	Fixed (open rack)	Fixed (open rack)	Fixed (open rack)
Array Tilt (deg)	0°	90°	0°
Array Azimuth (deg)	180°	180°	180°
System Losses (%)	14.08	14.08	14.08
DC to AC Size Ratio	1.2	1.2	1.2
Inverter Efficiency (%)	96	96	96
Ground Coverage Ratio	NA	NA	NA
Albedo	From weather file	From weather file	From weather file

3. RESULTS AND DISCUSSION

To comprehensively assess the environmental impact of the different prototypes, both endpoint and midpoint impact categories from the IMPACT WORLD+ methods were analyzed. Midpoint categories focus on specific environmental issues, such as climate change, water scarcity, fossil and nuclear energy use, and mineral resource depletion, providing a detailed view of individual impact sources through multiple indicators. Endpoint categories aggregate these effects to evaluate their broader consequences on ecosystem quality and human health, offering a higher-level assessment of overall environmental damage. Initially, the aggregated impacts on ecosystem quality and human health were examined. However, to gain a more detailed understanding of specific environmental concerns, the impacts of climate change and water scarcity were excluded from the total and evaluated as separate categories. Additionally, fossil and nuclear energy consumption, along with mineral resource use, were highlighted independently from the midpoint impact categories, as they are not modeled within a specific area of protection. The results indicate that Prototype 2 demonstrates a comparatively lower environmental impact with respect to residual total ecosystem quality and total human health impacts. However, upon closer examination of the four distinct categories—climate change, water scarcity, fossil and nuclear energy use, and mineral resource depletion—the differences between the two prototypes are relatively minor, with impact values remaining closely aligned, as illustrated in Figure 5. This suggests that certain impact areas may require further investigation to better understand the extent of variation and identify the primary contributing factors. Accordingly, Figure 6 presents a detailed breakdown of the endpoint impact contributions for both prototypes, offering additional insights into the observed patterns.

