Toward Pareto-Optimal Investment Mix to Achieve Carbon Neutrality: A Case Study

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Abstract: Leading institutions are committing to climate action by setting greenhouse gas emission (GHG) reduction targets to reach carbon neutrality. Institutional stakeholders are faced with the challenge of achieving these objectives through cost-effective investments in diverse and interconnected infrastructures, all while considering the existing infrastructure. In our prior work, we tackled this issue by creating an extensible investment model and tool known as GADGET - Green Assessment and Decision GuidancE Tool - to provide Pareto-optimal investment recommendations for heterogeneous infrastructures within energy service networks. In this study we employ GADGET to provide actionable investment recommendations to George Mason University's stakeholders on a mix of interrelated infrastructures for its Fairfax campus with the initial scope considering renewable energy certificates and carbon offsets, gas and electric boilers, on site solar panels, energy storage, and Dominion Virginia Energy contract schedule. Our analysis covers the period from 2025 to 2050, considering investment decisions at five-year intervals, with the overarching goal of achieving carbon neutrality by 2040. We also perform sensitivity analysis of recommended mixes to understand the implications of fluctuating REC and offset prices on projected outcomes. While our recommendations are specifically designed for George Mason University, the insights we provide may also be relevant and beneficial to other academic institutions.

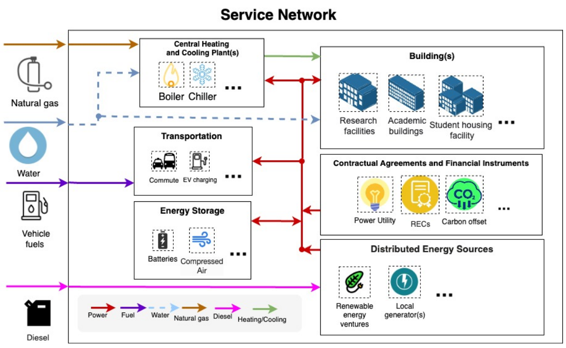

Figure 1: Service Network.

1 INTRODUCTION

Out of the 17 interlinked global goals adopted by all United Nations Member States in 2015 (United Nations, 2015), two goals deal with Affordable and Clean Energy and Climate Action. This prompted institutions worldwide to pledge reduction in carbon emissions and achieving carbon neutrality. George Mason University is part of this commitment, aiming to be carbon neutral by 2040.

To achieve this goal, stakeholders need to decide on how to invest in heterogeneous inter-related infrastructures including (1) building efficiency measures, such as retrofitting, insulation, lighting sensors, and certifications for new buildings; (2) heating/cooling efficiency, e.g., in chillers and boilers; (3) renewable sources of energy and local (co-) generation; (4) energy storage; (5) management of schedulable loads such as in heating/cooling and EV charging; (6) RECs and carbon offset credits; (7) investment in renewable energy ventures; (8) peak demand control and management vis-à-vis power utility contracts, e.g., with Dominion Virginia Energy; and (9) incentives for using green transportation; etc.

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However, developing an actionable strategy for investing in diverse modalities to achieve carbon neutrality is challenging due to (1) the complexity of the heterogeneous infrastructures and their components which interact with each other during operation in a non-trivial way; (2) the need to balance financial, environmental and quality of service KPIs, particularly when these objectives conflict; (3) the dependence of investment performance on operational efficiency (e.g., over 30-minute operational intervals) (4) the management of uncertainties arising from fluctuations in supply, demand, and market prices which are typically not steady-state but transient; (5) the adaptation to the ever-evolving landscape of carbon-reducing technologies and regulations; and (6) interoperation with pre-existing infrastructures constructed without considering emissions.

Due to the challenges outlined, progress toward carbon neutrality has not met the anticipated rates or scales. While there have been notable enhancements in the energy efficiency of some infrastructures, investments across mixed infrastructures are not achieving their full potential. Therefore, it is essential for stakeholders to formulate strategies that consider multiple infrastructures and resources simultaneously, placing a spotlight on the synergy between these infrastructures during operations.

In our review of past case studies designed to assist stakeholders in attaining carbon neutrality goals, represented by studies like (Alshuwaikhat and Abubakar, 2008) (Roberto et al., 2018) and (Kourgiozou et al., 2021), a common limitation became apparent. While these studies aimed to provide practical guidance, many of them presented frameworks that, rather than offering a clear and direct action plan, tended to provide broad theoretical guidelines.

Many case studies, exemplified by (Hanus et al., 2019) and (Li and Jia, 2022), develop actionable plans to assist stakeholders in formulating effective strategies to achieve carbon neutrality. However, a common drawback in these studies is their tendency to either narrowly focus on limited interventions or neglect the exploration of the intricate dynamics of operational interplay.

