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Original article

An option for the integration of solar photovoltaics into small nuclear power plant with thermal energy storage

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ABSTRACT

This paper is concerned with a concept for integration of solar photovoltaics into a small nuclear power plant. The photovoltaic electricity is firstly converted into heat that subsequently is used for nuclear steam superheating. The hybrid plant is equipped with thermal energy storage. The storage technology under evaluation in this study is borrowed by the concentrated solar power plants. When photovoltaic electricity is available, electric heaters heat molten salts. The steam that is generated in a small modular nuclear reactor is heated with hot molten salts in the external superheater. The hybrid plants and its PV section are modelled and simulated with appropriate software tools. As a result of the higher turbine inlet temperature, the hybrid configuration is more efficient than ordinary NPP. The efficiency of the hybrid nuclear plant can be considerably increased up to the effectiveness level of the modern thermal power plants. The additional power generated by the PV-nuclear plant is approaching the capacity of the standalone NPP. The integrated thermal storage acts as indirect and large electricity storage. Regarding round-trip efficiency and installation costs it surpasses compressed air storage and is competitive with the pumped hydro storage in the absence their geographical and environmental constraints.

Introduction

The recent decade has seen unprecedented development of renewable energy, particularly solar and wind energy. Once installed, power plants based on these sources provide electricity without producing any carbon dioxide emissions. Similarly to them, nuclear power plants are also capable of generating clean electricity. As a result, both renewable and nuclear energy can provide significant reduction in the global GHG emissions. The substantial difference between these two technologies is that while solar and the wind power generation is inherently intermittent, nuclear plants preferably producing base load electricity. Balancing fluctuating renewables with nuclear energy is a challenging task for the current and future energy systems. If the mankind wants to confront climate change, then the renewable and nuclear power generation has to be able to co-exist in a given energy system or even in a single hybrid power plant

Hybridization of different energy resources is an approach to compensate the disadvantages of a given system with the other one. As for example, the potential benefits of solar-fossil hybrid steam cycles have already been widely accepted, and several hybrid plants have been constructed [1]. The authors of this paper also provide useful definitions for different hybrid categories as light, medium and strong hybrid synergies. Accordingly, light hybrids only share minimal plant infrastructure and the operation of the different assets does not depend on each other. On the opposite, in strong hybrid plants different energy technologies are physically connected with each other and share all major equipment. Representative strong solar-fossil fuel hybrid is integrated solar combined cycle using exhaust gases of a gas turbine for superheating of the wet steam generated in parabolic through collectors [2].

An exemplary light hybrid concept for integration of nuclear and the wind power in a single virtual power plant is presented in [3]. It relies on the implementation of small modular reactors. This new generation reactor technology can ensure flexible operation by taking one or more reactors off-line over a period of days, or by enhanced power maneuverability for adjusting reactor power over a period of minutes or hours. The research concludes that the combination of 1000 MW off-shore wind farm with 700 MW nuclear plant consisting of several 100 MW modules creates virtual base load power plant. All generators share common capacity high voltage transmission line.

Such of nuclear/renewables hybrids relies on the flexibility of the nuclear island. There are two approaches for involving nuclear

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Nomenclature

AC	alternative current
CSP	concentrated solar power
DC	direct current
GHG	greenhouses gases
I	current
EPR	European pressurised reactor
P	DC Power
PV	photovoltaic
R	resistance
RPV	reactor pressure vessels
SAM	System Advisor Model (software)
SMR	small modular reactor
TES	thermal energy storage
V	voltage

power plants into cycling or load following operation differentiating USA from Europe. This type of operation is largely avoided in USA. One of the reasons is that the current fleet of nuclear reactors is not designed for flexible operation [4]. The second reason is that the flexible operation of nuclear power plants limits their profitability. Nuclear plants need to operate as base load units at full output levels in order to recover their high investment costs. On the contrary, in Europe and especially in France, load following operation is well-established practice [5]. In addition, all new nuclear reactor designs incorporate some degree of flexibility. French EPR reactor, for example, is designed to be able to change its output from 25% to 100% in less than 30 min [6].

