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Dynamic performance analysis of two regional Nuclear Hybrid Energy Systems

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A B S T R A C T

In support of more efficient utilization of clean energy generation sources, including renewable and nuclear options, HES (hybrid energy systems) can be designed and operated as FER (flexible energy resources) to meet both electrical and thermal energy needs in the electric grid and industrial sectors. These conceptual systems could effectively and economically be utilized, for example, to manage the increasing levels of dynamic variability and uncertainty introduced by VER (variable energy resources) such as renewable sources (e.g., wind, solar), distributed energy resources, demand response schemes, and modern energy demands (e.g., electric vehicles) with their ever changing usage patterns. HES typically integrate multiple energy inputs (e.g., nuclear and renewable generation) and multiple energy outputs (e.g., electricity, gasoline, fresh water) using complementary energy conversion processes. This paper reports a dynamic analysis of two realistic HES including a nuclear reactor as the main baseload heat generator and to assess the local (e.g., HES owners) and system (e.g., the electric grid) benefits attainable by their application in scenarios with multiple commodity production and high renewable penetration. It is performed for regional cases – not generic examples – based on available resources, existing infrastructure, and markets within the selected regions. This study also briefly addresses the computational capabilities developed to conduct such analyses.

1. Introduction

1.1. Background

Energy generation and utilization in the U.S. has historically exhibited one to one source use pairings [1]. Each major natural energy source is primarily used for one purpose; e.g., nuclear and coal for electricity, natural gas for heating (with a fraction going to electricity), and petroleum for transportation fuels. This constricted architecture may lead to undesired consequences or externalities if any one of these sources is disrupted. The upsets might also be in the uses of energy, for instance, if fuel cell and electrical vehicles or plug in hybrid vehicles running primarily on electricity become predominant. The consequences of these types of events can be social, economic, geopolitical, or environmental in nature.

Although expected to provide important benefits, it has been largely recognized that increasing renewable penetration and inclusion of time varying loads, such as electric vehicles, poses significant technical and economic challenges in terms of electric grid integration, stability, and modernization [2]. This is due to the unpredictability, non-dispatchability, and high variability associated with renewable energy sources, such as wind and solar power, and the variability in modern loads. Although small levels of renewable penetration and variable loads have tolerable effects on grid operation, high levels may require significant changes in the traditional energy systems topology and grid infrastructure. In general, it may be more cost effective and less complex to attenuate the variability introduced by renewable energy and modern demands via both electrical and thermal means. This variability smoothing may be accomplished by using energy storage devices such as electric batteries and flywheel systems (e.g., [2,3]), or by extending the architecture of traditional energy systems to enable multiple energy commodity exchanges, including dispatchable electricity, other energy storage products, such as hydrogen and chemicals, and basic products, such as fresh water. In addition to

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Acronyms

AHG	auxiliary heat generation
BOP	balance of plant
DME	dimethyl ether
DNI	direct normal irradiance
ESE	energy storage element
FCV	flow control valve
FER	flexible energy resource
FGR	flexible generation resource
FLR	flexible load resource
FOM	figures of merit
FWPP	fresh water production plant
GHG	Greenhouse Gas
GPP	Gasoline Production Plant
HES	Hybrid Energy Systems
ISO	Independent System Operator
LPG	liquefied petroleum gas
MSL	Modelica Standard Library
MTG	methanol-to-gasoline
NG	natural gas
NHES	Nuclear Hybrid Energy Systems
NSSS	Nuclear Steam Supply System
PCV	pressure control valve
PHG	primary heat generation
PV	photovoltaic
PWR	pressurized water reactor
REN	Renewable
RO	reverse osmosis
RTO	Regional Transmission Organization
SMR	small modular reactor
TEC	thermal to electrical conversion
VER	variable energy resource

facilitating the incorporation of high levels of renewable penetration, it is equally important for energy solutions to be economically attractive while minimizing environmental impacts.

In order to increase the robustness, resiliency, adaptability, and flexibility of the U.S. and world energy network towards more effectively responding to resource costs and market drivers or conditions, a more flexible, distributed energy flow landscape and infrastructure is needed to combine various energy generation sources and multiple energy users. This leads to the notion of a HES (hybrid energy systems): multiple energy inputs converted to multiple energy products using complementary energy conversion processes. By adding non-traditional energy sources, such as renewable generation, and non-electricity products, such as transportation fuels, energy system hybridization is a promising strategy to achieve energy security and resilience through diversification and integration of energy portfolios. In this manner, not only undesirable economic conditions but also environmental concerns can be resolved. In order to reduce pollution and dependence on fossil resources and to cost-effectively produce basis products such as fresh water, a coordinated energy strategy may aim to derive electricity from clean energy sources (e.g., nuclear and renewable energy) and to produce basis commodities and transportation fuels from regional carbon resources (e.g., natural gas, coal, and biomass). Higher levels of renewable energy penetration in the current energy portfolio are a desirable goal as a means of attaining improved resource utilization and environmental sustainability. Multiple efforts (e.g., [4–6]) have explored, to various degrees, the idea of closely combining multiple energy sources with diverse energy utilization paths. There are also examples of HES being proposed to act in a stand alone manner at off the grid locations. The selection of the particular NHES (Nuclear Hybrid Energy Systems) configurations studied herein, and the potential locations for their deployment (discussed in Sections 2.1.1 and 2.2.1), were motivated by the efforts and findings reported in Refs. [7], which set the foundation for the current regional studies. SMRs (Small Modular Reactors) are selected for the baseload generation system integrated within the selected NHES configurations due to their anticipated technical and economic advantages, including:

- Scalability;
- Incremental capital investment with phased installation;
- Complementary in energy output with renewable generators;
- Amenable to distributed energy solutions.

While the primary objective of this paper is to investigate the performance characteristics of two selected NHES configurations, the dynamic modeling, control, simulation, and optimization capabilities developed to support such dynamic analysis is also briefly discussed.

1.2. Objective and approach

The goal herein is to evaluate the value proposition of HES that incorporate nuclear and renewable energy. The objective of this study is to analyze NHES that can:

- enable greater penetration of renewable energy in a cost effective manner, while providing energy for commodity production and grid services comparable to traditional electricity generation;
- support smooth integration of diverse energy sources and products within existing power and energy infrastructures, while also reducing GHG (greenhouse gas) emissions;
- change the manufacture and delivery of trade-able energy commodities (e.g., hydrogen, methanol, and ammonia);
- enhance the use of carbon resources for the production of chemical commodities (e.g., fertilizers and transportation fuel) and consumer products (e.g., textiles, polyethylene, and plastics);
- promote conversion of non-consumable resources, such as brackish, salty, and waste water, to essential commodities, such as fresh water;
- provide an approach to produce and deliver energy that is constrained by local markets, geography, water availability, and transportation/delivery systems;
- improve the thermodynamic efficiency and work productivity through coordinated dynamic control of energy conversion systems;
- enhance both power and energy quality and management, in addition to improving reliability, security, and value optimization;
- provide sustainable energy security.

1.3. Proposed methodology

In order to effectively design, evaluate, operate, and optimize multi-domain energy system solutions, innovative physical and