GCEP Progress Report

2.11.1 Energy Systems Analysis

Investigators

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Abstract

Energy systems analysis uses the concept of *net energy* in order to appraise developing technologies and assess medium- to long-term energy scenario feasibility. The methodology focuses on meta-analysis and harmonization of studies from the research fields of net energy analysis and life-cycle assessment. A number of projects have been undertaken looking in the past year studying the energetic and material requirements of deploying PV, wind and storage technologies and the interaction of these technologies. Work is also being done on the use of hydrogen as a storage medium.

Introduction

Most economic activities "consume" more energy than they produce. For example, steel production facilities consume energy to produce useful material products. Vehicles consume fuel to provide transport services for people and goods. In contrast, primary energy extraction activities (e.g., oil extraction or deploying wind turbines) supply fuel to society by delivering more energy than they consume. The laws of thermodynamics bound the efficiency of these activities and necessitate a fundamental truth: *you have to "spend" energy to "make" energy*.

Net energy analysis (NEA) combines fundamental energy analysis of a resource or device with evaluation of the wider technological system. Consequently, not all energy resources are created equal. For example, wind resources currently deliver a greater fraction of their energy to society than solar resources, despite being smaller in total magnitude, spatially heterogeneous, and more intermittent in nature.

NEA provides a more fundamental perspective by which to gauge the potential costs and barriers to technology development than purely financial analysis. Nascent technologies have highly uncertain financial cost structures, particularly when considering, for example development of new materials, new production processes, or translating lab-scale prototyping to production at large scale.

Energetic and material requirements are subject to fundamental physical laws, which can provide envelopes by which to assess technological development. For example, there is a minimum amount of energy required to purify silicon for production of PV cells defined by the chemical exergy. This fundamental physical reality provides a benchmark by which to assess the performance of current production processes and what may be realistically achieved through further research and technology development.

Additionally, NEA sheds light on the many paths the energy transition can take and allows quantitative comparisons of their energetic performance. Employing NEA, we can predict material and energetic stumbling blocks various development pathways may face. We can determine whether or not fossil fuels resources are being used effectively when invested into transition projects. We can estimate the rates of growth an energy industry can support while still maintaining an energy ‘profit’ [20].

Results and Progress

A number of projects have been undertaken in the last year. The major findings are outlined below.

Curtailing vs. storing wind- and PV-generated electricity [1]

Rapid deployment of power generation technologies harnessing wind and solar resources continues to reduce the carbon intensity of the power grid. But as these technologies comprise a larger fraction of power supply, their variable nature poses challenges to power grid operation. Today, during times of power oversupply or unfavorable market conditions, power grid operators curtail these resources. Rates of curtailment are expected to increase with increased renewable electricity production. That is unless technologies are implemented that can provide grid flexibility to balance power supply with power demand. Curtailment is an obvious forfeiture of energy and it increases the lifetime cost of electricity from curtailed generators. What are less obvious are the energetic costs for technologies that provide grid flexibility. In this study we employ net energy analysis to compare the energetic cost of wind and solar generation curtailed at various rates to the energetic cost of those generators paired with storage. We find that energetic cost depends on the generation technology, the storage technology, and the rate of curtailment. In some cases it is energetically favorable to store excess electricity. In other cases, it is favorable to curtail these resources. Our goal is to stimulate the identification of new and optimum uses for excess renewable energy and research and development directions for technologies providing grid flexibility.

In this paper we present a theoretical framework to calculate how storage affects the energy return on energy investment (EROI) ratios of wind and solar resources. Our methods identify conditions under which it is more energetically favorable to store energy than it is to simply curtail electricity production. Electrochemically based storage technologies result in much smaller EROI ratios than large-scale geologically based storage technologies like compressed air energy storage (CAES) and pumped hydroelectric storage (PHS). All storage technologies paired with solar photovoltaic (PV) generation yield EROI ratios that are greater than curtailment. Due to their low energy stored on electrical energy invested (ESOIe) ratios, conventional battery technologies reduce the EROI ratios of wind generation below curtailment EROI ratios. To yield a greater net energy return than curtailment, battery storage technologies paired with wind generation need an ESOIe>80. We identify improvements in cycle life as the most feasible way to increase battery ESOIe. Depending upon the battery's embodied energy requirement, an increase of cycle life to 10,000--18,000 (2--20 times present values) is required for pairing with wind (assuming liberal round-trip efficiency [90%] and liberal depth-of-discharge [80%] values). Reducing embodied energy costs, increasing efficiency and increasing depth of discharge will also further improve the energetic performance of batteries. While this paper focuses on only one benefit of energy storage, the value of not curtailing electricity generation during periods of excess production, similar analyses could be used to draw conclusions about other benefits as well.