Some case studies utilize design guidance tools to craft actionable plans using a mix of modalities for power systems in microgrids to achieve carbon targets. These studies aim to utilize operational control to optimize system configurations, attaining cost-effective and efficient solutions in carbon reduction. Examples of such studies are (Danish et al., 2023) and (Venkatachary et al., 2017), which utilize HOMER (Lambert et al., 2006), a simulation model developed by the National Renewable Energy Laboratory (NREL), to reach optimal system configurations. However, these tools depend on simulations to reach optimal solutions. In contrast, optimization tools grounded in mathematical programming tend to yield superior results, excelling in both optimality of results and computational efficiency. Additionally, these tools were not initially designed for multi-period investment optimization; they often enforce investments at the beginning, which may not be optimally cost-effective, especially when dealing with relatively new technologies subject to changing maturity levels and prices over time.

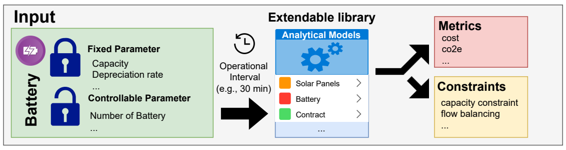

Figure 2: Atomic Analytical Models.

In our recent study (Alyahya and Brodsky, 2023), we introduced the Green Assessment and Decision GuidancE Tool (GADGET) to address the aforementioned limitations. GADGET produces actionable Pareto-optimal recommendations with respect two sets of metrics: (1) financial metrics including Present Value Cost (PVC) and IRR, and (2) environmental metrics, such as CO_2e emissions. GADGET deploys a Mixed Integer Linear Programming (MILP) solver and is based on the Service Network Investment Model (SNIM) (Alyahya and Brodsky, 2021), which calculates cash flows and performance metrics. SNIM formalizes both (1) nontrivial operational interactions within these infrastructures (e.g., at 30-minute intervals), and (2) investment controls at different stages in the time horizon (e.g., every 5 years over 25 years). Simultaneous optimization of these two control levels enables a more effective utilization of the infrastructure, minimizing waste that could occur when addressing each component in isolation.

In this study we employ GADGET to provide actionable investment recommendations to George Mason University's stakeholders on a mix of interrelated infrastructures for its Fairfax campus with the initial scope considering renewable energy certificates (RECs) and carbon offsets, gas and electric boilers, on site solar arrays, energy storage, and Dominion Virginia Energy contract schedule. Our analysis covers the investment time horizon from 2025 to 2050, considering investment decisions at five-year intervals, with the overarching goal of achieving carbon neutrality by 2040.

We produce optimal actionable recommendations for a number of scenarios associated with carbon neutrality targets ranging from 2040 to 2025, as well as baseline scenarios of business-as-usual, RECs and carbon offsets only, and optimal investment that ignores carbon emissions.

Additionally, we conduct sensitivity analysis on the most promising scenario to understand the implications of fluctuating prices for RECs and carbon offsets on the projected outcomes. While we provide optimal recommendation specifically tailored for George Mason University, our findings also offer valuable insights that may be advantageous to other institutions.

The remainder of this paper is organized as follows. Section 2 presents a review of the Service Network Investment Model and the GADGET tool. Section 3 details the methodology including the assumptions used in conducting the case study. Section 4 discusses the results of the case study and derives its implications. Finally, Section 5 summarizes the research and offers conclusions, highlighting the contributions of this study.

2 OVERVIEW OF THE SERVICE NETWORK INVESTMENT MODEL AND GADGET

The Service Network Investment Model (SNIM) is structured to provide across operational intervals, which extend over different investment periods: (1) A diverse range of metrics that span financial, operational, performance, and quality indicators (e.g., present value cost (PVC) and CO_2e), and (2) various constraints including capacity, supply, demand, and other relevant business constraints. These metrics and constraints are defined as functions of both fixed and controllable parameters that span across the investment time horizon. These parameters encapsulate the intrinsic configuration of the service network and its operating conditions over the designated investment periods. Consequently, they play a important role in shaping and influence strategic investment choices. To understand how SNIM operates, let's begin by explaining the input structure. This involves a central component comprising the hierarchical arrangement of all components within the power micro-grid, referred to as the *Service Network* (SN), as seen in the example of the GMU service network, depicted in Figure 1. This visualization reveals a hierarchical assembly of interconnected services, highlighted by nested boxes. Services integrated into this structure encompass cooling and heating plants, loads, utility contracts, among others, encapsulating the dynamic resource flow throughout the network (e.g., fuel, power,...). Positioned at the bottom of this hierarchy are the *atomic services*, visually highlighted with dotted boxes (e.g., Batteries) in the diagram. Whether these atomic services are currently owned or under consideration for investment, they come with specific fixed and controllable parameters. For example, parameters for the battery atomic service may encompass aspects like battery efficiency or the number of units charging/discharging within a given operational interval. These parameters are associated with specific analytical models tailored to their type (e.g., Battery Analytical Model), each residing within a modular library.

