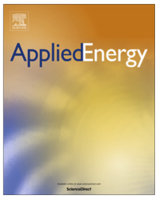
Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



Seasonal aspects of the energy-water nexus: The case of a run-of-the-river hydropower plant

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HIGHLIGHTS

- Seasonality patterns are a key aspect of the energy-water nexus.
- Changes in streamflow seasonality slightly affect future revenue.
- Changes in price seasonality may significantly affect the losses of revenue.
- Price seasonality brings about more uncertainty on revenue than climate change.

ARTICLE INFO

Article history:
Received 1 December 2016
Received in revised form 21 January 2017
Accepted 1 February 2017
Available online xxxx

Keywords:
Nexus
Climate change
Seasonality
Uncertainty
Run-of-the-river hydropower
Alps

ABSTRACT

The energy-water nexus presents important implications at seasonal scale. For instance, electricity prices and streamflow have complex seasonal patterns and changes in both may adversely impact hydropower plant revenue. In order to quantify the effect of changes in price and water seasonality on future revenue distribution and its related uncertainty, we consider the case of a run-of-the-river plant. To this end, we integrate a hydrologic model, a hydropower model, two glacier inventories, six climate scenarios and five electricity price seasonal scenarios. Our results show that the impact of climate change on streamflow of the considered run-of-the-river plant will decrease the revenue by 20% in a business-as-usual price scenario. This decrease is mostly driven by a reduction of the annual streamflow due to glacier shrinkage rather than by the evolution of seasonality. From this perspective, the difference between the various climate scenarios is low. In contrast, change in electricity price seasonality induces a marked uncertainty in revenue. According to our scenarios, which assume no change in the mean annual electricity price, a change in price seasonality may indeed exacerbate or mitigate the impact of climate by 50 or 33% respectively, compared to the business-as-usual scenario. Our analysis highlights the need for considering intra-annual dynamics when investigating the energy-water nexus.

1. Introduction

Water, energy and food are the most important elements supporting life, sustainable development and modern civilization [1]. Also, water and energy are intimately interconnected [2–4] and strategic in Europe [5]. Energy production may consume or divert water. Water availability and temperature may represent a stringent constraint in electricity generation [6–8]. In contrast, water supplying, treatment, and distribution require energy [9]. For instance, desalinisation is energy consuming. This interconnection is known as “energy-water nexus” [10].

Investigating water and energy as interconnected is fundamental for sustainable development and provides strategic information for decision makers, institutions, and economic stakeholders [10,11]. This nexus has been, however, poorly investigated in the literature, as water and energy have been generally studied as independent variables [9,12]. The need for reducing greenhouse gas emissions as well as the observed shortage of water resources due to over-exploitation and climate variability have recently posed the question of investigating the energy-water nexus in view of a more sustainable use of both [13].

An important case of the energy-water nexus is hydropower generation. Water is indeed centrally involved in energy

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http://dx.doi.org/10.1016/j.apenergy.2017.02.003
0306-2619/

Please cite this article in press as: Gaudard L et al. Seasonal aspects of the energy-water nexus: The case of a run-of-the-river hydropower plant. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.02.003

generation by hydropower, which directly depends on the yearly hydrologic budget, including precipitation and snow melt [14]. In addition, investigating the nexus for hydropower is topical since it represents about 15% of the global electricity generation [15], and about 85% of renewable energy [16]. In several countries, it accounts for over 50% of all electricity generation including: Iceland, Brazil, Canada, Nepal and Mozambique [15]. Hydropower represents almost a quarter of the electricity in the western United States [17], and about 10% of the entire electricity consumed in the United States. It supplies over half of the electric energy mix in Austria (62%) and Switzerland (57%) [18]. Importantly, dams used for hydropower are usually multipurpose. As an example, the Hoover dam in California provides about 33% of freshwater used in Los Angeles and originally covered 75% of the necessary energy for the city [14].

Some hydropower plants can accumulate water in a reservoir, i.e., storage hydropower. These plants provide an operational flexibility that can compensate wind variability [19,20] or solar photovoltaic intermittency [21,22]. Storage hydropower may even be an energy-storage technology if the installation includes pumps, which are used to relocate water in an upper reservoir relying on surplus of energy when the demand is low [23]. Energy is thereafter generated when the price is high. This technology represents 99% of the large-scale electricity storage capacity in the world [24,25]. The management of the reservoir is the result of the equilibrium between water availability and energy demand [26]. Nonetheless, this management may represent an issue from an environmental perspective. While runoff affects energy generation, hydropower management influences water streamflow [27,28]. It also perturbs the whole water cycle by increasing the rate of evaporation [29]. In fact, hydropower has a water footprint [30,31].

