Charging the Renewable Transition:
Modeling the Role of Battery Storage in the Energy Grid

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ABSTRACT

Several strands of literature study the economics of energy grids. One recent working paper (Holland, Mansur, and Yates 2022) creates an economic model based on a social planner's optimization problem: under economic and technological constraints, what role would different electricity generation and storage technologies play in long-run equilibrium? I extend this paper's theoretical model by modifying the quality of the battery and the elasticity of demand for electricity. Theoretically, accounting for batteries' loss of charge during charging and discharging should decrease the role of storage in long-run equilibrium, while making demand less elastic should increase its role. I seek to answer the question: when changing these two assumptions in the model, which effect dominates? Under what conditions does battery storage play a large role in a long-run equilibrium model of the energy grid? I present three key findings. First, battery capacity is 0 when demand for electricity is least elastic (-0.001) and the battery cost is highest (baseline), if the round-trip efficiency is 70% or lower. Second, for a 75% reduced cost battery, one arc elasticity of charging losses relative to elasticity is 0.5063; for a 95% reduced cost battery, one arc elasticity of charging losses relative to elasticity is 3.7801. Third, for a -0.05 elasticity case, one arc elasticity of charging losses relative to battery cost is 5.6057; for a -0.001 elasticity case, one arc elasticity of charging losses relative to battery cost is 8.7977.

INTRODUCTION

A major policy challenge over the coming decades will be addressing climate change, including adapting the energy grid to to developments like electric vehicles, the rise of renewable energy, and influential policies.

One aspect of the energy grid that has gained increasing attention is the role of energy storage, including battery storage. In 2020, the capacity of battery storage in the entire U.S. was 1.5 Gigawatts, but the U.S. Energy Information Administration projects that by 2025, this capacity will catapult to 30.0 Gigawatts (U.S. EIA 2022). Energy storage connects energy supply across time/hours (Junge et al. 2021), but adding storage to the grid has costs and benefits (Mallapragada, Sepulveda, and Jenkins 2022).

Not all studies conclusively find a large role for battery storage in models of future energy grids incorporating variable renewable energy sources like solar and wind. In fact, Holland, Mansur, and Yates (2022) find an unexpectedly low role of battery storage in long-run equilibrium. I seek to answer the question: how do battery quality (i.e., charging and discharging losses), elasticity of demand for electricity, and battery capital costs determine the model's resulting battery storage capacity?

THEORETICAL MODEL

I aim to contribute to the rich literature on modeling storage and the energy grid by extending the long-run equilibrium model of Holland, Mansur, and Yates (2022),:

$$max \ \sum_t [U_t(Q_t) - \sum_i c_i q_{it}] - \sum_i r_i K_i - r_s \bar{S}$$

The choice variables are: hourly energy consumption (Q_t); hourly electricity generation by solar, wind, gas combined-cycle, gas peaker, and nuclear (q_{it}); annual generation (K_i) and ($\bar{S}$) battery capacities; hourly battery state (S_t); and hourly battery discharging (i.e., from battery to grid) (b_t^d).

The exogenous variables are: marginal costs of electricity generation by technology (c_i), capital costs of generation (r_i) and battery storage (r_s), and hourly capacity factors (f_{it}).

Due to imperfect batteries that lose electricity during charging and discharging, the battery's state in hour t is:

$$S_t = \alpha * S_{t-1} + (1 - \beta) * b_t^c - (1 + \beta) * b_t^d$$

Finally, the optimization program is under many constraints. One key constraint prevents hourly electricity taken from the grid (consumption and battery charging) from being greater than electricity added to the grid (electricity generation and battery discharging). A second key constraint is a capacity constraint: hourly production cannot be greater than hourly capacity., particularly key for solar and wind. Third, battery charging cannot be negative.

$$1) \ -Q_t + \sum_i q_{it} - \frac{1}{1-\beta} * S_t + \frac{\alpha}{1-\beta} * S_{t-1} + (1 - \frac{1+\beta}{1-\beta}) * b_t^d \geq 0$$

$$2) \ f_{it} * K_i - q_{it} \geq 0$$

$$10) \ b_t^c \geq 0 \rightarrow \frac{1}{1-\beta} * S_t - \frac{\alpha}{1-\beta} * S_{t-1} + \frac{1+\beta}{1-\beta} * b_t^d \geq 0$$

