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Dynamic analysis of hybrid energy systems under flexible operation and variable renewable generation – Part I: Dynamic performance analysis

Humberto E. Garcia*, Amit Mohanty, Wen-Chiao Lin, Robert S. Cherry

Idaho National Laboratory, 2525 N. Fremont Drive, Idaho Falls, ID, USA

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ABSTRACT

Dynamic analysis of HES (hybrid energy systems) under flexible operation and variable renewable generation is considered in this two-part communication to better understand various challenges and opportunities associated with the high variability arising from integrating renewable energy into the power grid. Unique consequences are addressed by devising advanced HES solutions in which multiple forms of energy commodities, such as electricity and chemical products, may be exchanged. Dynamic models of various unit operations are developed and integrated within two different HES options. One HES option, termed traditional, produces electricity only and consists of a primary heat generator, a steam turbine generator, a wind farm, and a battery storage. The other HES option, termed advanced, includes not only the components present in the traditional option but also a chemical plant complex to repurpose excess energy for non-electricity services, such as for the production of chemical goods. In either case, a given HES is connected to the power grid at a point of common coupling and requested to deliver a certain electricity generation profile as dictated by a regional power grid operator based on a predicted demand curve. A dynamic performance analysis of these highly-coupled HES is conducted in this part one of the communication to identify their key dynamical properties and limitations and to prescribe solutions for best managing and mitigating the high variability introduced from incorporating renewable energy into the energy mix.

1. Introduction

1.1. Background

Energy utilization in the U.S., rather than exhibiting a diverse landscape of energy flows that provide energy security by not having any one energy use overly reliant on just one energy source, is instead has rather concentrated source-use pairings [1]. Each major natural energy source is primarily used for one purpose: nuclear and coal for electricity, natural gas for heating (with a modest fraction going to electricity), and petroleum for transportation fuels. Each purpose is likewise dependent on one or only a few sources: transportation on petroleum, heating on natural gas and electricity, and electricity primarily on coal but with significant fractions coming from nuclear and natural gas. Other sources like geothermal, solar, wind, and biomass make only very minor contributions. This constricted architecture may lead into undesired consequences or externalities if any one of these sources is disrupted as happened in the 1970s oil embargoes or with the long-term shutdown of nuclear reactors in Japan and elsewhere after the Fukushima accident. The upsets might also be in the uses of energy, for instance if fuel cell vehicles or plug-in hybrid vehicles running primarily on electricity become predominant in the next 20–40 years. The abandonment of coal for space heating over the last century is another example. The consequences of these types of events can be social, economic, geopolitical, or environmental in nature.

To provide more robustness to the U.S.'s and the world's energy supply network, a more flexible energy flow landscape should be developed that could, for example, to a greater extent use NG (natural gas), biomass, coal, and nuclear energy for the production of transportation fuels. This leads to the definition of a hybrid energy system: multiple energy inputs converted to multiple energy products using interacting complementary conversion processes. Liquid transportation fuels similar to existing petroleum-derived fuels can efficiently be produced from a carbon source and a separate energy source (Table 1).

* Corresponding author. Tel.: +1 208 526 7769; fax: +1 208 526 3677.
E-mail address: humberto.garcia@inl.gov (H.E. Garcia).

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Nomenclature

AEG	auxiliary electricity generation
AG	achievable generation
AGD	average generation deficit
AHG	auxiliary heat generation
CAES	compressed air energy storage
CP	chemical plant
CPC	chemical plant complex
EA	energy accommodation
ESE	energy storage element
GHG	greenhouse gas
HES	hybrid energy system(s)
HTE	heat transfer element
MIMO	multiple input, multiple output
MISO	multiple input, single output
NG	natural gas
ISO	independent system operator
I&C	instrumentation & controls
O&M	operations & maintenance
PCC	point of common coupling
PHG	primary heat generation
PP	power plant
REN	renewable generation
RG	required generation
RP	renewable penetration
RTO	Regional Transmission Organization
SMR	small modular reactor
STG	steam turbine generator
USD	US dollar