The second main type of hydropower is the run-of-the-river scheme. One may generally find it in flat areas where the installation takes advantage of water volume rather than of the head of water [32]. It may represent an environmentally friendly option, since it does not significantly interfere with the river's flow [33]. But environmental impacts of hydropower substantially depend on local characteristics [34]. Run-of-the-river plants usually have no water reservoir, or a small one compared to annual streamflow. They generate base-load electricity, which varies with streamflow seasonality.

Recently, attention has been posed on the quantification of the impacts of climate change on hydropower [35], including an increase in temperature or a change in the spatial and temporal patterns of liquid and solid precipitation [36,37]. In mountain areas, precipitation and temperature may combine and result in a shift in the onset of snow melt [38] and a progressive decrease in peak snow accumulation [39,40]. Hydropower impacts are filtered by hydrological impacts and result in a decrease or increase in generation basing on local conditions [35]. Moreover, several hydropower plants worldwide are built downstream glaciers, which are, however, shrinking [36]. Glacier shrinkage may provide room to build new installations in areas currently covered by glaciers [41,42]. It also temporally provides increased meltwater through the so-called peak water [43,44], but this effect will progressively disappear in the future, thus resulting in a net loss of yearly water volume [38,44] and in associated impacts on ecosystems. Also, climate change may alter the seasonality of streamflow in snow- or ice-dominated catchments. Thus, climate change may hamper existing regulations and represent a reason for vulnerability of future hydropower [35,43].

This paper discusses the seasonal aspects of the energy-water nexus in the context of hydropower production and under a changing climate. In particular, we aim at showing how the correlation between water availability and electricity prices may affect revenue. This issue, sometimes neglected, is important because seasonality often triggers problems in the energy-water nexus, such as water stress or energy scarcity. When water availability is low compared to the demand, conflict of usage may occur. But it is not necessarily during dry years that the stress is high. In general, some specific seasons of the year face lack of water. The same issue occurs with the flood season [45], which generally takes place when precipitation is high during a short period. A larger amount of water during a short period may be in fact spilled rather than profitable [46]. It may occur even in a year with lower precipitation than the normal. The point is that climate change tends to exacerbate some of these issues and highlights the need for considering seasonality in the energy-water nexus debate.

In addition, many drivers may affect the future seasonality of electricity prices as well. First, the demand may increase in summer and decrease in winter because of global warming [47]. Second, the operational flexibility may increase thanks to the interconnection [48–50], demand-side management and smart grid [51–53], backup technology such gas turbine, or storage energy [54]. This is important because any increase in flexibility tends to smooth the price volatility and seasonality. Finally, the electricity price is determined by the supply too. With the increasing use of photovoltaic energy, summer electricity generation may significantly increase and this would decrease summer prices [55].

The originality of our paper resides in considering the evolution of both water and energy seasonality. There are plenty of investigations that independently consider the impact of climate change on either water seasonality or energy demand [56], but Madani et al. [57] argue the need for investigating them together. Some papers filled the gap considering catchment dominated by storage-hydropower plants [56–59]. These plants are rather robust to climate variability due to the possibility of adapting their storage management strategy [18,59]. Similarly, they may accommodate the possible variability in the seasonality of streamflow. Conversely, we consider a run-of-the-river power plant. To our knowledge, there has been little attention on the impact of climate change on this type of hydropower plants [60]. These are directly affected by climate change impacts on streamflow in terms of both quantity and seasonality because they do not have any regulation capacity. Therefore, such case studies bring more insights than storage-hydropower to understand the impacts of seasonality in the energy-water nexus. Contrary to already quoted research [56–59], we also consider that seasonality is not only affected by climate change. We therefore built five electricity price seasonality scenarios. This is another originality of the paper, which allows further understanding of the issue.

To perform our investigations, we integrate hydrological and hydropower models with electricity prices, for a specific run-of-the-river power plant. We opt for investigating a specific aspect and case study of the complex nexus, which is complementary to comprehensive approaches [61]. We consider two glacier inventories in order to account for the uncertainty linked to ice volume. We also use six climate scenarios to simulate future streamflow. Last but not least, we carry out a sensitivity analysis of the results to five specific scenarios of electricity prices rather than using some long-term electricity price seasonality projections, which are highly uncertain. The outcome is quantified in terms of energy generation and revenue. This is an intuitive and integrative way to understand the impacts of changing seasonality.

In Section 2, we describe the case study, the hydrological model, the future climate scenarios, the future price scenarios, and the method for the calculation of hydropower generation and revenue. In Section 3, we report the results in terms of seasonality of streamflow and electricity prices and we comment on the relevance of the results with respect the existing literature. Section 4

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