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Perspectives

The hidden economic benefits of large-scale renewable energy deployment: Integrating heat, electricity and vehicle systems

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A R T I C L E I N F O

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A B S T R A C T

The transition to large-scale renewable energy in order to mitigate climate change is necessity. Much academic literature has begun to focus on the technical and economic plausibility of such a transition to renewable energy, but these studies often explore one to several potential energy systems and their costs and benefits as compared to the existing system. This paper summarizes the policy implications of a recent analysis that builds on the literature of the integration of renewable electricity, electric vehicles and electric heat by modeling and testing nearly 86 million different combinations of wind, solar, natural gas, vehicle-to-grid capable electric vehicles, and electric heat. After each system was modeled for four years of operation to ensure reliability, the costs of energy systems were then calculated both with and without externalities to better understand how this cost affects implementation. We present the results and policy implications of our analysis across the 86 million energy systems and conclude with the role of social science in future research.

1. Introduction

Large reductions of carbon dioxide to mitigate climate change will likely require shifting completely from conventional fossil fuels to renewable sources in the electricity, transportation, and heat sectors. In many parts of the world, this shift would substantially and drastically change the characteristics and operation of the regional electricity grid and transportation system. Thus, in order to understand this shift, several studies have investigated the potential development and integration of large-scale renewable energy in these sectors. However, this transition to large-scale renewable energy implicates technical, economic, spatial and temporal aspects that complicates modeling and understanding the operation of large-scale renewable energy systems.

Much of the literature originally explored the technical plausibility and resource availability of a large-scale change to renewable energy sources, generally finding that with sufficient recycling methods there is enough raw material and resources available for a large-scale transition to renewables [1–3]. Building upon this work, several of the next studies researched the technical and economic feasibility of large-scale renewables, often framed looking towards the future [4–7]. Some of these papers focus on a single or several pathways to large-scale renewable energy, while others develop complex models and algorithms to minimize costs or other criteria to find an optimum solution. Generally speaking these studies conclude that large-scale renewable energy systems are cost effective as compared to business-as-usual conventional energy system, though these results are often qualified with assumed future costs and inclusion of social costs. Yet, many of these energy system configurations are often limited in their scale, and often do not include a more comprehensive approach to energy systems, typically modeling only the electricity grid, rarely connecting the system to the transportation and heat sectors.

In this Perspective, we summarize the results of a recent analysis that calculated the costs of various different potential large-scale renewable energy system configurations [8]. Like previous work, we present analysis on the cost-optimized transition to large-scale renewable energy. However, our analysis also builds upon previous work by adding several layers of new analysis. First, we present our cost-optimized findings both with and without externalities, to understand the implications of monetizing externalities. Secondly, we take a more comprehensive approach to modeling and include the electricity and storage, transport, and heating sectors. Thirdly, we not only present the characteristics of the cost optimized system, but we also present results for each of the 86 million simulated energy systems we iteratively modeled. Based on this dataset of 86 million, we can analyze not only the singular cost-optimal large-scale renewable energy systems, but also compare across all potential energy systems. In addition, we conducted several sensitivity analyses to test various model assumptions on future costs, subsidies, discount rate, and dispatch behavior.