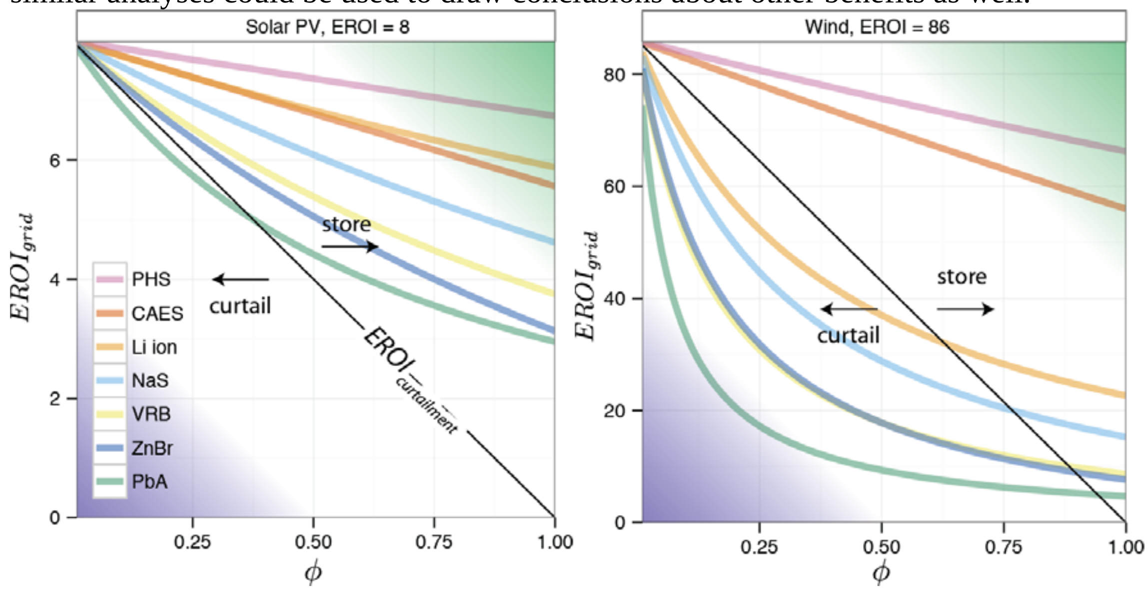

Figure 1: Calculated grid EROI values for PV (left) and wind resources (right) used with storage technologies (colored lines) as a function of the fraction of the resource that is stored or curtailed, phi. The solid black line bisecting the plots indicates the EROI value due to curtailment, spanning a range from original resource EROI to zero. The green region to the right of this line indicates combinations of EROI, ESOIe and phi in which storage yields better energy returns than curtailment. To the left, in blue, storage implementation is more energetically costly than simply curtailing the resource.

