CLIMATE CHANGE ON A BUDGET: DEFINING OPTIMAL NET ZERO STRATEGIES FOR INFRASTRUCTURE PROJECTS

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Highlights

- Net Zero strategies are critical to mitigating global warming.
- Aligns with Sustainable Development Goals 7, 11, and 13.
- Scalable method adaptable to various sectors and projects.
- Incorporates uncertainty by considering economic and technological changes.
- Optimizes multiple objectives, balancing corporate standards and budgets.

ABSTRACT

In response to the growing impacts of climate change, Net Zero initiatives have emerged as a global effort to mitigate its effects. However, despite extensive research, a critical gap persists in developing strategies that address the complex interdependencies between corporate standards and economic constraints in a rapidly changing world. To address this gap, we propose a Net Zero framework designed to prioritize actions, establish decision thresholds, and formulate effective courses of action. Our framework integrates the Analytical Network Process (ANP), Multi-objective Optimization (MO), and Decision Making under Deep Uncertainty (DMDU). We demonstrate the application of this framework using the case of a privately-operated highway in Mexico City, though its adaptability makes it suitable for any infrastructure project. The results identify optimal solution sets that ensure Net Zero targets are met by 2030 and 2040, accounting for the uncertainties of future technological advancements and economic constraints. This approach provides a systematic method for stakeholders to navigate the complexities of achieving Net Zero goals.

Keywords: complexity, uncertainty, pathways, sustainable development, EGS, Net Zero.

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1. Introduction

Climate change is one of the most pressing global challenges of our time, requiring coordinated action across international, national, and local levels. Since the Paris Agreement in 2015, global mitigation efforts have primarily focused on reducing greenhouse gas emissions (GHG), with carbon dioxide (CO_2) playing a central role due to its significant contribution to global warming (IPCC, 2023). The concept of "Net Zero" has emerged as a key approach for addressing climate change, wherein GHG emissions are balanced by carbon capture and reductions. Achieving Net Zero is a complex challenge, requiring the careful evaluation of multiple, often conflicting criteria, such as environmental sustainability, economic feasibility, and policy alignment. These challenges are amplified in infrastructure projects, which must not only align with Sustainable Development Goals (SDGs) but also meet high-level corporate standards, such as Environmental, Social, and Governance (ESG) criteria, while adjusting their investment strategies to limited budgets. The key issue, thus, relies on designing optimal cost-effective Net Zero strategies that balance the ESG over time.

This paper addresses this key issue by proposing a novel Net Zero framework that integrates the Analytic Network Process (ANP), Multi-objective Optimization (MO), and Decision Making under Deep Uncertainty (DMDU). In particular, we use the ANP to systematically evaluate various conflicting criteria, while MO enables us to optimize across different objectives that may have competing interests (Ragsdale, 2007). Our framework addresses three fundamental objectives: (1) maximize ESG goals alignment, (2) maximize the reduction of greenhouse gas emissions, and (3) minimize total costs.

DMDU encompasses a range of decision-making and risk management approaches designed for complex and uncertain conditions (Marchau *et al*., 2019). Our framework is built on Dynamic Adaptive Policy Pathways, a DMDU approach that integrates alternative sequences of decisions (adaptation pathways) across multiple scenarios. This method highlights path dependencies, emphasizing the need for continuous monitoring of indicators to guide decision-making over time. DMDU adds robustness to MO by accounting for future uncertainties, such as policy shifts or technological advancements, which are critical in long-term climate strategies. We demonstrate the practical application of this method through a case study involving a 5.24 km privately-operated highway in Mexico City, offering insights into how this approach can be adapted to other sectors and contexts globally.

2. Literature Review

Recent work on Net Zero encompasses a wide array of strategies and methodologies (Muryani *et al*., 2023). For instance, MCDA has facilitated optimizing energy systems, developing adaptive CO_2 tax strategies, reducing GHG emissions, and allocating green infrastructure. In transportation sector, particularly, MCDA has been particularly useful in the cement industry for technology evaluation and optimization. However, most of these studies have narrowly focused on either construction technologies and assets or end-users.

Despite these significant studies, there remains a critical gap in the development of optimal Net Zero strategies that account for the complexities and uncertainties of infrastructure projects, which include both rapid changes and intricate interactions between technological development, policy, economic constraints, and social interests. The gap, therefore, lies in the lack of integrated strategies that not only consider these factors but also optimize for multiple objectives such as GHG reduction, cost efficiency, and long-term sustainability.