Every atomic analytical model in this library presents a mathematical model of the operation for its particular service, determining its performance metrics and constraints, as illustrated in Figure 2. When the SNIM operates, it integrates the flows, metrics, and constraints, starting from the bottom level of the hierarchy and moving upwards, for each operational interval (for instance, every 30 minutes) throughout the specified time horizon.

Above the core structure of the service network is another layer called 'Financial Instruments.' The role of this layer is to adjust the cash flow originating from the service network to account for financial transactions that affect the metrics without involving physical infrastructure. Instruments of this nature, such as RECs (Renewable Energy Certificates) and carbon offsets, are particularly influential in decisions on whether to make a purchase or refrain from it within specified financial intervals (e.g., every month)

GADGET employs the SNIM to generate Pareto-optimal actionable recommendations, presenting them as optimized investment scenarios. Users can access summaries, visualize charts, compare scenarios, explore specific solutions, and conduct 'what if' and sensitivity analyses. In each scenario, GADGET not only determines the most effective mix of modalities, including RECs and offsets but also identifies the optimal timing. This selection is strategically studied based on achieving optimal operational efficiency, with the overarching goal of maximizing returns and achieving carbon reduction within a specified time period. With the investment mixes being formulated under the assumption of optimal operational controls, we effectively minimize resource wastage that might occur if each infrastructure were optimized in isolation. This stands in contrast to traditional energy reduction models, which primarily focus on high-level financial terms and aim to optimize simple payback periods.

The tool adeptly tackles the scalability optimization challenge of representing every operational interval (e.g., 30 minutes) across investment periods covering the entire time horizon (e.g., 25 years). Equipped with a preprocessing engine, it represents the supply and demand pattern by creating a sequence of representative windows. For example, each window encapsulates a day of operational intervals (e.g., 48 intervals of 30 minutes each), serving as proxies of actual windows. These representative windows effectively capture similar supply and demand patterns, alleviating the computational burden of modeling every individual window.

The GADGET tool incorporates a library of analytic models specifically designed for a range of system components, encompassing various investment modalities and instruments related to power. Currently, the library includes: (1) gas and electric boilers; (2) power storage; (3) solar; (4) transformer; (5) carbon offset credits and renewable energy certificates (RECs); (6) Peak demand control and management in relation to power utility contracts, for example, with Dominion Virginia Energy. In addition, the library is designed with extensibility in mind. This ensures that new component models can be integrated without modifying the existing SN model or previously defined components. These enhancements can span various facets.

3 METHODOLOGY

In structuring the methodology for our study, we have divided the process into several sections. Initially, in our first section, we define the current state and establish the scope of our study. Following this, Section 3.2 outlines the assumptions made concerning our input data model to the GADGET tool. This encompasses elements like demand, supply, and pricing parameters. Progressing to Section 3.3, we describe the time horizon for our study and elaborate on how we generate the operational windows. Transitioning to Section 3.4, we elaborate on the performance metrics employed. This section also addresses the business constraints that guide our trajectory towards achieving carbon neutrality. We round off our methodology in Section 3.5, where we introduce the diverse scenarios explored in our quest for carbon neutrality.

3.1 Current State & Scope of the Study

Annually, Mason allocates between \$9 to \$10 million for energy expenses across all its campuses. A breakdown reveals that academic structures are responsible for approximately 40% of this energy consumption, while auxiliary facilities account for another 40%. Residential housing makes up the remain-

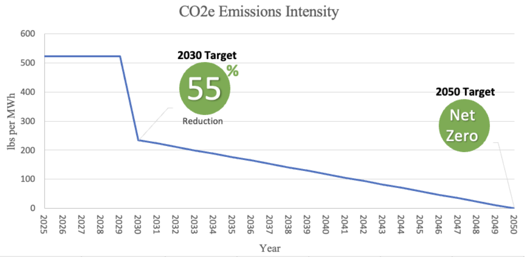

Figure 3: CO_2e Intensity projection for Dominion Energy.

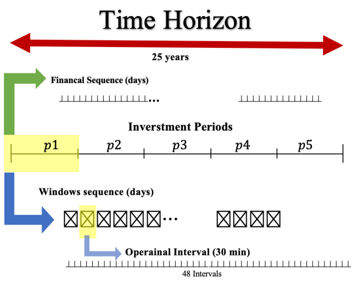

Figure 4: Time horizon.

ing 20%. Significantly, the Fairfax campus consumes 78% of Mason's entire energy (George Mason University, 2023b).