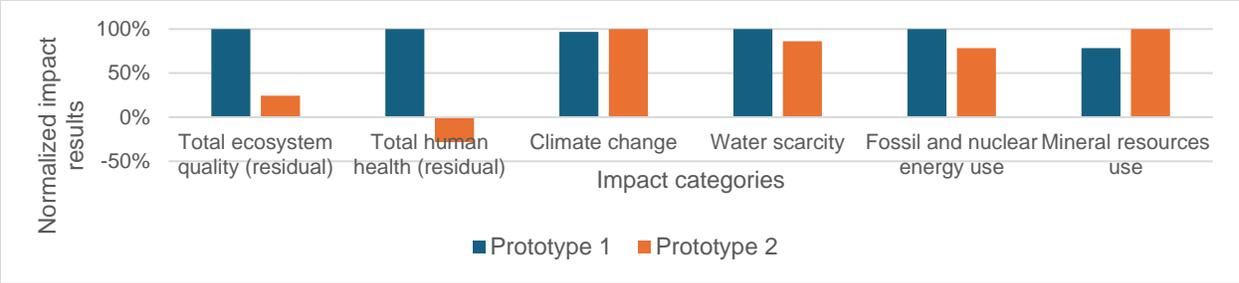


Figure 5: Prototypes associated impacts

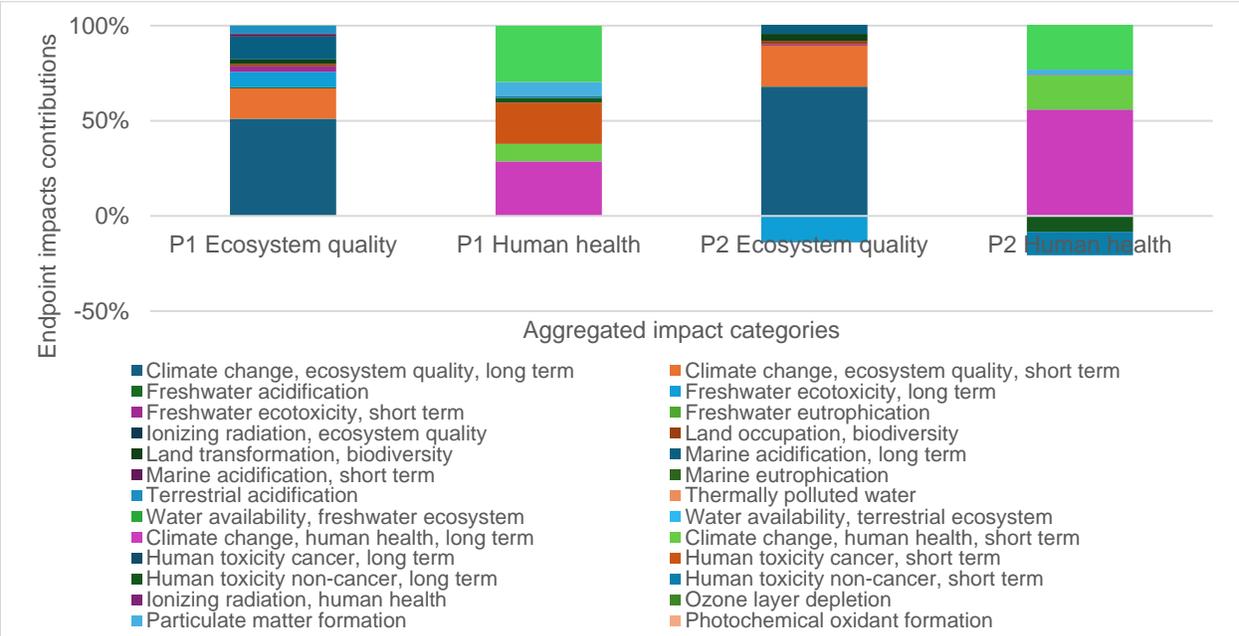


Figure 6: Prototype 1 endpoint impacts contributions

As illustrated in Figure 6, the long-term climate change impact represents the most significant contributor to the overall ecosystem quality, accounting for 51% in Prototype 1 and 68% in Prototype 2. Similarly, within the aggregated human health impacts, long-term climate change exhibits the highest contribution, with 29% and 56% for Prototypes 1 and 2, respectively. Water availability also plays a notable role, contributing 30% and 44% for Prototypes 1 and 2, respectively. The mid-point impacts of climate change are presented in Figure 6, where Prototype 1 demonstrates relatively lower CO₂ emissions compared to Prototype 2, across both short and long-term. Here, short-term impacts are evaluated using a 20-year time horizon, while long-term impacts reflect a 100-year perspective. Given the substantial influence of climate change on the aggregated endpoint impacts for both ecosystem quality and human health, the processes contributing to these climate change impacts are further analyzed in Figure 7.

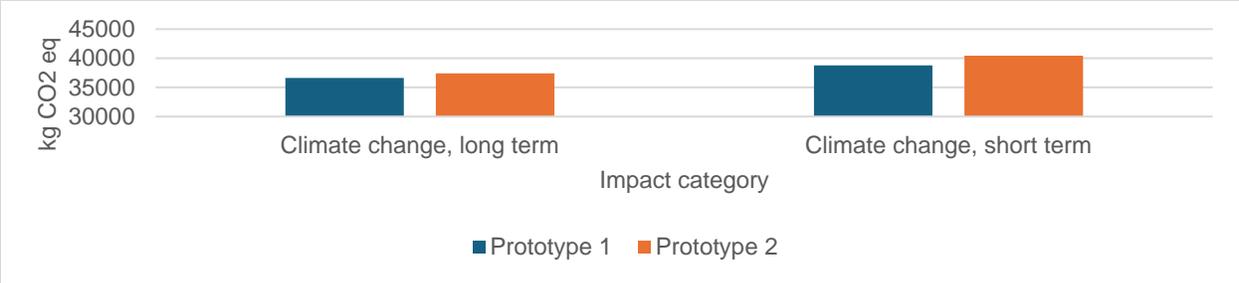


Figure 7: Climate change impacts

As observed in Figure 8, photovoltaic (PV) energy generation exhibits a positive impact on both short- and long-term climate change for both prototypes, with Prototype 2 demonstrating a more pronounced negative CO₂ contribution, indicating a net reduction in atmospheric CO₂ through carbon offsetting. The majority of climate change impacts originate from the production phase, with PV module manufacturing representing the most significant contributor. This is followed by steel production in Prototype 1 and concrete production in Prototype 2. These findings are supported by a study conducted by Thiel et al., which identified that the largest environmental impacts in a Net-Zero energy building come from the production of building materials, specifically concrete, structural steel, and photovoltaic (PV) panels (Thiel et al., 2013). However, some studies suggest that buildings with concrete frames typically have a lower environmental burden compared to those with steel frames (Alshamrani, 2016; Stoiber et al., 2021). In the context of this study, the greater environmental impact of concrete compared to steel can be attributed to its higher density and the larger quantity used in Prototype 2. Furthermore, studies indicate that different types of concrete exhibit varying environmental impacts; for example, carbon concrete tends to have a lower environmental footprint due to its lighter weight (Stoiber et al., 2021).