Several other studies investigated different aspects of the combination of renewables and nuclear energy. However, most of them are dealing with a task to increase nuclear power plant flexibility. One innovative concept envisages integration of high-temperature thermal storage into large nuclear power plant equipped with prospective gas cooled reactor [7]. The storage system is similar to those in concentrated solar plants and uses molten salts. During the periods of low demand, part of the generated thermal energy is placed into storage for later use. Under this configuration, the authors expect that the reactor can work at nearly constant output while the whole plant can cycle its power generation daily in response to the variability of the solar and wind generation.

A similar approach but implemented at a larger scale is presented in Ref. [8]. According to it, nuclear plants operate at full capacity varying only steam flow to turbines to match electricity demand with generation (renewables and nuclear). Excess steam at times of low electricity prices or low electricity demand goes to hybrid fuel production and thermal storage systems. As this system is intended to cover seasonal mismatches between power generation and consumption, it must have huge thermal storage. The author proposes a geothermal heat storage system. It would use the nuclear reactor heat when electricity consumption is low to heat a cube of rock. This cube has to be approximately 400 m on a side, and it is put underground to create an artificial geothermal heat source. Very similar concept but with miscellaneous application of the stored nuclear heat in different industrial processes is proposed in [9]. Most of the employed reactors design and thermal energy storage media within the studies mentioned above are at very early stages of development.

Solar photovoltaic has seen explosive growth in the recent years. According to European Photovoltaic Industry Association 2015 report, the world's cumulative installed PV capacity reached 178 GW by the end of 2014 while being only 23 GW in 2009 [10]. This growth is driven by many factors like technological progress, economy of scale and different form of subsidies. Some researchers, however, are not optimistic about the future fast and unsubsidized deployment of this sustainable energy source. Their conclusions are based on accurate and detailed economic analysis [11]. The author of this study aims to quantify the real market value of the photovoltaic electricity. He takes into account all complications associated with the integration of this intermittent energy source into current electricity grids. The conclusion is that at low penetration rates (<2–5%) photovoltaic electricity's market value is higher than the average electricity price. However, with increasing penetration it rapidly declines – its relative price decreases by 3.3–5.5 percentage points per percentage point market share. Similar analysis and results are presented in [12]. The author concludes that any additional solar generation inflicts progressive displacement of flexible fossil-fired generation. As a result, the higher solar penetration leads to lower energy value for incremental solar additions without storage, whether CSP or solar PV. However, CSP with thermal storage can continue to shift energy to the highest value hours.

Hybridization of PV systems with other energy sources has been extensively considered in the literature. Hongxing et al. [13] have developed optimal design model for designing hybrid solar PV/wind systems employing battery banks. Similarly to them Ekren et al. [14] have studied size optimization of PV/wind hybrid energy conversion system with battery storage by applying a refined optimization algorithm. Saheb-Koussa et al. [15] have designed more complex hybrid PV/wind system by adding to it diesel generation to provide uninterrupted electricity supply in remote energy system. Kalantar et al. [16] have studied the dynamic behavior of hybrid solar PV/wind plant including small gas turbine instead of diesel generator and battery storage. Nosrat et al. have investigated hybridization of solar PV system with combined heat and power generation unit [17]. This small-scale hybrid plant has an ability to produce electricity, heating, and cooling. Breyer has focused his studies on the economics of the large hybrid PV-fossil fuels power plants like PV-coal and PV-natural gas plants. [18]. Likewise all previous researchers Breyer has studied light hybrids. According to his comprehension, every PV-fossil fuel hybrid consists of co-operating power generation units. The co-ordination of their operation takes place by utilization of advanced power electronics systems. It well known that the lights hybrids allow minimal cost savings. That is because the co-operating units can share only the cost for construction of new transmission infrastructure.

In conclusion, the open literature survey identifies a significant shortage of strong hybrid power plant concepts integrating solar PV with nuclear power generation. By sharing a large set of major equipment such of hybridization, can achieve significant costs reduction.

This study aims at conceptualising innovative, strong hybrid plant consisting of solar photovoltaics and small nuclear reactor. Such of plant can contribute to the sustainability of the future power generation. The primary purpose is to assess its feasibility for short term practical implementation and to analyse its efficiency at the design point. Another novel point should be the integration of thermal energy storage as a vital part of the proposed hybrid system. Such of approach might be able to provide cost efficient grid-scale storage of PV electricity. The next section conceptually builds up appropriate plant structure. Section 'Hybrid