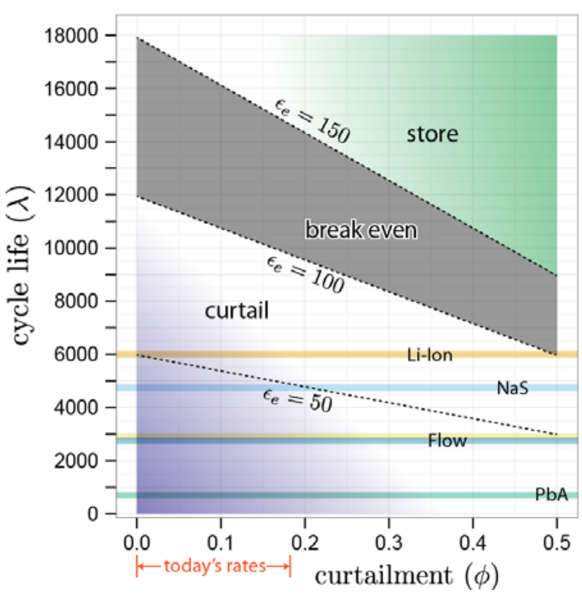

Figure 2 (left): A line plot of minimum cycle life values electrochemical storage technologies must achieve to yield better EROI ratios than curtailment as a function of phi when paired with wind generation (Wind EROI is 86). Dashed lines indicate different embodied electrical energy values per unit storage capacity. Typical values for battery storage range from 100 to 150 kWh/kWh. This plot sets technological benchmarks for promising grid-scale storage technologies to achieve.

Can the wind and PV industries 'afford' storage? [2]

Global wind power and photovoltaic (PV) installed capacities are growing at very high rates (20% per year and 60% per year, respectively). These technologies require large, ‘up-front’ energetic investments. Conceptually, as these industries grow, some proportion of their electrical output is ‘re-invested’ to support manufacture and deployment of new generation capacity. As variable and intermittent, renewable generation capacity increases grid penetration, electrical energy storage will become an ever more important load-balancing technology. These storage technologies are currently expensive and energy intensive to deploy. We explore the impact on net energy production when wind and PV must ‘pay’ the energetic cost of storage deployment. We present the net energy trajectory of these two industries (wind and PV), disaggregated into eight distinct technologies—wind: on-shore and off-shore; PV: single-crystal (sc-), multi-crystalline (mc-), amorphous (a-) and ribbon silicon (Si), cadmium telluride (CdTe), and copper indium gallium (di)selenide (CIGS). The results show that both on-shore and off-shore wind can support the deployment of a very large amount of storage, over 300 hours of geologic storage in the case of on-shore wind. On the other hand, solar PV, which is already energetically expensive compared to wind power, can only ‘afford’ about 24 hours of storage before the industry operates at an energy deficit. The analysis highlights the societal benefits of electricity generation–storage combinations with low energetic costs.

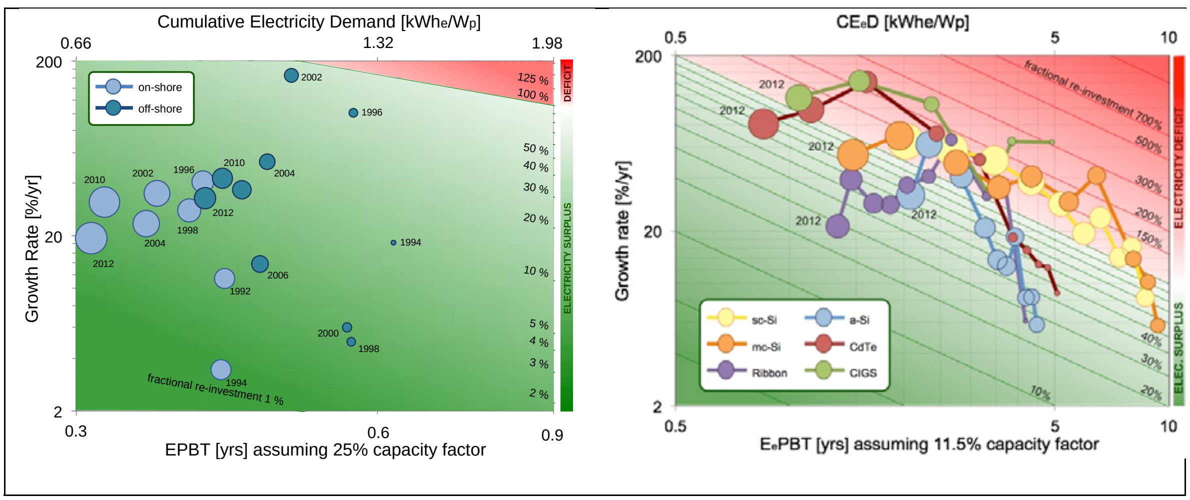

Figure 3. Net energy trajectories for the wind (left) and PV (right) industries. The red region represents a net energy deficit and the green region a net energy surplus. Diagonal sloping lines represent the fractional re-investment, i.e. how much of the gross output from the industry is consumed by the growth of the industry.