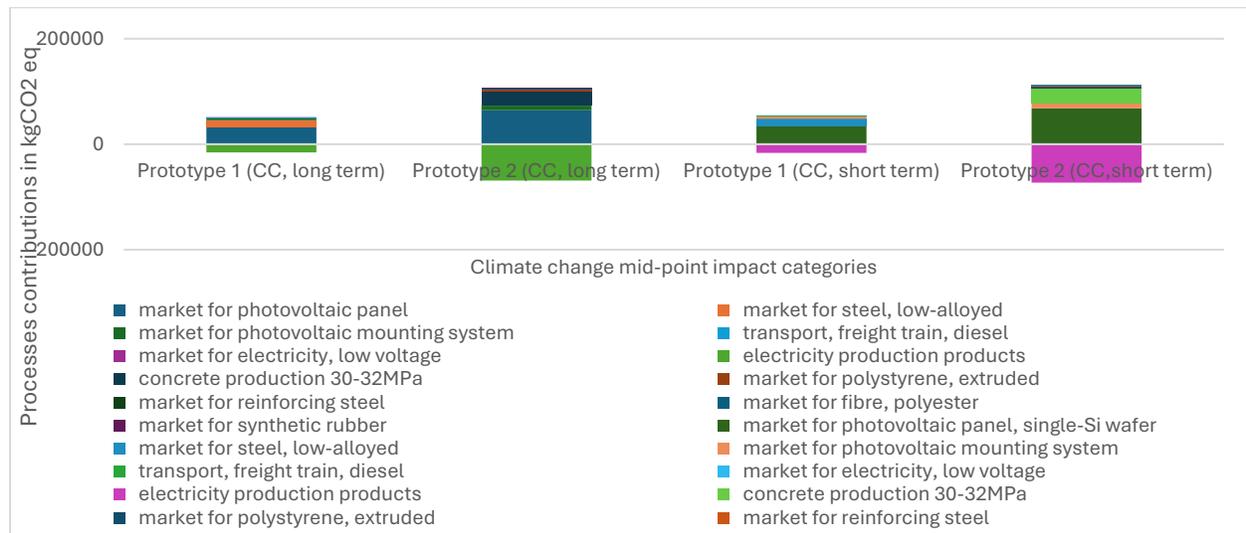


Figure 8: Climate change processes contributions

Table 5: Mid-point impacts from highlighted categories

Mid-point impact categories	Prototype 1	Prototype 2	Unit
Climate change, long term	36622.29491	37403.97976	kg CO2 eq (long)
Climate change, short term	38774.23863	40435.08556	kg CO2 eq (short)
Fossil and nuclear energy use	589933.8	462279.5	MJ deprived
Water scarcity	42814.54	36920.96	m3 world-eq
Mineral resources use	5598.496	7144.07	kg deprived

Table 5 presents the highlighted mid-point impact categories for both prototypes. As previously noted, the performance of the two prototypes is closely aligned across these categories, with Prototype 2 exhibiting a moderate advantage in some categories. A detailed analysis was conducted to assess the influence of various processes on the aggregated impact categories. As shown in Figure 9, the use phase results in a net positive environmental impact across both aggregated endpoint impact categories, with Prototype 2 performing better due to higher energy generation. Additionally, the production-related impacts for Prototype 1 are lower than those for Prototype 2, suggesting that, if Prototype 1 were to generate more energy, its overall environmental burden would be lower than that of Prototype 2. This finding is further supported by the sensitivity analysis presented in Figure 10, which reveals that, in the absence of PV systems, Prototype 1 exhibits a lower environmental impact compared to Prototype 2. Specifically, when PV is not installed, Prototype 2 experiences a 36% increase in ecosystem quality impact compared to Prototype 1 (no PV), and a 28% increase in human health impact relative to Prototype 1 (no PV). Moreover,

Prototype 2 with PV performs 72% better than its non-PV counterpart in the ecosystem quality category and 92% better in the human health category. Similarly, Prototype 1 with PV outperforms Prototype 1 (no PV) by 27% in the ecosystem quality category and 56% in the human health category, as illustrated in Figure 9. To further analyze the effect of PV, an optimized scenario for Prototype 1 is proposed, where both the East and West facades incorporate PVs, and the South façade is tilted at 60°. As demonstrated, in this scenario, the optimized Prototype 1 outperforms all other scenarios across both aggregated impact categories, achieving a 10% improvement over Prototype 2 in the ecosystem quality category while performing comparably to Prototype 2 in the human health category.