Currently, Mason relies on natural gas for 100% of its heat demand, classified as a Scope 1 emission. On the other hand, Scope 2 emissions arise from the electricity supplied to the Fairfax campus by Dominion Virginia Energy (George Mason University, 2023b). While Mason has extensively explored the prospect of introducing major renewable energy solutions, like solar panels and energy storage, they haven't yet been able to scale these solutions extensively. Despite this, Mason has seen commendable progress since its 2007 environmental pledge (George Mason University, 2023a). This includes conducting multiple Greenhouse Gas (GHG) Emissions Inventories to gauge emissions, creating its Climate Action Plan (CAP) as a guide to attain climate neutrality, and consistently updating its sustainability endeavors through the Sustainability Tracking, Assessment, and Rating System (STARS) report (George Mason University, 2023a).

The CAP's milestones aim to reduce emissions by 15% by 2030, and to achieve complete carbon neutrality by 2040. Acknowledging the CAP's commitment to a clear and attainable action plan, this study explores multiple scenarios. One scenario adheres to the carbon reduction goals set out in the CAP's timeline, while others pursue a more accelerated trajectory towards these objectives. In this study, we focus on the Fairfax campus, with particular emphasis on Scope 1 and Scope 2 emissions, as defined by the

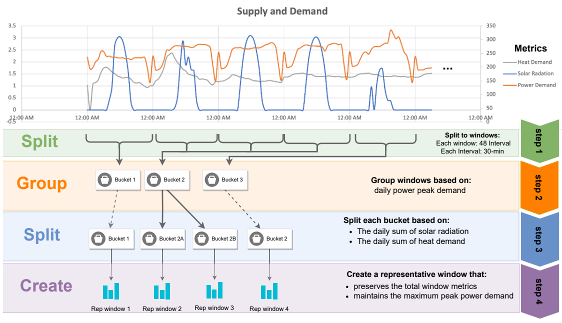

Figure 5: Windows Generation.

Greenhouse Gas Protocol and in accordance with ISO 14040 standards and World Resources Institute (WRI) guidelines (International Organization for Standardization, 2006; Sotos, Mary Elizabeth, 2015). We delve into various modalities, including solar panels, power storage, gas and electric boilers, the Dominion contract (schedule 6VA), RECs and carbon offset. The study's timeframe spans 25 years, from 1/1/2025 to 12/31/2049. In the subsequent section, we outline the assumptions related to supply, demand, and the modalities previously mentioned.

3.2 Sources and Assumptions

For GMU's electrical demand, we use historical data, taken in 30-minute intervals, from GMU's energy management system for 2019 (the year before COVID) and assume a 0.5% annual growth. As for the heat demand, since we only have the gas bills, we utilize the heat demand curve from American University to regress GMU's heat demand based on the monthly GMU gas consumption. We have incorporated an assumed 0.5% annual growth in our calculations. Additionally, the gas price projection is sourced from the U.S. Energy Information Administration. To estimate the Carbon Dioxide CO_2 equivalent emissions from one ton of natural gas, we utilized the greenhouse gas equivalencies calculator provided by the United States Environmental Protection Agency (EPA) (United States Envirmometal and Protection Agency, 2023b).

For our solar energy estimates, we utilize the PVWatts calculator software developed by NREL. This software calculates energy production in 30-minute intervals, leveraging data from NREL's solar radiation database. We've based our calculations on the assumption of a 4kW solar PV unit, set in a fixed (open rack) position, employing a standard module, and undergoing a system loss of 14.08%. We anticipate a serviceable lifespan of 30 years for each cell (National Renewable Energy Laboratory, 2023).

Regarding energy storage, our model assumes that each battery storage provides a duration of 4 hours with a total capacity of 2400 KWh. Operating conditions are presumed to maintain a consistent temperature of about 25°C. Additionally, we factor in a battery degradation rate of roughly 2% for every 1,000 charge-discharge cycles, projecting a total life expectancy of 20 years for each battery.

Additionally, we utilized the NREL database to estimate the capital expenditures (CAPEX) and operation and maintenance (O&M) costs for solar panels and storage technologies. These estimates are based on moderate R&D advancement scenarios, both currently and with projections up to 2050 (National Renewable Energy Laboratory, 2023).

We've constructed our Dominion Energy model based on the specifications outlined in Schedule 6VA. According to this schedule, Dominion Energy charges encompass both the supply (generation and transmission) and delivery (distribution) of electric service. The rate structure exhibits time and seasonal variations, classified into three pricing tiers: On-Peak, Off-Peak, and Rolling Peak. Notably, the pricing for the 'Rolling Peak' tier is determined by considering the peak of the current month as well as the preceding eleven billing months, as highlighted in (Dominion Energy, 2023). In our model, we project that changes in charges, including the Basic charge and Distribution Demand charge, will align with expected shifts in the electricity price per kW from 2025 to 2050. This projection is informed by data presented in the U.S. Energy Information Administration's (EIA) ANNUAL ENERGY OUTLOOK 2022 (U.S Energy Information Administration , 2023).