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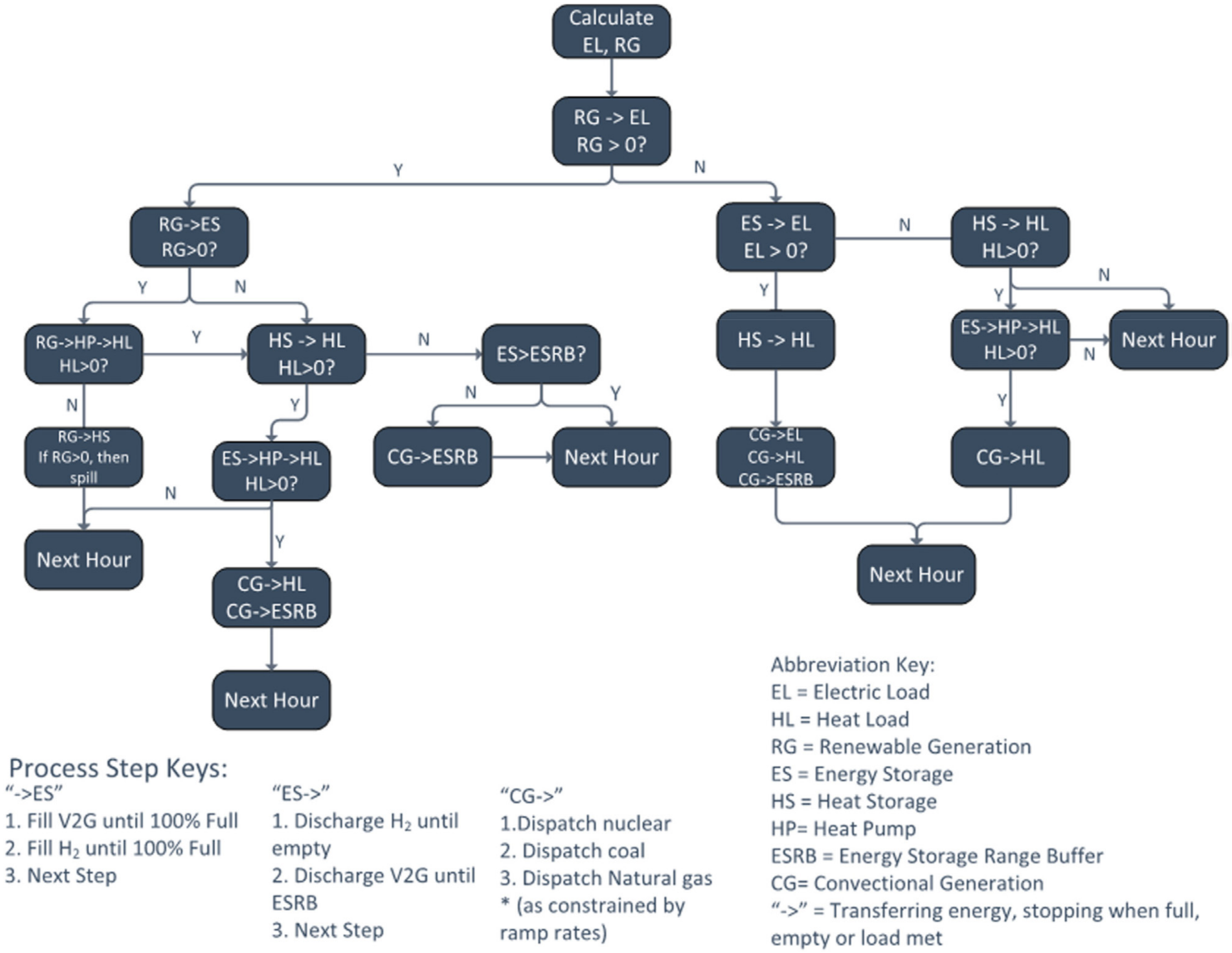

Fig. 1. Flow Chart of the Hourly Operation of the Model's Electricity System with Electric, Transportation and Heat Loads.

2. Summary of research design and methods

We developed an iterative model that steps through 21 increments of possible values for six input variables: solar, land-based wind, offshore wind, vehicle-to-grid (V2G) capable electric vehicles, hydrogen storage (H_2), and electric heat (EH). This creates $21^6 = 85{,}766{,}121$ (86 million) different combinations of renewable electricity, transportation, and heating. We also include the possibility of new natural gas capacity as additional capacity when needed across the 86 million configurations, including energy systems with and without large-scale renewables. Additionally, in a sensitivity analysis we tested our assumptions of building new natural gas only when additional capacity was necessary, instead using new natural before the existing conventional generation capacity and found in all cases this was more expensive, validating the decision to build new natural gas only when new capacity is required for reliability of the grid.

Next, we test the reliability of each of the 86 million energy system configurations by modeling four years of operation in the PJM interconnection, a large transmission system operator (TSO) in the United States, based on various resource assessment and electricity operation data [9–15]. The model determines the reliability of the electricity grid at each hour, as determined by renewable energy production, as constrained by electricity demand, transportation needs, and heating requirements, as summarized by Fig. 1. When renewable energy production and available storage is insufficient at any given hour, then existing conventional generation is dispatched to meet these loads, constrained by installed capacity and ramp rates. If this is not enough, the model then constructs new natural gas to fill in these needs. Conversely, if renewable energy production exceeds the aggregated electric, transportation and heating loads, then excess generation goes into either electric vehicle storage (beyond what is needed for driving needs) or in electric heat storage.

At the end of these simulations, the lifetime costs of each of these energy systems are calculated in net present value over 25 years using today's prices for renewable energy, fuel and operation and maintenance costs, and health and climate externalities, with different cost scenarios to account for the inclusion and exclusion of externalities [16–21]. Thus, there are four cost scenarios, first, only including capital and fuel costs ("Market"), then adding upon these health externalities ("M + H"), then adding both health externalities and a moderate climate externality ("M + H + SCC1"), and finally, adding both a health externality and a realistic worst-case climate externality ("M + H + SCC2"). Disaggregating externalities in the various cost scenarios allows exact comparisons for how the cost of each potential configuration of renewable energy changes when cost assumptions change. Then, for each cost scenario, the least-cost energy system is found and compared to the other potential energy system configurations.

It should be noted that, as with all models of large-scale renewable energy transitions, we make several simplifying assumptions. The model assumes that there is not importing or exporting of energy to other regional electricity grids, excludes the possibil-