Investigation of climate change impacts on hydropower generation: the case of a run-of-river small hydropower plant in North Western Greece

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\textbf{Abstract.} Services and uses arising from surface water’s availability, such as hydropower production, are bound to be affected by climate change. The object of the research is to evaluate climate change impacts on energy generation produced by run-of-river small hydropower plants with the use of future river discharges derived from two up-to-date Regional Climate Models. For doing so, the hydropower simulation model HEC-ResSim, calibrated and validated over real power data, was used to simulate the generated energy in the two future periods of 2031-2060 and 2071-2100. The future river discharges in the case study area are derived from the hydrological model E-HYPE that uses as forcing the climatic variables of the CSC-REMO2009-MPI-ESM-LR and KNMI-RACMO22E-EC-EARTH climate models under two Representative Concentration Pathways, namely RCP4.5 and RCP8.5. The research outputs demonstrate a decrease of the generated energy varying from 2.86\% to 25.79\% in comparison to the reference period of 1971-2000. However, in most of the simulated scenarios the decrease is less than 10.0\%, while increased energy production is projected for one of the scenarios. Overall, it can be concluded that the case study run-of-river small hydropower plant will be marginally affected by climate change when the decrease of the relevant river discharges is up to 10-15\%.

1. Introduction

Renewable energy sources can have a crucial role in providing clean energy services and contributing to climate change mitigation, by replacing the traditional fossil fuel energy production sources responsible for Green House Gas (GHG) emissions. The importance of renewable energy is attributed to all future climate change scenarios. The more optimistic scenarios, i.e. slight impacts due to climate change, are related with large scale penetration of renewables in the energetic grid, while the worst case scenarios, i.e. severe impacts due to climate change, are connected with minor transition to sustainable energy technologies. Following the current worldwide policies on climate change [1], the use of renewables has significantly increased in recent years and according to the statistical office (Eurostat) of the European Union (EU), at EU level the share of gross final energy consumption from
renewable sources reached 19.7% in 2019\(^1\). Apart from its role in mitigating climate change, recent studies [2] foster the importance of renewable energy sources to climate change adaptation.

Water is the fuel for hydropower generation and any alterations in the hydrological cycle affecting the surface water availability, such as those derived from climate change [3], will impact the viability of this renewable energy source. The Mediterranean basin is considered a hotspot in terms of climate change projections with models and scenarios of all Intergovernmental Panel on Climate Change (IPCC) Assessment Reports [4] concluding that the basin’s future climate will be governed by monthly net rainfall decrease during winter and potential evapotranspiration increase during summer due to temperature augmentation. Hence, climate change in conjunction with manmade pressures, such as water resources overexploitation, is expected to affect surface fresh waters’ availability.

Hydroelectricity production is a mature and well-established technology, however the derived social and environmental impacts of large-scale hydropower plants having reservoir structures [5] have played a crucial role in the promotion of small-scale hydropower schemes, known as small hydropower plants (SHP) [6]. In most cases, SHPs are “run-of-river” plants, i.e. plants with no dam or water storage structures, with their benefits as one of the most cost-effective and environmentally friendly energy technology, as well as their attributed impacts, to be reviewed by scholars [7]. The importance of coupling legislative frameworks for the co-exploitation of water and energy is also presented in the literature [8]. Although a unique definition of SHP does not exist, most countries consider as SHP those plants having installed capacity of up to 10.0 MW, nevertheless there are several exceptions to this norm, such as in Bulgaria, Greece and Russia, where the max capacity is set to 1.0, 15 and 30 MW respectively. Currently in Europe, the overall installed capacity of SHP is 19,699 MW, with this figure to equal 232 MW in the case of Greece. This capacity comes from 115 SHP stations of around 2.0 MW each, with the World Small Hydropower Development Report of 2019 [9] demonstrating that only 11% of the Greek SHP potential have been developed.

The aim of the research is to evaluate the impact of climate change on an existing run-of-river small hydropower plant. For that purpose, the triggering of a hydropower simulation model with future river discharges derived by a hydrological model fed with climatic variables from two Regional Climate Change Models (RCMs) under two Representative Concentration Pathways (RCPs) is proposed. For assessing the future energy generation variations, the simulation outputs for the future periods are compared with relevant hindcasts. The outputs demonstrate the buffering operational zone of small run-of-river SHPs against river discharge variations and specific conclusions are discussed.

2. Methodology

2.1. Case study SHP and river basin
The SHP under investigation is the Gitani run-of-river small hydropower plant, Table 1, located on the Kalamas River in the Water District of Epirus (EL05) in the North Western part of Greece. Its construction was finalized in 2006 and it was built on the right side of the homonymous irrigation dam. The latter was constructed in 1962 for raising the water level and diverting specific river’s water volumes to two irrigation channels; hence the SHP takes advantage of the upstream and downstream water’s elevation difference, caused by the irrigation dam, to satisfy the required hydraulic head for its operation. The water diversion structures are located few meters upstream from the plant intake canal and redirect 5.25 m\(^3\)/sec during the irrigation period, i.e. from early April until the end of September. Kalamas River’s basin covers an area of 2,523 km\(^2\) and is the largest basin within the Water District of Epirus [10]. The headwaters are located in the mountainous part of the basin (basin’s higher and mean elevation is 2,157 m and 544.0 m respectively) with the river following an east west direction of 115 km long before flowing into the Ionian Sea. The mean historic water discharges close to the river outlet are 65 m\(^3\)/sec [10].