3. Implementation

Our framework includes three phases (Fig 1): (1) ANP, to identify and evaluate the multiple decision criteria and alternatives; (2) MO, to define solution sets; and (3) DMDU, to develop adaptive pathways.

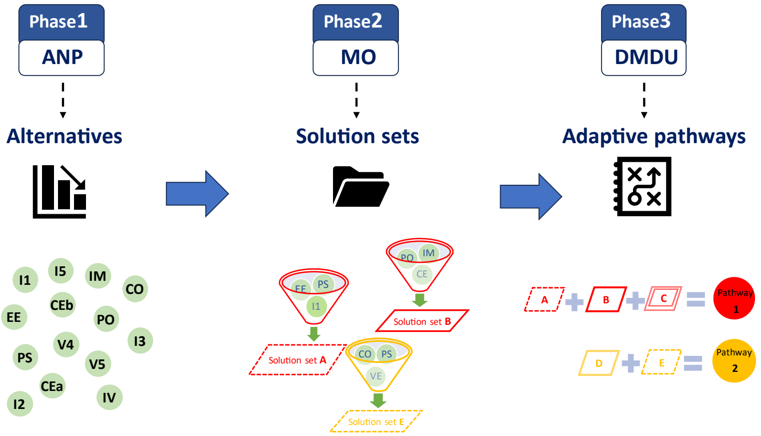

Figure 1. Methodological framework.

3.1 Phase 1: ANP

The objective of Phase 1 was to evaluate the multiple decision criteria and alternatives. We developed an ANP through a literature review focused on technology assessments and planning processes that analyzed ESG in infrastructure Net Zero projects, particularly in the transportation sector. We used the software *Superdecisions* to develop the ANP model that considered both tangible (e.g., technologies) and intangible (e.g., prestige) criteria, as well as their relationships and feedback. The model thus included one general hierarchical structure (Fig. 2), and four sub-networks (see Appendices) that corresponded to a BOCR analysis (Saaty and Vargas, 2006).

We conducted a series of workshops with decision-makers from the highway operating company, including staff (i.e., engineers and biologists), area managers, and the corporate director. During the workshops, participants provided information on the current status of the highway regarding GHG emissions, developed pairwise comparison matrices, and identified 23 feasible technologies to reduce GHG emissions (alternatives, t_j). These technologies were classified into four groups: illumination systems, power sources, transport technologies, and ventilation systems. From each sub-network, we selected the criteria with a priority weight of at least 0.10 (Table 1) and applied a rating scale to evaluate each technology. The rating scale was based on both Miller's and Weber Fechner's laws, comprising five categories of desirability:

$$\{\text{very low } (0.06), \text{low } (0.13), \text{moderate } (0.25), \text{high } (0.50), \text{very high } (1.00)\}$$

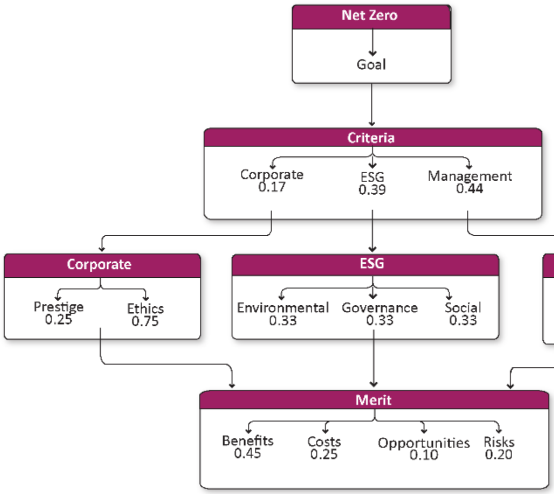

Figure 2. General Net Zero model.

Table 1. Selected BOCR criteria (normalized weights in parenthesis).