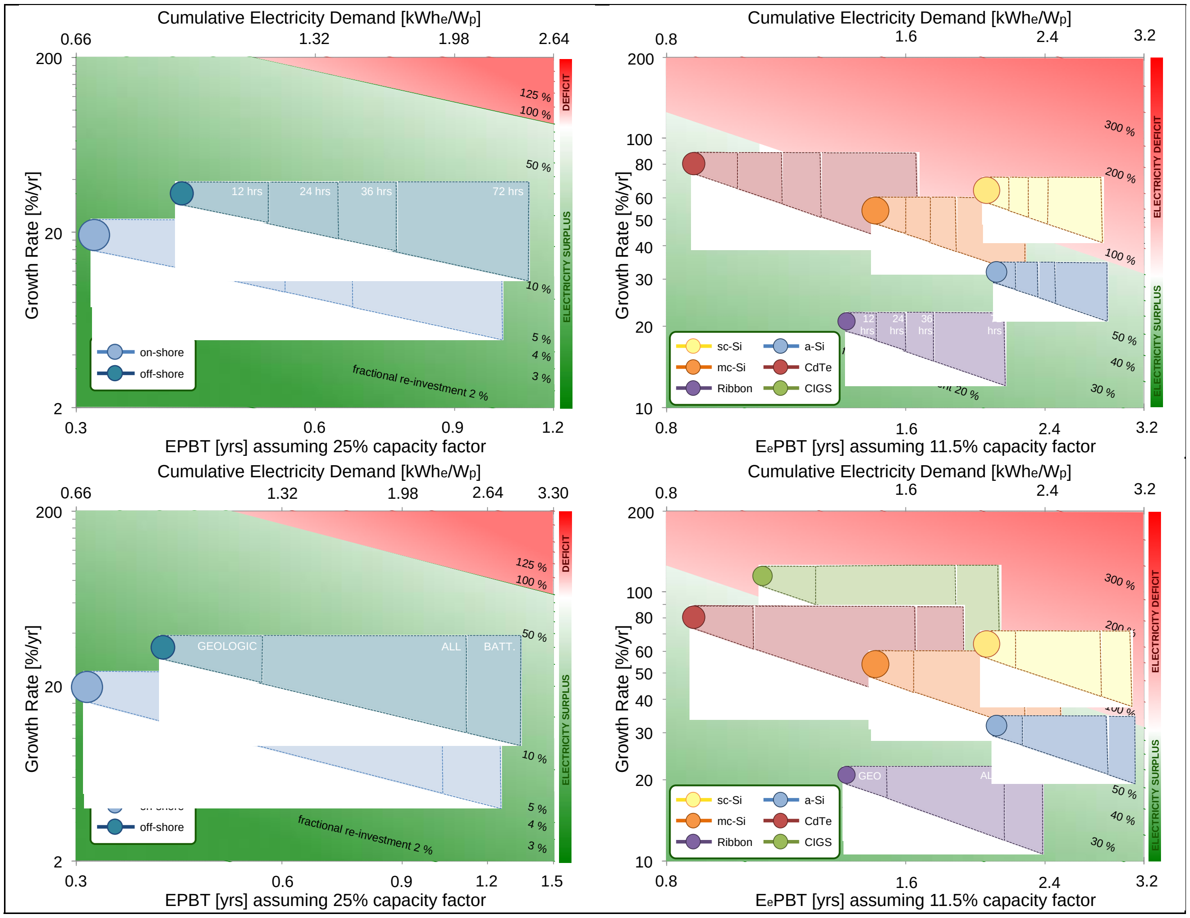

Figure 3. Net energy diagrams for wind (left) and PV (right) technologies with the additional cost of 12, 24, 36 or 72 hours of an equal mix of all storage technologies (top row) or up to 72 hours of storage represented as shaded regions, assuming either only geologic storage (GEO), all storage technologies allocated equally (ALL), or only electrochemical storage technologies (BATT).

Future Plans

1) Why is net energy important?

