



Cost minimization of generation, storage, and new loads, comparing costs with and without externalities



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HIGHLIGHTS

- The study models a large regional transmission organization, with various amounts of renewable energy.
- The cost of 86 million iterations of energy systems is calculated, with and without externalities.
- When including externalities, society should implement 50% renewable energy.

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ABSTRACT

The goal of this research is to understand the economics of anticipated large-scale changes in the electric system. 86 million different combinations of renewable generation (wind and solar), natural gas, and three storage types (hydrogen storage, electric vehicles equipped with vehicle-to-grid (V2G) technology, and building heat) are modeled within the PJM Interconnection. The corresponding electric systems are then operated and constrained to meet the load every hour over four years. The total cost of each energy system is calculated, both with and without externalities, to find the least cost energy systems.

Using today's costs of conventional and renewable electricity and without adding any externalities, the cost-minimum system includes no renewable generation, but does include EVs. When externalities are included, however, the most cost-effective system covers 50% of the electric load with renewable energy and runs reliably without need for either new conventional generation or purpose-built storage.

The three novel energy policy implications of this research are: (1) using today's cost of renewable electricity and estimates of externalities, it is cost effective to implement 240 GW of renewable electricity to meet 50% of the total electric load; (2) there is limited need to construct new natural gas power plants, especially from a system-wide perspective; and (3) existing coal plants may still be useful to the energy system, and instead of being retired, should be repurposed to occasionally provide generation.

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1. Introduction

Large reductions in CO₂ emissions may require shifting from fossil fuels to electric power for light vehicles and building heat, while also generating increasing fractions of electricity from fluctuating renewable sources. Previous papers have investigated the plausibility and benefits of large-scale renewable energy penetration. Jacobson and Delucchi [1] investigated the possibility of powering the entire world's energy demand by wind, water and solar

power and concluded that, although significant investments would be required, it is plausible for wind, water, and solar to power the world's energy demand, given resource capacity and physical and material constraints.

Focusing on the U.S. electric system, Arent et al. investigated the feasibility of large-scale renewable, finding that there are substantial benefits (without calculating the costs) of reaching 80% renewable [2]. Likewise, Mai et al. calculate a pathway to 80% renewable by 2050, finding a 30% increased cost compared to current generation cost (not including externalities) [3]. Another model, SWITCH, has been used to study how the US Western generation mix would change with carbon pricing [4], also finding 80% reduction in carbon emissions by 2050. Finally, a recent study [5] compares new wind and solar generation, and hypothesizes a future

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Nomenclature

Cap _{MW/MWh}	capital cost per MW/MWh	CG	conventional generation
EH	electric heat	EL	electric load
ES	energy storage	ESRB	energy storage range buffer
EV	electric vehicle	FOM	fixed operation & maintenance cost
Gen _k	average annual generation for generation type k	GHG	greenhouse gas
GIS	geographic information system	H	health externality cost
H ₂	hydrogen storage	HL	heat load
HP	heat pump	HS	heat storage
ICE	internal combustion engine	ITC	investment tax credit
LCOE	levelized cost of energy	LMP	local marginal prices
METSTAT	meteorological-statistical model	MW _k	installed power capacity for generation type k
MWh _k	installed storage capacity for generation type k	NGH	natural gas heaters
O&M	operation and maintenance	PTC	production tax credit
PUC	public utility commission	PV	photovoltaic
r	discount rate	RG	renewable generation
RHTS	resistive heating with thermal storage	RPS	renewable portfolio standard
RREEOM	regional renewable electricity optimization model	RTO	regional transmission organization
SCC	social cost of carbon	SoC	state-of-charge
SOFC	solid oxide fuel cell	V2G	vehicle-to-grid
VOM	variable operation & maintenance cost	WRF	wind research & forecasting model

national electricity market, continent-wide transmission, and balancing over a national grid, finding a 80% renewable national grid in 2030 will cost the same as average electricity costs in 2012. Two previous studies based on the model used in this analysis [6,7] compared fixed proportions of renewables via one price metric, and found that a significant percentage of hours could be covered with renewable energy, and that, at expected future costs, more than 90% of hours could be covered by renewable energy at a cost lower than current prices.

Rather than fixing the target fraction of renewable energy, this study models a large U.S. electric system (now 165 GW generation, with 85 GW_a average load), iterating to create 85,766,121 possible variants of generation, storage and new loads, then running each through 4 years of hourly operation. Building on previous literature, the costs and benefits of each of these possible energy systems are evaluated to find those that minimize the net present cost to society. An innovative aspect of this approach is that the optimal fraction of renewable energy generation is therefore an outcome, not a constraint.

For perspective, the cost minimization calculations in this article are not a reflection of current decision-making. In the United States, decisions regarding electricity systems are reviewed and approved by state public utility commissions (PUCs), which minimize only the market cost of electricity, ignoring the health and environmental external costs. Outside the PUC evaluation, other state or Federal agencies use regulatory mechanisms to reduce pollution. The model here provides a common metric to compare the minimization of only internal costs versus the minimization of all costs to society. The model does not project future population nor continuing declines in the cost of renewable generation. Rather than predicting a least-cost future, one can think of this analysis as answering the question: “If policies had been minimizing social cost, what would the energy system look like today?” Or, looking forward, the results could be a guide to the energy system if external costs are incorporated into the price of fuels.

This article models four types of new generation—land-based wind, offshore wind, solar photovoltaics (PV), and natural gas. The model also includes two new types of load (i.e., the conversion of vehicles and building heat to electricity), along with the benefits and costs of such fuel switching; secular load growth is not modeled. For possible new storage, the model includes hydrogen as

purpose-built storage and two other forms of inherent end-use storage, vehicle-to-grid (V2G) electric vehicles (EVs), and electric heat storage (EH), with the latter two becoming available only as their associated loads do as well. Because the model includes transportation and heating sectors, most of the calculations consider changes in the societal cost of energy including displacing vehicle and heating fuels, not just electricity (some cost-minima change when both are included). Electricity, transport and building heat represent more than two thirds of carbon emissions in the U.S. [8] and have commercially ready renewable alternatives. The model, based on [6], is constrained to meet electric and heating load each hour. It models a real electric grid, the PJM Interconnection, a large US regional transmission organization (RTO), using hourly load, weather, and solar data for years 2010 through 2013.

Compared to previous studies, the work presented in this article contributes to the literature in three novel ways. First, the model integrates electricity, storage, transportation and heating systems. In contrast, previous models only focused on the electricity system, and often ignored EVs and EH, with even fewer including V2G and heat storage. Secondly, this study models over 86 million different combinations of energy systems, compared to previous studies that reported the characteristics of one to several energy systems, allowing for comparisons across different types of energy systems. The iterative nature of the model can more precisely estimate the marginal cost of increasing renewable share of electric load and, at the same time, capture the various technological pathways of reaching a certain percentage of renewable. Lastly, this work is unique to analyze the costs of each energy system both with and without externalities and to explore the differences in the cost-minimum systems and their renewable penetration. In sum, this research analyzes a currently-existing market, adds new types of load, storage and generation, and compares cost-optima with and without externality costs. The methods are described in the Methodology and in the [Supplemental Section](#).

2. Methodology

This study utilizes and modifies the Regional Renewable Electricity Economic Optimization Model (RREEOM), developed by Budischak et al. [6]. The [Supplemental Section](#) describes the

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