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Nuclear-renewable hybrid energy systems: Opportunities, interconnections, and needs

Mark F. Ruth [a,*], Owen R. Zinaman [a], Mark Antkowiak [a], Richard D. Boardman [b], Robert S. Cherry [b], Morgan D. Bazilian [c]

[a] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA
[b] Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415, USA
[c] Joint Institute for Strategic Energy Analysis, 15013 Denver West Parkway, Golden, CO 80401, USA

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ABSTRACT

As the U.S. energy system evolves, the amount of electricity from variable-generation sources is likely to increase, which could result in additional times when electricity demand is lower than available production. Thus, purveyors of technologies that traditionally have provided base-load electricity—such as nuclear power plants—can explore new operating procedures to deal with the associated market signals. Concurrently, innovations in nuclear reactor design coupled with sophisticated control systems now allow for more complex apportionment of heat within an integrated system such as one linked to energy-intensive chemical processes.

This paper explores one opportunity – nuclear-renewable hybrid energy systems. These are defined as integrated facilities comprised of nuclear reactors, renewable energy generation, and industrial processes that can simultaneously address the need for grid flexibility, greenhouse gas emission reductions, and optimal use of investment capital. Six aspects of interaction (interconnections) between elements of nuclear-renewable hybrid energy systems are identified: Thermal, electrical, chemical, hydrogen, mechanical, and information. Additionally, system-level aspects affect selection, design, and operation of this hybrid system type. Throughout the paper, gaps and research needs are identified to promote further exploration of the topic.

1. Introduction

The U.S. energy system, like many others, is evolving to better meet environmental constraints and at the same time continuing to provide secure, reliable, and affordable energy services to the economy. In practice, this has led to an increased interest in producing low-carbon electricity in the power sector and utilizing domestically sourced alternatives to imported petroleum in the transportation sector.

To this end, in the electric power industry, significant capacity additions of variable renewable energy systems such as wind and photovoltaic power are likely to continue. These changes, although beneficial in terms of greenhouse gas (GHG) emission reductions and improved fuel diversity, in some cases have led to a need for additional operating reserves and other ancillary services [1]. Continued integration of these variable renewable resources drives the need for flexible generation to accommodate fluctuations in supply and demand. Such load-following flexible facilities typically are used as intermediate or peaking plants (utilized for a relatively small number of hours during times of high net demand[1]). Thus, under the current paradigm, a large amount of capital equipment (and, ultimately, investment capital) is not being utilized near its capacity when demand is lacking. In many cases, the equipment could be out of use during the majority of the year.

At the same time, energy use by industrial processes (e.g., major chemical manufacturing and minerals conversion industries) is large in scale and diverse in the proportions and types of energy services required. Fig. 1 shows a breakdown of energy use by industry for 2004. The breakdown is based on energy used directly by the industry; it does not show primary energy use that would include the efficiency losses in generation of electricity and steam.

* Corresponding author. Tel.: +1 303 384 6874.
E-mail addresses: Mark.Ruth@nrel.gov (M.F. Ruth), Owen.Zinaman@nrel.gov (O.R. Zinaman), markantkowiak@yahoo.com (M. Antkowiak), richard.boardman@inl.gov (R.D. Boardman), robert.cherry@inl.gov (R.S. Cherry), Morgan.Bazilian@jisea.org (M.D. Bazilian).

[1] Net demand, as defined herein, is the output the grid requires from an individual generator to make supply and demand equal in the generator's balancing area (the metered segment of the electric power system in which electrical balance is maintained). High net demand can occur when demand for electricity is high and/or variable production is low. Low net demand can occur when demand is low and/or variable production is high.

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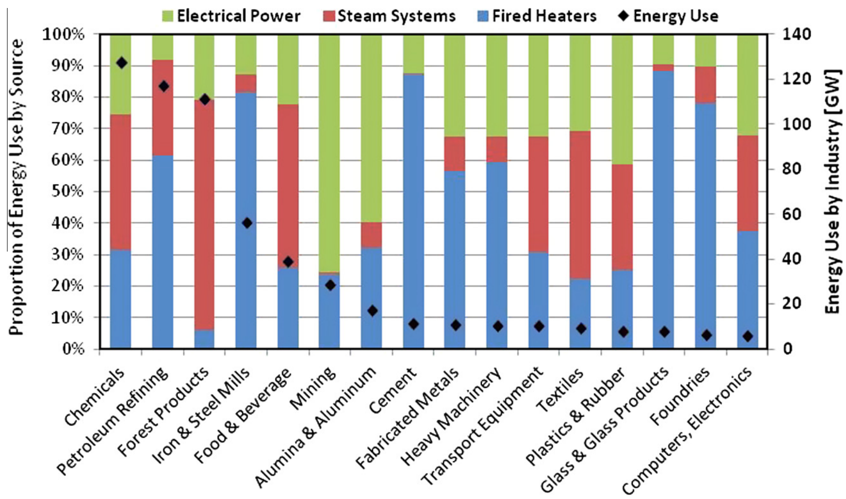

Fig. 1. Energy use by U.S. manufacturing and mining industries for 2004 (Pellegrino et al. [2]).