For the forecasting of REC prices, we utilize Aurora, a specialized energy forecasting software (Aurora Energy Research Limited, 2023). Furthermore, our modeling approach to REC purchasing is designed for flexibility in timing the acquisitions, aligning with the Yearly Reporting Requirement set by the United States Environmental Protection Agency (EPA). According to this EPA guideline, RECs can be bought up to 6 months before and 3 months after the reporting year, and still be recognized within that specified year (United States Envirmometal and Protection Agency, 2023a). For the carbon offset price forecast, we use one provided by BloombergNEF, utilizing a hybrid scenario that includes both offsets that avoid emissions and those that remove them (BloombergNEF, 2023).

Currently, Mason operates five gas boilers. Two of them have reached the end of their operational life. The remaining three have capacities of 25 MMBTU, 18.75 MMBTU, and 24.89 MMBTU with respective life expectancies of 6, 10, and 16 years. We assume that Mason has two main options for their heating infrastructure: either to reinvest in gas boilers similar to their current ones or to transition to electric boilers. Should they opt for the latter, this would also entail upgrading their transformer. Each of the electric boilers under consideration possesses a capacity of 1,800 KW. With assistance from the GMU facilities team, we've estimated the capital expenditures, O&M costs, and life expectancy of newly purchased units. We've also applied an inflation rate of 2.37% to forecast cost increases over time.

3.3 Time Horizon & Representative Daily Windows

We segment our 25-year time horizon into five distinct investment periods, each encompassing a duration of five years. It's our presumption that investments materialize at the onset of each respective period, guaranteeing immediate availability of the infrastructure. To assess cash flow, we adopt a sequential daily approach, identifying the specific intervals when particular sums are accrued, as depicted in Figure 4. Each period is segmented into representative daily windows, where each window stands as a proxy for a day, reflecting specific supply and demand patterns. Every window is further subdivided into 48 intervals, each spanning 30 minutes. To ensure these representative windows accurately capture the system's behavior, we devised the following methodology:

First, to construct a precise representation of the system's behavior across a 5-year investment period—comprising approximately 1,825 windows (days)—we categorize these windows based on their peak power demand. Employing a bucketing technique, windows that fall within an initial minimal distance (ε) of 300 kW from the peak are grouped together. As we navigate further from the highest recorded peak throughout all windows, the width of our grouping (denoted by ε) doubles, allowing for broader peak variations within the same bucket. This methodology ensures that, within each bucket of windows, we capture a less diverse range of peaks when the peaks are high. Such an approach emphasizes refining the buckets of windows with high peaks due to their substantial impact on demand contract charges, as depicted in Figure 5: step 2.

After the initial categorization, we further refine our buckets by segmenting them based on other metrics, such as the daily sum of solar radiation and the daily heat demand (refer to Figure 5: step 3). From each of these buckets, we create a representative window of demand and supply. This representative window is created based on two criteria: (1) the aggregate metric of all windows within a particular bucket should match the product of the representative window's metric and the count of windows in that bucket; (2) the peak power demand of the representative window should match the highest peak found in any window within that particular bucket (see Figure 5: step 4 for reference).

3.4 Performance Metrics

While the GADGET can depict a diverse range of metrics, our primary emphasis lies on two specific metrics: total cost of ownership and CO_2e emissions (covering both scope 1 and 2). Our objective function is geared towards minimizing the Present Value Cost (PVC) from 2025 to 2050. To determine the PVC, we incorporate a 5% discount rate. Additionally, for calculating the residual value, we employ the straight-line depreciation method. To achieve carbon neutrality, we run various scenarios wherein we set constraints on annual carbon emissions to align with target reductions over the designated periods. The specifics of these reductions are contingent on the scenarios, which we elaborate upon in the following section.

3.5 Scenarios

1. In the Business As Usual (BAU) scenario, investments are solely directed toward replacing outdated infrastructure or addressing the growing demand. In this scenario, green solutions are not considered, nor are carbon emissions constrained. Nevertheless, operational controls are still optimized with the primary goal of minimizing the present value cost (PVC).
2. Base 2040 (RECs and Offset): Aiming to minimize the PVC and meet CAP's milestones, this scenario adopts a 'BAU' strategy. However, it strategically purchases offsets and RECs in the most economical manner to fulfill CAP's designated targets.
3. Greedy Scenario: Operational and investment controls are optimized with the primary objective of minimizing the present value cost (PVC). Carbon reduction is not taken into account, and all green infrastructures are considered as potential investment opportunities.
4. Green 2040: In this scenario, the primary objective is to minimize PVC by optimizing the operation and investment controls with the ultimate goal of achieving carbon neutrality by 2040. This approach may encompass various strategies, in-

Table 1: Scenarios settings.