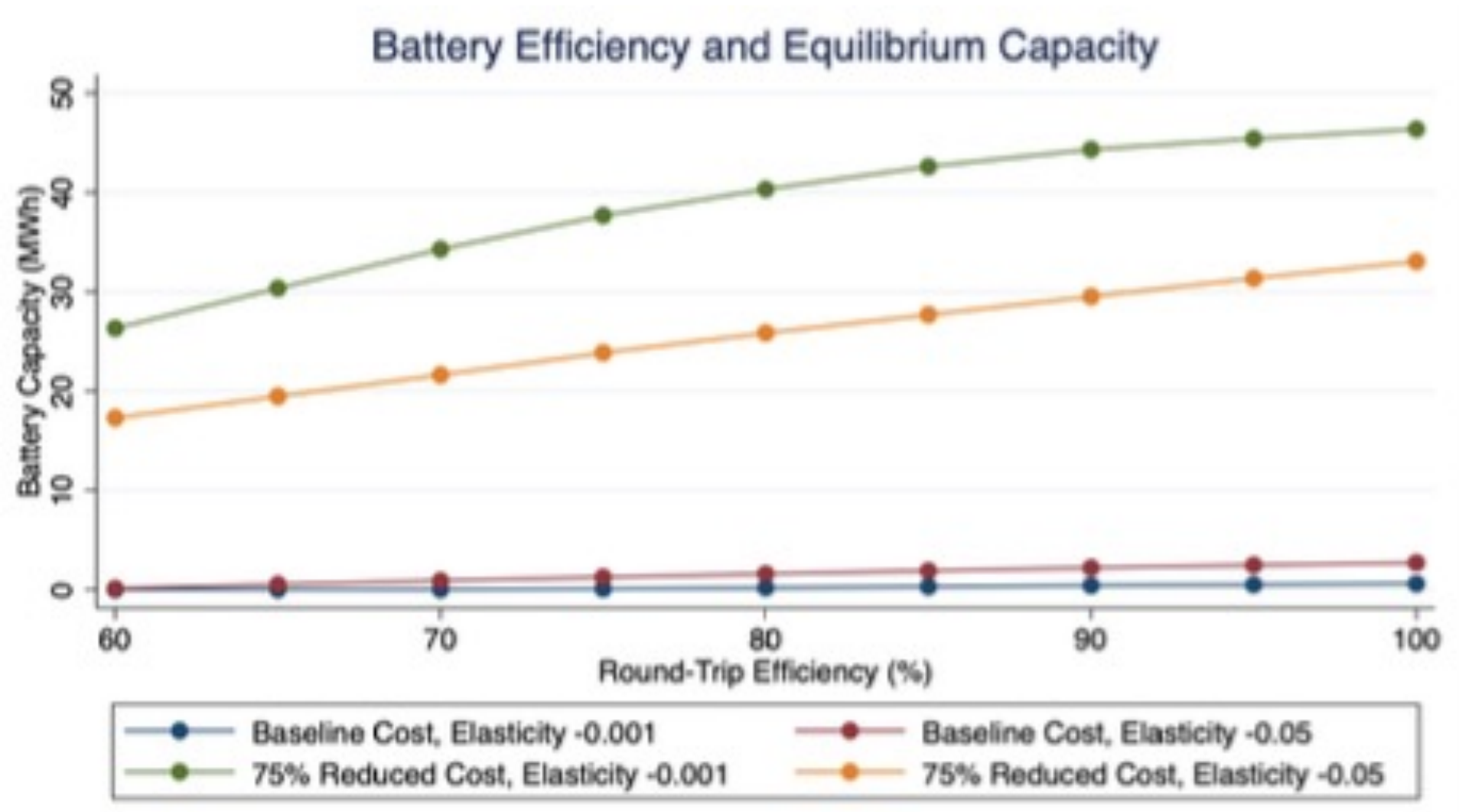
METHODOLOGY

I examine the impact of input parameters on the OSQP solver's battery capacity output. To model imperfect batteries, I test battery round-trip efficiencies between 60% and 100% to reflect estimates in the engineering literature (Arbabzadeh et al. 2017, 10). I also change the elasticity of demand for electricity from -0.15 to a range between -0.15 and -0.001. Third, I test a variety of battery capital costs, ranging from a 0% to 95% reduction from a baseline of $18,934.75/MWh. I run the optimization program for all combinations of these three inputs.