Sub-network	**Criterion**	**Definition**
Benefits (0.45)	Climate Change (0.11)	GHG emission reduction effects
	Savings (0.08)	Reduction in electricity consumption expenditures
	Health (0.05)	Population's physical and psychological status
Opportunities (0.10)	Green energy (0.03)	Use and generation of green energy
	Involvement (0.03)	Relationship with neighboring communities
	GHG emissions (0.04)	Zero GHG emissions
	Research (0.07)	Technical scientific support for decision-making
	Performance (0.07)	Improvement in sustainability indicators
Costs (0.25)	Insecurity (0.03)	Vandalism and theft of installed technologies
	Fragility (0.05)	Malfunctioning of new technologies
	Acquisition (0.07)	Expenditures associated with new technologies
	Execution (0.09)	Expenditure for operation and maintenance
Risks (0.20)	Legal (0.03)	Increased environmental liabilities
	Costs increase (0.23)	Ongoing costs for lowering GHG emissions

We used the weighted linear combination to aggregate the results of each sub-network. For example, the aggregation of *Benefits* was obtained with

$$B_j = \sum\nolimits_j^J w_i^{\mathrm{b}}\, x_{ij}^{\mathrm{b}}$$

where w_i^{b} are the global priority weights and x_{ij}^{b} are the rating values of the i-th criterion and the j-th technology.

Then, we aggregated the four sub-networks using a multiplicative procedure (Wijnmalen, 2007):

$$BOCR_j = \frac{B_j^{w_b} O_j^{w_o}}{C_j^{w_c} R_j^{w_r}} \qquad j = 1,2, \ldots J.$$

where w_b, w_o, w_c, w_r are the local priority weights of *Benefits*, *Opportunities*, *Costs*, and *Risks*, respectively, while B_j, O_j, C_j, R_j are the aggregated sub-network values for each j-th technology.

3.2 Phase 2: MO

The objective of Phase 2 was to explore different budget scenarios and define solution sets, which represent the technologies selected for implementation to meet the objectives specified for each scenario. We conducted a scenario analysis to identify the solution sets that would satisfy three goals: (1) maximize ESG goals alignment, (2) maximize the reduction of greenhouse gas emissions, and (3) minimize total costs. Using the Solver complement of Excel sheets, we implemented a multi-objective optimization model that considered the 23 technologies as decision variables ($t_1, t_2, \dots, t_{23} = bin$). We explored a total of 64 scenarios, defined by four restrictions related to goal satisfaction:

MAX: $t_1, t_2, \dots, t_{23} \geq 25\%, 50\%, 75\%, 100\%$ $\}\ degree\ of\ BOCR\ to\ fulfill$
MAX: $t_1, t_2, \dots, t_{23} \geq 25\%, 50\%, 75\%, 100\%$ $\}\ amount\ of\ GHG\ to\ reduce$
MIN: $t_1, t_2, \dots, t_{23} \leq 25\%, 50\%, 75\%, 100\%$ $\}\ amount\ of\ money\ to\ invest$

Of the total scenarios explored, 14 had no solution from the optimization model. This mainly occurred in scenarios targeting 100% GHG reduction, especially when BOCR fulfillment was high and total costs were limited to 25%. Additionally, scenarios with 100% BOCR fulfillment failed even when the GHG reduction target or budget was set at 50%. These results suggest that achieving significant GHG reductions becomes unfeasible when the budget is restricted, particularly under high BOCR fulfillment expectations.
Results from Phase 2, thus, included 50 solution sets, detailing the technologies to be implemented, the total amount of GHG emissions that could potentially be reduced, the cost of implementation, and the degree to which the BOCR criteria were met.

3.3 Phase 3: DMDU

The goal in Phase 3 was to determine adaptive pathways, considered as the GHG reduction strategies in relation to decision thresholds within dynamic external conditions. To determine the decision thresholds, the maximum GHG value and the minimum cost of each solution set from Phase 2 were considered. Next, solution sets were filtered to ensure a 50% reduction in current GHG emissions by 2030 and a full reduction by 2040, targeting 700 tCO2eq and 1,400 tCO2eq, respectively. Ensuring complementarity between the 2030 and 2040 alternatives was a *conditio sine qua non* for the pathway design. In other words, short-term decisions had to align with long-term objectives, ensuring coherence and continuity in the implementation of the adaptive pathway.