Scenarios	Objective	Carbon reduction					Explore solutions	
		Period 1 2025 to 2030	Period 2 2030 to 2035	Period 3 2035 to 2040	Period 4 2040 to 2045	Period 5 2045 to 2050	Green solutions	RECs and offset
BAU	min PVC	0%	0%	0%	0%	0%	No	No
Base 2040 (RECs and offset)	min PVC	0%	15%	15%	100%	100%	No	Yes
Greedy	min PVC	0%	0%	0%	0%	100%	Yes	Yes
Green 2040	min PVC	0%	0%	0%	100%	100%	Yes	Yes
Green 2040 enhanced	min PVC	0%	15%	15%	100%	100%	Yes	Yes
Green 2035	min PVC	0%	15%	100%	100%	100%	Yes	Yes
Green 2030	min PVC	0%	100%	100%	100%	100%	Yes	Yes
Green 2025	min PVC	100%	100%	100%	100%	100%	Yes	Yes

Table 2: Comparative Summary of All Scenarios.

	Period 1	Period 2	Period 3	Period 4	Period 5	PVC	Break Point	IRR (Base2040)	IRR (BAU)
BAU	Gas Boiler(18.75): 1		Gas Boiler (25): 1 Gas Boiler(18.75): 1		Gas Boiler(18.75): 1	Total: 133.31 M Investment: 2.67 M Sunk: 0 Residual: 0.67 M Saving: 0	N/A	N/A	0%
Base 2040 (RECs and Offset)	Gas Boiler(18.75): 1	REC: 11,337 Offset: 7,270	Gas Boiler (25): 1 Gas Boiler(18.75): 1 Offset: 16,760	Offset: 99,132	Gas Boiler(18.75): 1 Offset: 85,393	Total: 146.66 M Investment: 2.67 M Sunk: 13.32 M Residual: 0.67 M Saving: 0	N/A	0%	NA
Greedy	Gas Boiler(18.75): 1 Energy Storage: 1	Solar Panels: 4,720 Energy Storage: 1	Gas Boiler (25): 1 Gas Boiler(18.75): 1 Solar Panels: 883	Solar Panels: 434 Energy Storage: 1	Gas Boiler(18.75): 1 Solar Panels: 632 Energy Storage: 1	Total: 127.81 M Investment: 18.31 M Sunk: 0 Residual: 3.71 M Saving: 21.14 M	2038-10-17	14.36%	8.23%
Green 2040	Gas Boiler(18.75): 1 Energy Storage: 1	Solar Panels: 4,394	Gas Boiler (25): 1 Gas Boiler(18.75): 1 Solar Panels: 1,197 Energy Storage: 1	Solar Panels: 702 Energy Storage: 2 Offset: 90,910	Gas Boiler(18.75): 1 Solar Panels: 851 Offset: 81,998	Total: 136.21 M Investment: 18.35 M Sunk: 8.66 M Residual: 4.09 M Saving: 21.34 M	2038-12-17, 2040-04-16	11.67%	2.94%
Green 2040 enhanced	Gas Boiler(18.75): 1 Energy Storage: 1	Solar Panels: 6,004 REC: 275 Energy Storage: 2 Offset: 923	Gas Boiler (25): 1 Solar Panels: 961 Electric Boiler(1800): 3 Offset: 834 Transformer: 1	Solar Panels: 1,728 Offset: 82,731 Energy Storage: 1 Electric Boiler(1800): 1	Gas Boiler(18.75): 1 Solar Panels: 359 Offset: 74,086	Total: 137.15 M Investment: 24.11 M Sunk: 8.08 M Residual: 4.8 M Saving: 25.69 M	2042-01-16	9.44%	3.13%
Green 2035	Gas Boiler(18.75): 1 Energy Storage: 1	Solar Panels: 6,004 Energy Storage: 2 REC: 301 Offset: 938	Gas Boiler(18.75): 1 Solar Panels: 2,303 Electric Boiler(1800): 4 Offset: 90,858 Transformer: 1	Solar Panels: 386 Energy Storage: 1 Offset: 83,164	Gas Boiler(18.75): 1 Solar Panels: 485 Offset: 73,227 Electric Boiler(1800): 1	Total: 145.63 M Investment: 25 M Sunk: 16.32 M Residual: 4.76 M Saving: 26.33 M	2046-06-16	5.55%	-0.47%
Green 2030	Energy Storage: 1 Electric Boiler(1800): 2 Transformer: 1	Solar Panels: 8,577 Energy Storage: 2 Electric Boiler(1800): 3 REC: 20,731 Offset: 74,434	Gas Boiler (25): 1 Solar Panels: 130 Offset: 88,692	Solar Panels: 152 Offset: 82,119 Energy Storage: 1	Gas Boiler(18.75): 1 Solar Panels: 562 Offset: 73,215 Energy Storage: 1	Total: 160.17 M Investment: 28.65 M Sunk: 29.2 M Residual: 4.58 M Saving: 28.32 M	N/A	1.47%	-3.03%
Green 2025	Energy Storage: 1 REC: 26,269 Offset:172,757 Electric Boiler(1800): 2 Transformer: 1	Solar Panels: 8,601 Energy Storage: 2 REC:20,721 Offset: 74,252 Electric Boiler(1800): 3	Gas Boiler (25): 1 Gas Boiler(18.75): 1 Solar Panels: 98 Offset: 88,683	Solar Panels:147 Energy Storage: 1 Offset: 82,254	Gas Boiler(24.89): 1 Solar Panels: 332 Offset: 73,268	Total: 168.77 M Investment: 27.8 M Sunk: 37.67 M Residual: 4.4 M Saving: 27.33 M	N/A	0.04%	-4.11%