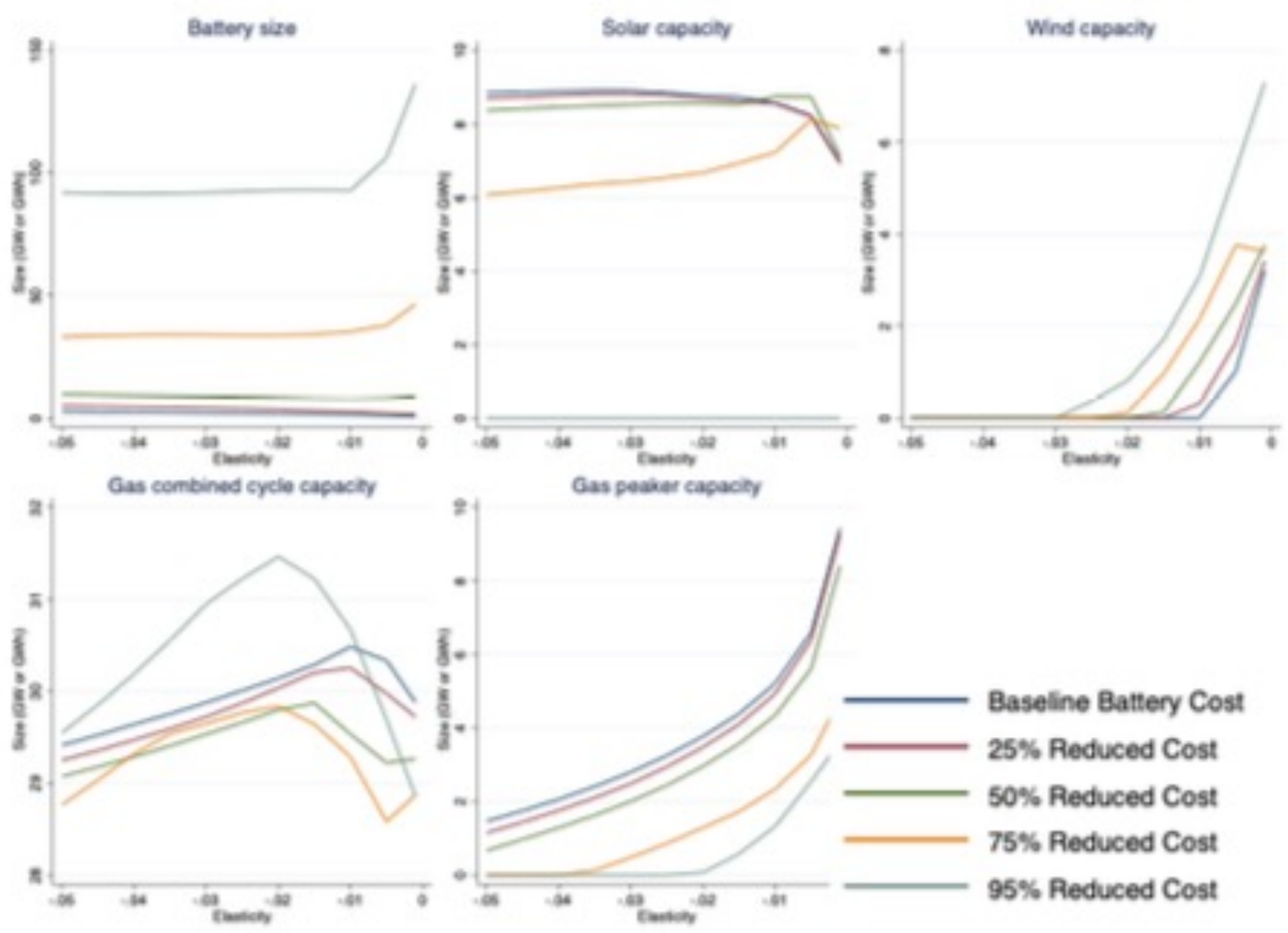
I focus on the Central U.S. region, a region with relatively stable hourly wind and highly variable solar availability.