We have drafted a paper that presents a series of arguments in support of net energy and material flow analysis as a supplement to traditional economic policy and planning tools. We identify three themes that are important to sustainable policy planning: appropriately valuing natural resources; net energy as a driver of economic activity and growth; environmental impacts of energy production and consumption; early technology appraisal; and managing the energy transition. We highlight the important perspective that net energy analysis brings to each of these topics.

2) A techno-economic comparison of regenerative fuel cell performance.

Postdoctoral fellow Matthew Pellow is championing research into regenerative fuel cell life cycle analysis. Energy storage is crucial for incorporating low-emissions, intermittent electricity generation into the power grid. Thoughtful global stewardship requires critical evaluation of different storage technology options using life-cycle assessment approaches such as net energy analysis. We apply net energy analysis to evaluate a regenerative hydrogen fuel cell (RHFC) as an energy storage system. To compare RHFC's to other storage technologies, we use the energy stored on invested (ESOI) ratio: the ratio of energy stored in the device over its lifetime to the energy required to build and operate the device. Our sensitivity analysis shows that the ESOI ratio of a RHFC installation is strongly sensitive to the lifetimes of the electrolyzer and fuel cell stacks (up to lifetimes of 50,000 h and 20,000 h respectively), and also to the ratio of hydrogen storage capacity to the fuel cell power. The ESOI ratio is only weakly sensitive to the efficiencies and embodied energies of the electrolyzer, hydrogen storage system and fuel cell. We first consider a reference scenario with existing technology performance characteristics (alkaline electrolyzer stack lifetime of 100,000 h; PEM fuel cell stack lifetime of 5,000 h). In this scenario, the ESOI ratio of an RHFC is similar to that of the best battery technology (Li-ion, ESOI = 10; as determined by Barnhart and Benson, Energy Env. Sci., 2013, 6, 1083), though still lower than those of pumped hydro (ESOI = 240) and compressed air (ESOI = 210). We then illustrate the opportunities for further technology development to improve the net energy balance of RHFC's. For instance, if the fuel cell stack lifetime can be extended to 50,000 h, and electrolyzer stack lifetime to 150,000 h, the RHFC would achieve an ESOI ratio of almost 80, well above that of any battery technology.

3) The energetic costs and carbon emissions of grid flexibility technologies: comparing natural gas combustion turbines to renewables paired with storage.

As wind and solar driven energy resources occupy a larger fraction of society’s electricity generation mix, the power grid will need increased flexibility. Technological solutions not only need to be affordable, they need to be aligned with the principles of environmental stewardship that guided policy makers to spur the use of renewable energy resources. Quantitative analysis of the life-cycle energetic costs and the carbon emissions of energy resource systems compliment economic analysis by providing insight into energy system interactions with Earth’s systems. Today, spinning reserve, supplemental reserve and backup reserve resources are supplied predominately by hydro-generation (where available) and natural gas electricity generation. Numerous reports show that electrical energy storage can provide these services among others with monetary benefit in today’s markets. Whether or not electrical energy storage can provide these benefits at an energetic benefit to society and with reduced carbon emissions remains an open question. This work will report the life cycle energy costs of several energy storage technologies paired with several sources of electricity and compare them to the energy costs of various natural gas fired electricity generators supplied by gas and oil fields of varying energetic quality. Quantities will be computed using net energy ratios in electrical energy equivalents including energy returned on energy invested (EROI) and energy intensity ratios (energy required to produce a unit of energy, lower numbers are more beneficial to society). Preliminary results suggest that system energy efficiency for wind charged storage is better than natural gas peaker plants which are, in turn, less energetically costly than solar charged storage but with greater carbon emissions. Carbon emissions per MWh of electricity generation depend greatly on the source of electricity charging the storage technologies and the efficiency of the natural gas generators.

Publications and Patents

[1] Barnhart, C. J.; Dale, M.; Brandt, A. R. and Benson, S. M. (2013) The energetic implications of curtailing or storing wind and solar generated electricity, *Energy and Environmental Science*, 6, 2804-2810

[2] Carbajales-Dale, M.; Barnhart, C. J. and Benson, S. M. (2013) Can we afford storage? A dynamic net energy analysis of renewable electricity generation firmed by energy storage, *Energy and Environmental Science*, IN PRESS

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