By adding non-traditional energy sources, such as renewable generation, and products, such as transportation fuels, energy system hybridization is a promising strategy to achieve energy security through diversification and integration of energy portfolios. In this manner, not only undesirable economic conditions but also environmental concerns can be resolved, as fuel transportation solutions using alternative fuels (e.g., biomass to liquids with carbon capture and storage) often produce less GHG (greenhouse gas) emissions than using conventional fuels. In order to reduce pollution and dependency on oil, a coordinated energy strategy may aim to derive electricity from clean-energy sources (e.g., nuclear and renewable energy) and to produce transportation fuels from regional carbon resources (e.g., NG, coal, and biomass). Higher levels of renewable penetration in the current energy portfolio are consequently a desirable goal as a means of attaining improved resource utilization and environmental sustainability. As a decentralized power generation alternative, often called microgrids, HES (Hybrid energy systems) can utilize available energy resources in an efficient and cost-effective manner, as suggested in Refs. [2,3,4]. Advanced HES configurations discussed in this paper aim to:

- facilitate effective integration of renewable energies;
- promote usage of alternative carbon sources (e.g., NG, biomass, coal) for production of chemical products (such as transportation fuel);
- reduce environmental impact;
- enhance both power (electricity) and energy management, in addition to reliability and security;
- support smooth integration of diverse energy sources and products within existing power and fueling infrastructures.

Given the above drivers, HES that can accommodate high renewable penetration are increasingly receiving substantial consideration. Wind generation has grown tremendously in the last decade and Renewable Portfolio Standards will assure that wind energy continues to be significant. This work emphasizes the dynamic analysis of HES under flexible operation and variable renewable generation, without considering how federal and state policies might affect the manner in which future electric power is generated and controlled in the U.S. Thus, the paper assumes that renewable energy is generated on a must-take basis irrespective of the economics and the logistics of how it is generated, sold, transmitted, bought, and used. Given this must-take assumption, any other energy alternative that may be more profitable, environment friendly (lower life-cycle CO_2 emission), or user-friendly as compared to renewable are not explored in this work.

Table 1
Possible feeds and products of a hybrid energy system.

Energy sources	Carbon sources	Energy products
Nuclear	Natural gas	Electricity
Wind	Coal	Gasoline
Solar thermal	Biomass	Diesel fuel
Solar photovoltaic	CO_2 captured from flue gas	Hydrogen
Geothermal	CO_2 captured from atmosphere	Commodity chemicals such as methanol, ethylene, or ammonia
Combustion or oxidation of carbon (but emits CO_2)		District heat

1.2. State of the art

Neither the concept of combining various sources of energy nor the multiple utilization of energy produced is fundamentally new. Numerous researchers as well as academicians have explored these ideas to various degrees. Usually, the literature available suggests HES to act as energy supplier in three different contexts – first, as a grid-energy supplier; second, as supplier of electricity in off-the-grid locations; and third, as provider for production of energy products (e.g., hydrogen, fresh water, transportation fuel).

There are many examples of HES being proposed to act in a stand-alone manner at off-the-grid locations. In Ref. [5], authors applied total sites targeting, a successful strategy used in process industries to locally integrated energy sectors. This investigation showed that by using methods, such as total sites targeting, renewable can be integrated to energy mix even at a local level. Dali et al. showed HES capacity to operate in grid-connected as well as stand-alone mode under suitable control and energy management [6]. In their experimental work, the HES included wind and PV (photovoltaic) physical emulators, battery energy storage, load and a controlled interconnection to the LV (low voltage) grid. In Ref. [7], the cost-effectiveness of the solar PV system and the solar/hydro schemes for rural electrification, which are considerably different from conventional electric grid, are evaluated and shown to be more reliable and sustainable than the use of a diesel genset. Similarly, hybrid diesel power plants with high-penetration renewable and compressed air energy storage were explored for off-grid rural electrification in Ref. [8]. In Ref. [9], a techno-economic feasibility study of hybrid PV/diesel HES system over diesel gensets in a Malaysian remote area was conducted. The study showed that the fluctuating price and GHG emission of diesel fuel can be countered to great extent by an HES utilizing renewable sources. Similar case-studies were conducted by Reichling et al. for