Results of Phase 3 included nine solution sets arranged into four adaptive pathways (Fig. 3). Pathway 2 (yellow), for example, successfully met the 2030 target but failed to do so for 2040. However, the 2040 target can still be achieved when selecting pathway 1 though solution set C, pathway 3 (green) through solution set H, and pathway 4 (blue) through solution set C. These results were presented to the workshop participants to provide them with technical and scientific support for present and future decisions in their investment and operational strategies. Pathways 1 (red) and 4 (blue) exceeded the 2040 target but incurred maximum costs. Pathway 2 (yellow) failed to meet the specified goals. Pathway 3 was identified as the optimal solution, achieving both the 2030 and 2040 targets while minimizing costs.

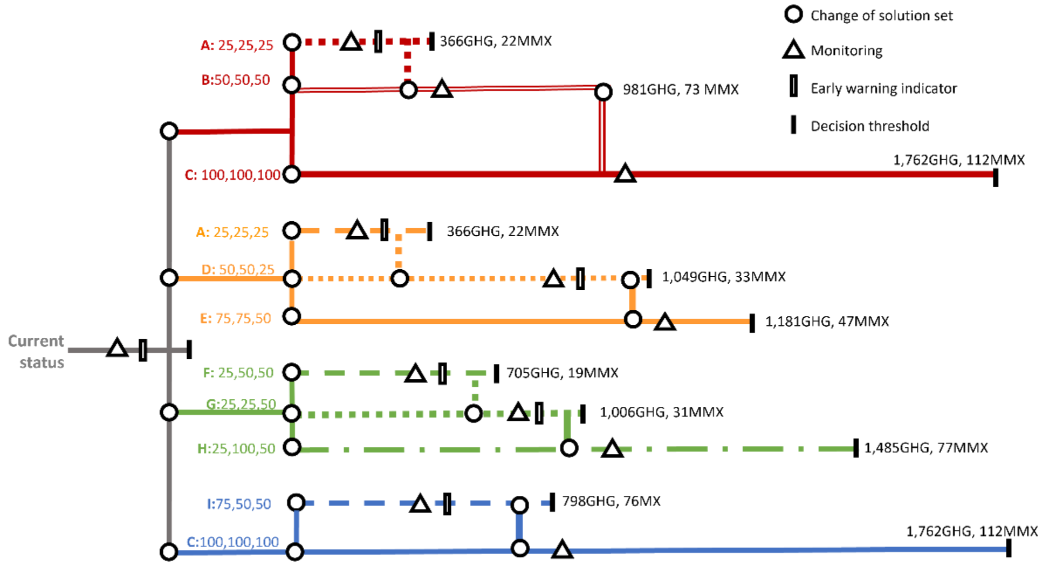

Figure 3. Adaptive pathways (by color) with solution sets (by line pattern). Letters indicate %BOCR, %GHG, and %budget. Decision thresholds indicate reduction of GHG (tCO2eq) and total cost (million Mexican pesos).

4. Conclusions

This study's primary contribution is the development and application of an integrated Net Zero framework that addresses the uncertainty and complexities of the development of infrastructure projects. By combining ANP, MO, and DMDU techniques, the framework enables decision-makers to prioritize actions, identify decision thresholds, and design adaptable pathways to reduce GHG emissions effectively. Unlike traditional approaches that focus on isolated aspects of transportation or energy systems, our framework offers a comprehensive, multidimensional evaluation tool. Results offer a quantitative assessment of feasibility and performance across BOCR criteria. This enables the exploration of multiple scenarios to identify the most effective sets of technologies for implementation, while ensuring alignment with economic and organizational objectives. Our framework provides policymakers and stakeholders with a clearer understanding of the ESG interdependencies at play in a way that aligns decision-making with Sustainable Development Goals 7 (Affordable and clean energy), 11 (Sustainable Cities and Communities), and 13 (Climate Action).

5. Limitations

We recommend incorporating Monte Carlo Simulation in future applications of our framework to explore a wider range of scenarios, from 25% to 100%, expanding potential solution sets. For decision thresholds, specialized methods like decision trees or compatibility analysis from DMDU and MCDA approaches should be used. This combination helps decision-makers assess proximity to thresholds and the likelihood of crossing them, providing a clearer understanding of the changes needed to achieve long-term Net Zero goals.

6. Abbreviations

GHG- Greenhouse Gases.

CO_2- Carbon dioxide, measured in tCO2eq.
ESG- Environmental, Social, and Governance criteria.
ANP- Analytic Network Process.
MCDA- Multicriteria Decision Analysis.
MO- Multi-objective Optimization.
BOCR- Benefits, Opportunities, Costs, and Risks analysis.
DMDU- Decision Making under Deep Uncertainty.