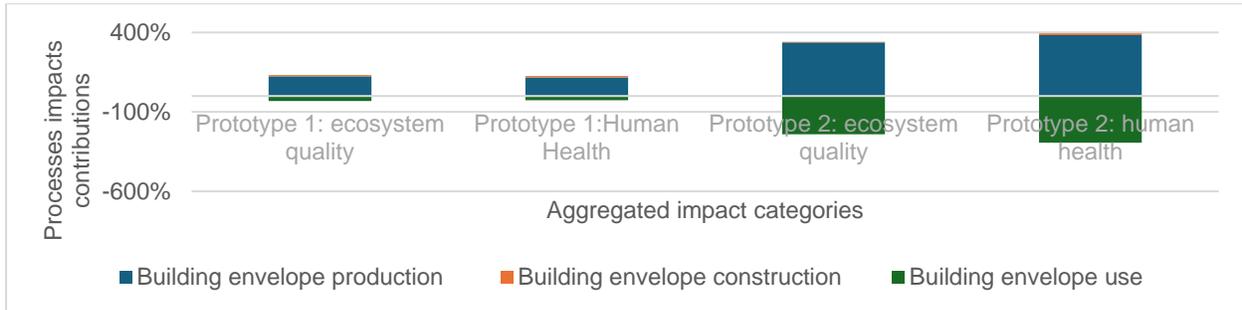


Figure 9: Processes aggregated endpoint impact contributions in each prototype

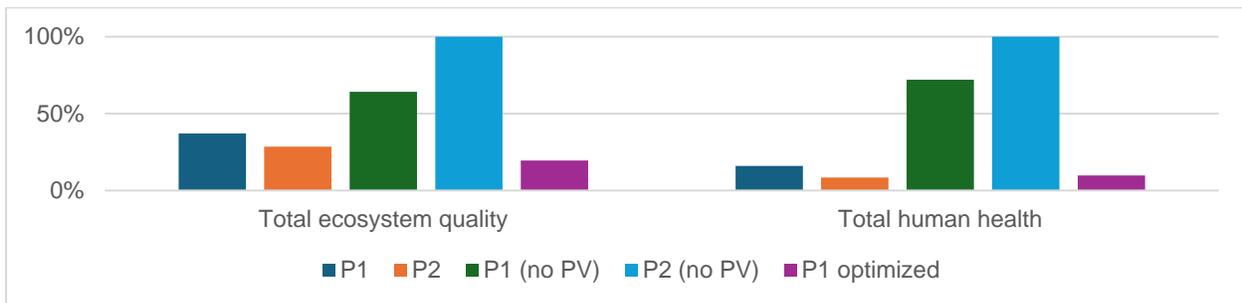


Figure 10: Impact of PV on the prototypes

4. CONCLUSIONS

This study presents a comprehensive Life Cycle Assessment (LCA) of two car parking prototypes in Canada: (1) an automated steel parking tower with photovoltaic (PV) panels on the roof and south-facing façade, and (2) a ground-level concrete covered parking structure with rooftop PV. The analysis examines the trade-offs associated with their design, energy use, and material choices. This study highlights the critical role of PV integration and material selection in reducing the environmental impact of net-zero carbon buildings. While Prototype 2 demonstrated a lower overall environmental burden, the differences between the prototypes were relatively minor across specific impact categories. Notably, Prototype 1 performed better in the production phase, whereas Prototype 2 excelled in the use phase, generating more electricity through PV. These findings underscore the importance of adopting a holistic sustainability approach when designing parking structures for net-zero applications. A key finding is the necessity of optimizing PV placement and integrating energy-efficient materials to enhance sustainability. The proposed optimization of Prototype 1, incorporating strategic PV positioning, resulted in a 10% improvement in ecosystem quality while maintaining comparable performance in the human health category relative to Prototype 2. Furthermore, this study underscores the potential of parking structures as integral components of net-zero developments. Rather than merely serving as passive urban elements, parking structures can be designed to function as active contributors to sustainability when effectively integrated with multi-story buildings. While this study focused primarily on environmental impacts, future research should explore the economic feasibility of various parking solutions when coupled with buildings. Additionally, further investigations should consider a wider range of prototypes, advancements in PV technologies, the potential for waste heat recovery from solar panels, and end of life scenarios. A limitation of this study lies in the uncertainty

associated with certain data inputs, particularly those obtained from secondary sources. This includes estimated values for construction energy consumption and transportation distances, which may not fully capture project-specific variations. While every effort was made to use credible and relevant data, these uncertainties could influence the accuracy of the results. Therefore, incorporating a formal uncertainty or sensitivity analysis is recommended for future studies to better understand the range of potential environmental impacts and to strengthen the robustness of the findings.

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