If primary energy use was shown, energy use by industry values would increase and the percentages for electrical power and steam systems would be higher. Overall, approximately 40% of the energy used in these industries was provided by fossil-fired heaters, 43% by steam systems, and 17% from electrical inputs, though each industry differs [2].

Additionally, changes—including advanced informatics, energy management systems and forecasting—are enabling new innovation in integrated plant design [3,4] and power system operations [5]. These innovations can be utilized to design new types of hybrid energy systems which (a) allow the use of traditionally base-load systems to generate economical load-following power, (b) improve grid flexibility[2] and allow for multiple types of ancillary services, and (c) produce additional commodities such as fuels for the transportation sector.

This paper explores a potential concept for accomplishing these goals—hybrid operation of nuclear reactors coupled with renewable energy technologies and industrial processes in a single facility which has the potential to provide secure, reliable, and affordable, low-carbon energy services. The intent is to define the concept for potential future development and implementation. Interface and system-level issues are explored (including ownership, regulatory, design, construction, and operational issues) to identify gaps and research needs as a way to promote further exploration of the topic. Detailed assessments of specific systems and their potential business cases are beyond the scope of this paper; however, examples from a growing body of literature on this subject are discussed briefly.

2. Hybrid energy systems

The term "hybrid energy system" is used to describe various concepts. As an example, a long history of work exists on small, decentralized hybrid energy systems which utilize multiple generation sources, often with storage, to provide electricity to remote populations. This includes concept proposals (see, e.g., Borges Neto et al. [6]), analyses of technical challenges and opportunities [7], feasibility studies (see, e.g., Nixon et al. [8], Rehman and Al-Hadhrami [9], Zoubeidi et al. [10]), and cost-benefit analyses (see, e.g., Kaldellis et al. [11]). Single energy source centralized generation facilities that provide multiple services (e.g., electricity, heating, cooling, water) also have been referred to as hybrid energy systems, and research has been exploring those concepts from various standpoints [12]. Co-generation (or combined heat and power (CHP)) optimizing both design and output in accordance with technical constraints and market signals [13] also can be termed a hybrid system.

A less extensive body of work exists for larger, hybridized electric generation facilities which use fossil fuels in combination with renewables. Kang et al. [14] developed a generalized computational framework to determine optimal operation procedures of an integrated system consisting of a coal-fired power station, a temperature-swing absorption carbon-capture facility powered by a natural gas combustion turbine, and a wind farm. Kieffer, et al. [15] proposed using the term flex-fuel poly-generation systems for multi-feed, multi-product energy systems. Researchers developed techniques to measure and optimize cost, sustainability, and resilience of such systems. Phadke et al. [16] performed an economic and technical feasibility assessment on a system consisting of a coal gasification combined-cycle power plant equipped with carbon capture, a wind plant, and the option for a fuel production or hydrogen/carbon monoxide gas mixture (referred to as syngas) storage facility. Inclusion of a syngas storage facility or fuel production plant in the integrated system increased utilization of capital and reduced the levelized cost of electricity. Cherry et al. [18] corroborated the results of Phadke in an evaluation of the technical and economic benefits of hybrid systems that integrate chemical and fuels synthesis plants with wind power to help ameliorate wind power intermittency. Work has also been done to assess the feasibility and added utility of a hybrid energy system in which solar-generated steam is injected into fossil power cycles, such as that described by Turchi and Ma [19]. Analysis indicated that a hybridized design of a gas turbine with a concentrated solar power (CSP) system could produce electricity more efficiently and dispatchably than either system could produce alone [20].

Some researchers have extended the definition of hybrid energy systems to include systems with components coupled across the electrical grid. Forsberg [21] explores several integrated system solutions for the larger U.S. energy system, which include combining nuclear, fossil, and renewable energy sources to sustainably create electricity and transportation fuels. Cherry et al. [18] concluded that the amount of excess capacity in the power-generation systems could be cost-competitively converted into chemicals and fuels, thus replacing one-third or more of all foreign oil imports into the United States. Accounting for electrical and thermal energy management, Garcia et al. [22] modeled and predicted the

[2] Grid flexibility is the ability of an electric system's conventional generators to vary output and respond to the variability and uncertainty of the net load [17].