cluding green infrastructure and the acquisition of RECs and offsets.

5. Green enhanced 2040: Similar to the Green 2040 scenario, but with an added target on carbon reduction. Starting from 2030, there's a constraint to reduce carbon by 15%, aligning with the targets specified in CAP's milestones.
6. Green 2035: This scenario is akin to Green enhanced 2040 but pushes for carbon neutrality by 2035.
7. Green 2030: This scenario mirrors the Green 2040 approach but accelerates the timeline, aiming for carbon neutrality by 2030.
8. Green 2025: Built on the Green 2040 approach, the aim here is to achieve carbon neutrality by 2025.

To optimize these scenarios, we employed a batch-processing cluster using a single core of the AMD Opteron Processor 6276. We leveraged the CPLEX 22.1.0 solver to establish optimal operational controls and to determine the ideal investments in infrastructure units to meet the objective and different scenario constraints, as detailed in Table 1. The termination conditions were set to a maximum duration of 5 days or when achieving a gap of 0.3%.

4 RESULTS

In Figure 6, we depict the annual carbon reductions and the PVC for each scenario. Table 2 offers a detailed breakdown of the results from these scenarios. Within the table, the Total PVC is categorized into

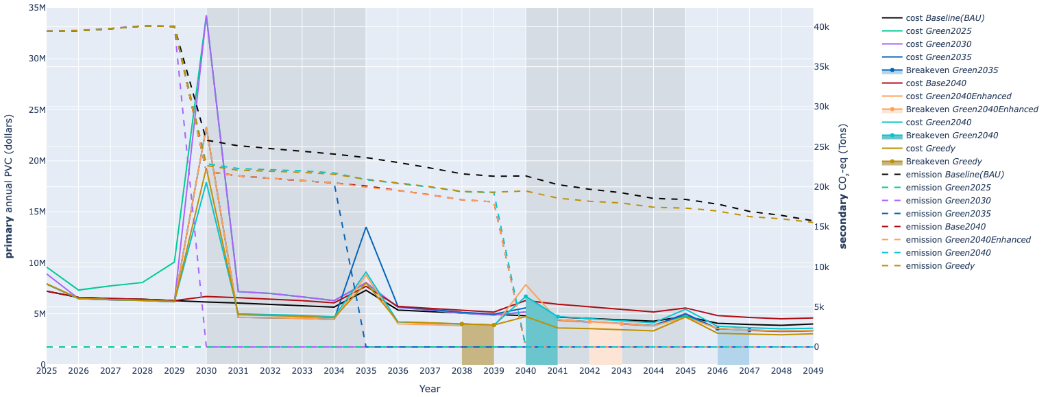

Figure 6: Scenarios.

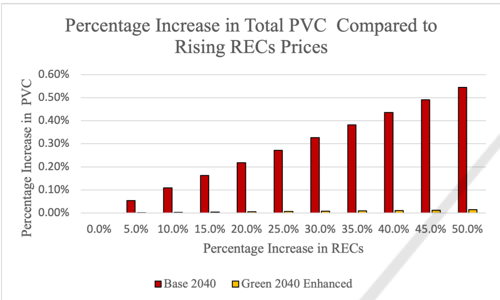

Figure 7: Sensitivity Analysis of RECs Price Increase.

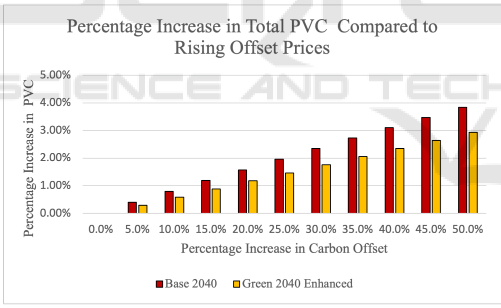

Figure 8: Sensitivity Analysis of Carbon Offset Price Increase.