RESULTS

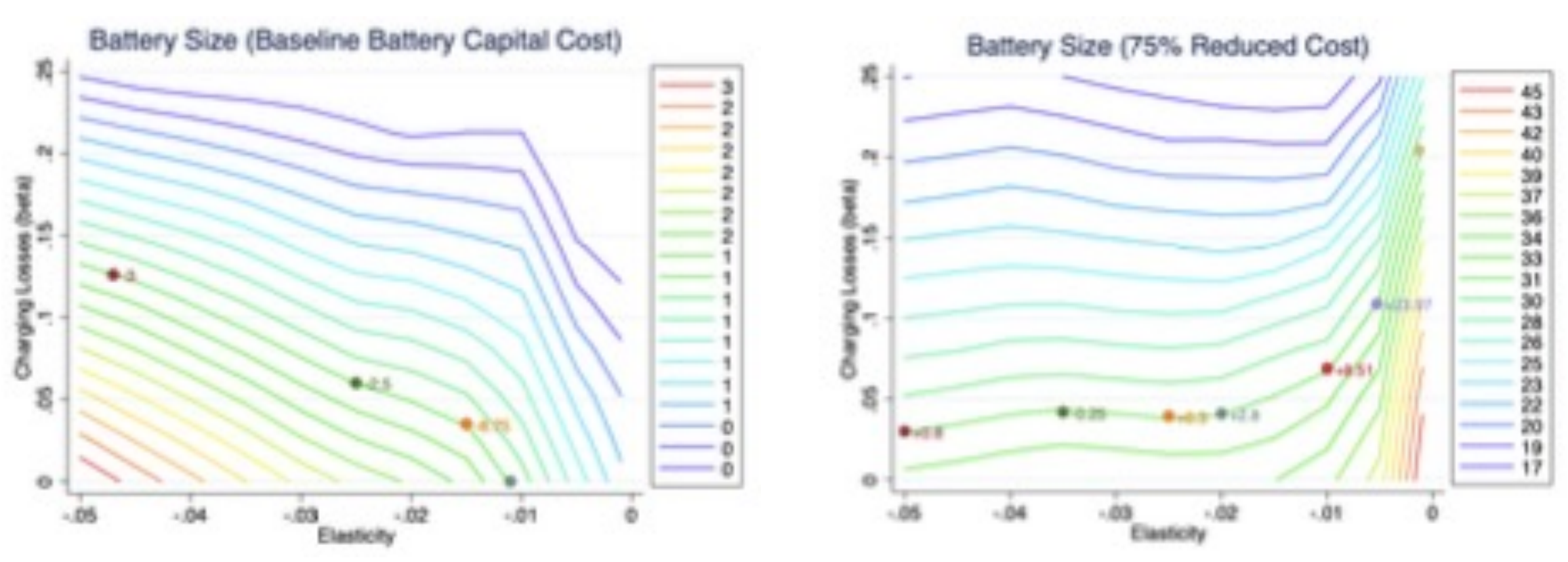
The Role of Round-Trip Efficiency:



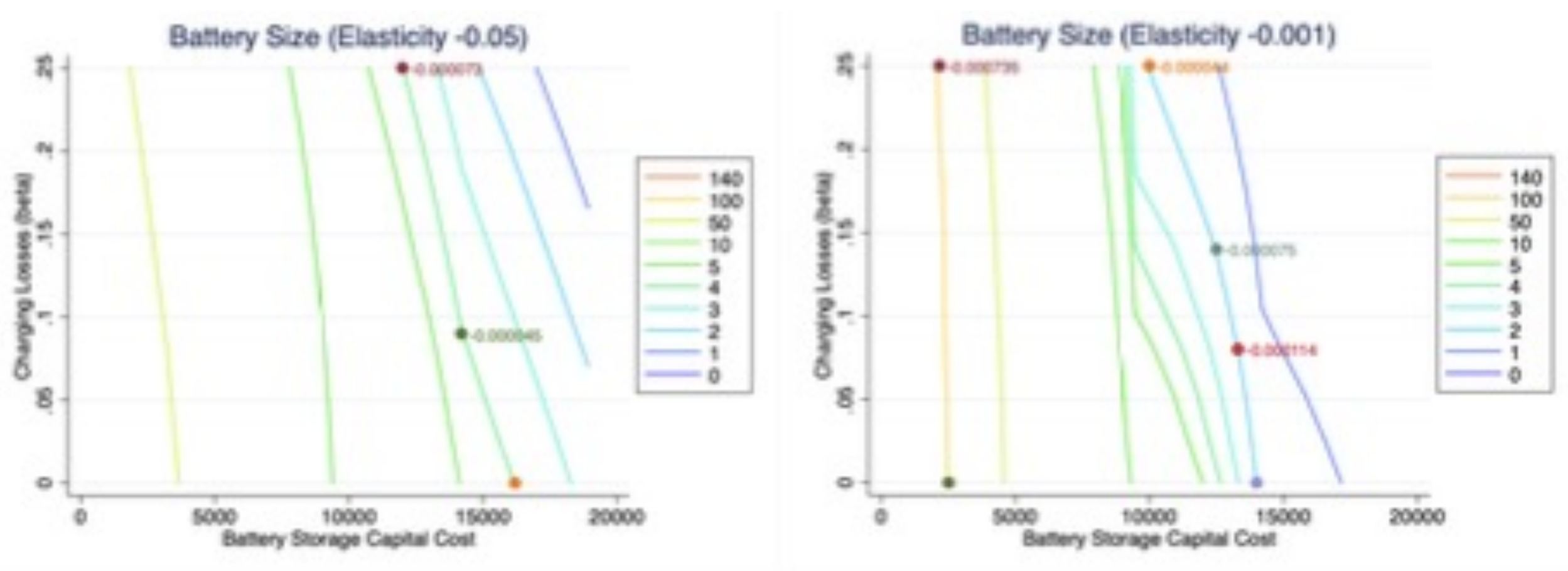
Inputs and Outputs of the Model, Given a 100% Efficient Battery:



Battery Size and the Trade-off Between Beta and Elasticity:



Battery Size and the Trade-off Between Beta and Capital Cost:



DISCUSSION

Overall, I find that both battery capital costs and the elasticity of demand for electricity are crucial determinants of the model's battery capacity output. Surprisingly, battery quality (beta; round-trip efficiency) does not play as large of a role as expected. I quantified my findings on the trade-offs between these three inputs using marginal rates of substitutions as well as arc demands of elasticity.

The energy grid is an essential part of modern life, with residential, commercial, industrial, and virtually all economic activity interacting with electricity in some way. It is important to reiterate that "no single model can perfectly represent all considerations related to renewables and energy storage" (Bistline et al. 2021, 9). For instance, this model assumes a grid that 'starts over' with no "legacy investments" following (Holland, Mansur, and Yates 2022, 1). Additionally, parameters representing the quality of battery storage such as β are not constant in reality, and instead rely on factors such as battery state of charge and temperature (Fonseca et al. 2020).

Despite these limitations, models can still provide important economic and policy implications. There are many directions for future research to take, including adding other technological battery parameters, extending analysis beyond the Central U.S. region, and including the Social Cost of Carbon explicitly in the objective function's costs. As renewable but variable energy sources like solar and wind power play a larger role in electricity generation, battery storage can help smooth this transition by storing electricity from high-supply hours for use in high-demand hours.

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(Note: These references reflect sources explicitly cited in the poster. Full bibliography included in paper).

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