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Integrating photovoltaics into energy systems by using a run-off-river power plant with pondage to smooth energy exchange with the power gird

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HIGHLIGHTS

- A novel MINLP model was developed for PV-ROR hybrid optimization & optimization.
- A ROR power plant with pondage eases integration of PV sources to the grid.
- The PV-ROR smooths energy exchange with power grid and increases RES share.
- Appropriate operation of ROR increases PV based energy source reliability.

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ABSTRACT

In order to slow climate change, economies need to quickly move away from finite energy sources and towards using low-carbon energy systems. However, the integration of non-dispatchable wind and solar sources comes with additional costs and can make the energy market unusual and unpredictable. Specifically, the presence of variable renewable energy sources makes it harder to accurately forecast energy demand. This paper is a first step in presenting a novel approach to overcoming the inherent variability of photovoltaics (PV) by combining them with a run-off-river (ROR) power plant. A mixed integer mathematical model has been developed and applied to simulate the operation of a PV–ROR hybrid energy source coupled with the national power system. Simulations demonstrate various configurations of parameters and their impact on the objective function which was to maximize the volume of energy from PV and hydropower used to cover energy demand, while ensuring that neither energy deficits nor energy surpluses exceed 5% of energy demand. Our analysis indicates that an ROR power plant with relatively small pondage is capable of subsidizing the varying energy output of the PV system. Besides conducting a simulation and optimization, this paper suggests an approach to smoothing the energy exchange with the grid based on fixed volumes of energy which should be delivered during daylight and nighttime hours.

1. Introduction

The world is heading towards a period of changes on a hitherto incomparable scale, most likely including a transition from fossil-based and non-renewable fuels to renewable, sustainable energy [1,2]. Renewability is quite a clear and strict criterion, while, conversely, sustainability is wide in scope, especially in energetics. On the one hand, sustainability requires that all stakeholders be treated fairly, that a reliable energy supply [3] be provided for society, and that reasonable use be made of non-renewable natural resources. On the other hand, renewable energy sources (RES) also have significant potential to decrease emissions and improve air quality [4]. As already mentioned, reliability is a very important criterion in energy systems, being the ability to provide both the required amount of power and the ability to ensure that the power conforms to a certain set of parameters, such as proper frequency and voltage, a safe level of reactive power, and so on [5], in the face of inconstant (but predictable) demand [6]. Additionally, it is impossible to control the abundant primary sources of renewable energy (such as wind, solar radiation, or wave power) [7], while only limited power is available from those which are easily

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Nomenclature

Abbreviations

CV	coefficient of variation
NPS	national power system
PSH	pumped storage hydroelectricity
PV	photovoltaics
ROR	run-off-river power plant
RES	renewable energy source
STD	standard deviation
VRES	variable renewable energy source

Indices

i	index of days ($i = 1, \ldots, N$)
k	index of hours in a day ($j = 1, \ldots, M$)

Parameters

a, b, c,	pondage dimensions [m]
α	pondage inclination [°]
E^{B}	scheduled energy demand covered from the gird [kW h]
E^{D1}	energy demand [kW h]
E^{D2}	modified energy demand [kW h]
E^{Def}	unscheduled energy demand covered from the grid [kW h]
E^{H}	actual water turbine energy generation [kW h]
E^{Pot}	energy which can be potentially obtained from water turbine [kW h]
E^{PV}	energy yield from PV installation [kW h]
E^{PV_D}	energy from PV installation used to cover demand [kW h]
E^{S}	energy surplus from PV installation
g	gravitational acceleration [m/s^2]
G^{STC}	irradiance in standard testing conditions [kW/m^2]
h^{I}	basic head of the ROR [m]
h^{II}	additional ROR head resulting from fluctuating water level in pondage [m]
H	irradiation [kW h/m^2]
H^{CS}	irradiation if the sky was clear [kW h/m^2]
Q^{Max}	designed water turbine flow throughput [m^3/s]
Q^{R}	observed flow rate [m^3/s]
Q^{Tur}	flow used by water turbine [m^3/s]
V	pondage energy storing capacity [kW h]
β	energy demand multiplayer [–]
η^{PV}	overall efficiency of the PV system [%]
η^{Tur}	overall efficiency of the water turbine [%]
ρ	water density [kg/m^3]

Variables

δ	coefficient – demand covered from the NPS during day [–]
γ	coefficient – demand covered from the NPS during night [–]
P^{PV}	installed capacity in PV [kW]

manageable, though not absolutely constant (water, biomass, geothermal sources, tidal energy). All of these factors combine to create a problem which is both theoretically and practically complex.

Because the most abundant [8] and widely-usable RES generate significantly variable power, connecting too many such energy sources to the grid may make it difficult to maintain proper energy quality, and this cannot be ignored [9]. So far, energy systems have been simple to maintain and organize because the power generation of conventional energy sources is easily controlled and predictable, and energy demand is also predictable. The problem of adapting to a system in which there are floating levels not only of demand, but also of energy generation, is very complex, especially assuming that power quality must be maintained. The problem is multi-faceted, with ecological, economical and production engineering aspects in particular. A rapid transition from traditional energetics to an RES-based power system is therefore practically impossible, so the current scientific literature focuses on easing the integration of RES into the power system.

Smoothing the energy demand curve (e.g. demand-side management [10]) is difficult; demand varies not only within a single day, but also on a weekly and annual basis. The most commonly proposed way to modify the demand curve is by applying smart grids with modern controllers which automatically initiate certain household activities when energy demand decreases (e.g. switching on laundry machines or dishwashers overnight). Although it may seem simple, the efficient use of smart grid networks requires significant investment, both on the provider and the customer side, making it a difficult solution to apply in practice.

Since the potential to smooth the demand curve is extremely limited, power generation must be made more predictable and controllable. However, international and state strategies which often involve increasing the amount of power generated by RES only make power generation less stable. These RESs include non-dispatchable sources of electricity whose power generation may be limited by having potentially to be shut down when the grid cannot accommodate increased power generation. This leads to the conclusion that RES needs be integrated into the grid in such a way as to provide stable energy generation.

There are a handful of solutions that might limit fluctuations in power generation. The first, energy storage, is already widespread.

Typically, pumped-storage hydroelectricity (PSH) facilities [11] are used, and these can easily absorb surpluses of power by storing unneeded energy when demand drops below supply and then releasing it when demand peaks. Unfortunately, this is not perfectly efficient and there is also the not-insignificant inertia of the turbine, which delays the release of energy, so during start-up PSH does not provide the required power immediately.

A faster response is provided by systems based on various types of rechargeable batteries, and other energy storage technologies have also been developed. These include: compressed air (gas is released and propels a wind turbine when an energy deficit occurs); hydrogen generation (hydrolysis is performed during power surpluses); and large-dimension flywheels. One specific kind of energy storage is vehicle-to-grid systems [12,13], which use the capacity potential of electric vehicle batteries. A recent paper [14] investigated this concept from the perspective of a local smart grid (a household equipped with a photovoltaic (PV) system and tenants using an electric vehicle). The results indicate that the control strategy which was developed can significantly reduce the cost of energy used to charge the electric vehicle. What is more, the increasing popularity of electric vehicles and the environmental cost of their batteries raises questions about their optimal management. This issue has been investigated in [15], where the authors indicate that vehicle-to-grid use may deteriorate car battery life and, consequently, its economic viability. It is important to note here that the problem of charging and discharging various batteries is analysed extensively in the literature where, for example,