its constituent elements: costs associated with investments, residuals, and sunk costs spent on acquiring RECs and offsets. It also presents the cost savings in comparison to the BAU scenario. Additionally, the table highlight the Return on Investment (ROI) set against the BAU and the Base 2040 (RECs and offset) scenarios, and concludes with an enumeration of units purchased at the beginning of each investment period for every explored scenario. By analyzing the results presented in this section, the following findings can be drawn:

1. Among all the models aligned with CAP's milestones, 'Green 2040 Enhanced' emerges as the most profitable scenario. Although the 'Green 2040' scenario may be less stringent in terms of achieving carbon reduction (it does not achieve the CAP's milestones) and is more cost-effective in terms of total present value cost, the 'Green 2040 Enhanced' scenario demonstrates a higher return on investment compared to the 'BAU' (Business As Usual) and also realizes greater savings. This is primarily attributed to early investments made to accommodate more aggressive carbon constraints.
2. In the 'Greedy' scenario, where the emphasis is largely on financial metrics with environmental impacts often sidelined, investments are predominantly directed towards green solutions, especially storage and solar. Importantly, it's evident that financial cost and carbon reduction aren't necessarily at odds, at least to a certain degree.
3. Energy management in a microgrid is essential for its smooth operation in a real-time environment. Achieving reductions in both cost and carbon emissions can largely be credited to an emphasis on optimal operations combined with the adoption of the proposed investment plans. Nonetheless, merely investing in the modalities without adopting a holistic strategy for overseeing these operations might not produce the expected outcomes.
4. While best practices advocate for combining energy storage and solar panels, offering benefits such as utilizing excess solar energy during non-sunny periods, maintaining grid stability, and ensuring resilience and backup, our scenario analysis revealed a different trend. In all scenarios that explore green solutions, we observed that, in period 1, energy storage is utilized exclusively (without accompanying solar) to mitigate peak demand from the Dominion contract.
5. In all scenarios analyzed for achieving carbon

neutrality, it's clear that carbon offsetting is crucial for GMU to attain a carbon-neutral status by 2040 in the most cost-effective manner.

6. Switching to electric boilers is intrinsically linked to the target year set for achieving carbon neutrality. A premature transition to electric boilers is not recommended, primarily because there are no associated cost savings to support such investments. Specifically, a shift to electricity would considerably augment the peak demand under the Dominion contract. This rationale is underscored in the 'Greedy' scenario, where investment in electric boilers is absent throughout all periods.
7. Through the implementation of green solutions, we can achieve carbon neutrality as early as 2035, with a favorable net present cost compared to the Baseline 2040 scenario. Additionally, this approach yields a positive return on investment (ROI) of 5.55%, in contrast to the Baseline 2040 scenario, which achieves carbon neutrality later at 2040 through the purchase of offsets and RECs.
8. In all cases, the investment in solar wasn't initiated at the beginning of 2025. This decision may be attributed to the fact that it might not be economically viable to invest in solar before Dominion reduces their emissions in 2030. As a result, opting to wait, purchase offsets and RECs to attain carbon neutrality, and investing in batteries to mitigate peak demand appears to be the optimal solution.

4.1 Sensitivity Analysis

As the Green 2040 Enhanced scenario exhibits the lowest Present Value Cost (PVC) and the highest Internal Rate of Return (IRR) among all scenarios that achieve the Mason CAP's milestones, we have chosen this scenario for further analysis.

In Figure 7, we illustrate the impact of changes in RECs pricing on the Total PVC. We conducted a similar analysis for carbon offset pricing in Figure 8. It is evident that, in general, RECs are less sensitive to changes in Total PVC compared to offset prices. This is attributed to the lower volume of RECs purchased in both the Base 2040 (REC=11,337) and the Green 2040 Enhanced (REC=275) scenarios, in contrast to the higher offset purchases in these scenarios (Base 2040=208,555, Green 2040 Enhanced=158,574).

Moreover, the Base 2040 scenario exhibits higher sensitivity to price changes when compared to the Green 2040 Enhanced scenario. To illustrate, when the price increases by 50%, the impact is more pronounced in the Base 2040 scenario. For offsets, this difference amounts to 6 million as opposed to 4 million, and for RECs, it's 798,000 compared to 19,000.

5 CONCLUSION

Utilizing GADGET, we presented George Mason University's leadership with investment recommendations aimed at achieving carbon neutrality by 2040. In this study, we utilized GADGET to provide George Mason University's leadership with targeted investment recommendations and delved into broader, ambitious carbon neutrality scenarios. Though our insights and recommendations are tailored for George Mason University, they can be helpful for other institutes as well. As we move forward, there's a compelling need to broaden our analytical scope. Specifically, we see potential in adding modalities such as building retrofits, energy efficiency retrofits, central utility electrification, and distributed energy sources. Refining our strategies for short-term investment periods, pinpointing specific technological preferences, and ensuring system reliability will be central to our future efforts. In the ever-evolving investment environment, continuous reassessment and adaptation are essential.

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