7. Key References

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9. Appendices

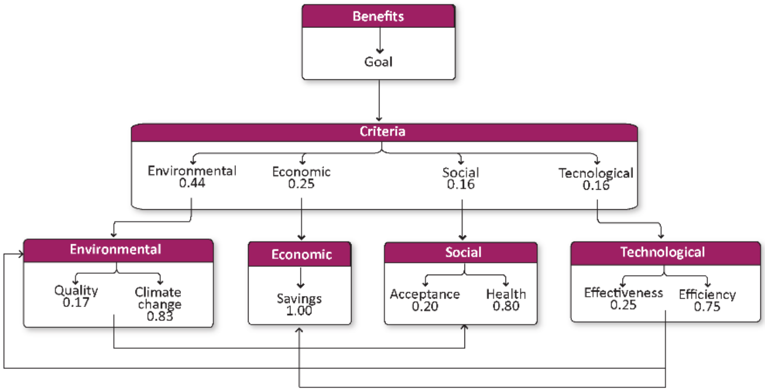

Figure A1. *Benefits* sub-network: positive results or immediate improvements.

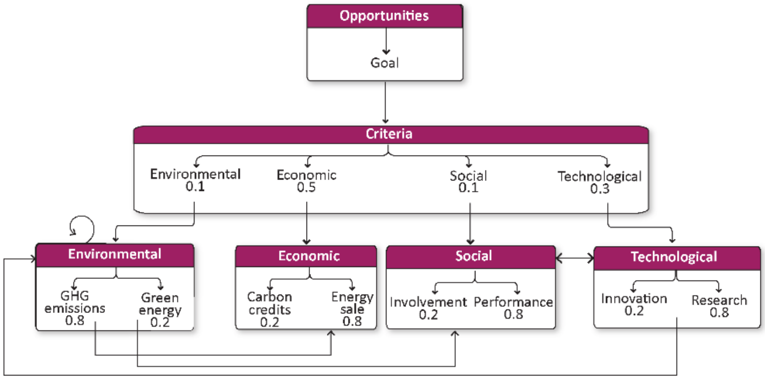

Figure A2. *Opportunities* sub-network: possibilities for growth, improvement or future advantages.

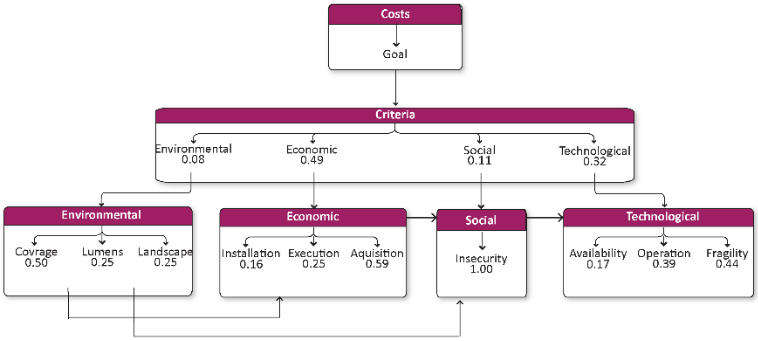

Figure A3. *Costs* sub-network: expenditures associated with the execution and operation in the present.

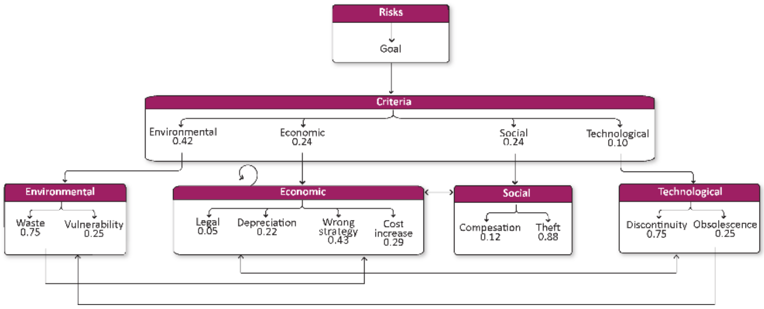

Figure A4. *Risks* sub-network: events and circumstances that could prevent the achievement of the ultimate objectives.