\(^1\) https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20201218-1
Table 1. Characteristics of the Gitani SHP.

| Capacity (MW) per unit | Number of units | Averaged annual produced energy (GWh) | Turbines’ type | Turbines’ max water discharges (m³/s) | Hydraulic head (m) | Dam’s overflow height (m) |
|-----------------------|-----------------|--------------------------------------|----------------|--------------------------------------|--------------------|--------------------------|
| 2.1                   | 2               | 15.2                                 | Kaplan (S-type) | 60                                   | ±7.12               | 13.77                    |

2.2. **Hydropower simulation model**

For the simulation of Gitani’s SHP the Reservoir System Simulation (HEC-ResSim) model developed by the U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center (CEIWR-HEC) [11] was used. The model has routinely been used for the simulation of large- and small-scale reservoirs and reservoir systems at worldwide cases and at various time events [12-15]. The model consists of three main modules, a) the watershed setup where the schematization of the hydrographic network together with the structural elements (e.g. junctions, routing reaches, diversions and dams) are designed, b) the reservoir network definition where the technical and operational characteristics of the dams, the various operational alternatives together with the river discharges at specific nodes are designated, and c) the simulation scenario management module focused on the development of the simulation scenarios under the various operational alternatives [11]. In our case study, the technical, Table 1, and operational characteristics of the SHP were retrieved by the operators of the dam². The model was calibrated and validated for the time periods 2015-2018 and 2019-2020 respectively based on real power production data. Thereafter, the validated version of the hydropower simulation model was fed with river discharges attributing future climate change conditions to assess the energy generation under climate change.

2.3. **Climate change data**

The water discharges of the Kalamas River under current and climate change were derived by the European version of the Hydrological Predictions for the Environment (E-HYPE) semi-distributed basin model [16]. The model simulates river flows by dividing the European territory at 35,408 catchments of mean size of 215 km², with the accuracy of the model validation available in the literature [17]. In this research, the forcing of E-HYPE under climate change comes from two Regional Climate Models (RCMs), Table 2, which have been developed and implemented in the framework of the COordinated Regional climate Downscaling EXperiment for the European domain (Euro-CORDEX) [18], under two Representative Concentration Pathways (RCPs), namely RCP4.5 and RCP8.5 representing a moderate and worst future climate respectively. Both RCMs have been routinely used for hydrological simulations under climate change [19].

Table 2. Synoptic description of utilized Regional Climate Models.

| RCMs          | Parent climate model      | Institute                          | RCP         |
|---------------|---------------------------|------------------------------------|-------------|
| CSC-REMO2009  | MPI-M-MPI-ESM             | MPI - Max Planck Institute, Germany| 4.5 and 8.5 |
| KNMI-RACMO22E | EC-EARTH                  | KNMI - Royal Netherlands Meteorological Institute, Netherlands | 4.5 and 8.5 |

For the validation of the hydrological model behaviour in the case study river, gauged discharge data from 2007 to 2010 were compared with E-HYPE’s historic simulations for the same period. Thereafter, the assessment of the SHPs’ future energy generation was assessed for the future periods 2031-2060 (hereinafter Short Term Future (STF)) and 2071-2100 (hereinafter Long Term Future (LTF)) by comparing them with the hindcast simulation of 1971-2000 (hereinafter Reference Period (REF)).

² https://www.ppcr.gr/en/hydroelectric/gitani-igoumenitsa
3. Results and discussion

3.1. HEC-ResSim model calibration and validation
The hydropower model’s calibration was conducted for the period 2015-2018 and its validation for the period 2019-2020. In both cases gauged discharges just upstream of the dam were used as input and the outputs of the simulations were compared to real power production data. The output of the calibration procedure, as depicted in Figure 1, demonstrated a high degree of correlation between simulated and observed power production (Pearson correlation coefficient (PCC) = 0.917, Nash–Sutcliffe efficiency coefficient (NSE) = 0.798 and coefficient of determination \( R^2 \) = 0.841). Similar performance results, Figure 1, were also observed for the validation period (PCC = 0.916, NSE = 0.794 and \( R^2 \) = 0.839).

![Figure 1](image1)

Figure 1. Hydropower simulation model’s calibration and validation outputs based on real power production data of the period 2015-2020.

3.2. River’s discharges under climate change conditions
Prior to the assessment of the future river discharges, which were derived from the hydrological model under climate change, a comparison between the Kalamas River gauged discharges and E-HYPE’s historical simulated discharges was conducted for the period 2007-2010, where common temporal data was available from both sources. The outputs, Figure 2, demonstrate the ability of the specific model to accurately simulate the specific river basin (PCC = 0.922, NSE = 0.829 and \( R^2 \) = 0.851).

![Figure 2](image2)

Figure 2. Simulated versus observed discharges of the Kalamas River for the period 2007-2010.

In terms of river discharges under climate change, a complete synopsis of the mean discharges per climatic model and scenario and their differences with the REF period (expressed both in m$^3$/sec and...
percentages) is given in Table 3. Apart from the CSC-REMO2009 model under the RCP4.5 for the STF period (2031-2060) where a small increase of 5.94% is presented in comparison with the relevant reference period, decreased future river discharges are estimated for all other cases. The larger decreases of 30.11% and 13.41% are observed for the LTF period (2071-2100) under RCP8.5 for the CSC-REMO2009 and KNMI-RACMO22E models, respectively. Reduced discharges of approximately 9.0% are also presented for both models under the RCP4.5 scenario and LTF period.

Table 3. Kalamas River future discharges under different simulation periods for the utilised RCMs and RCPs.

| Regional Climate Model | Simulation period | Representative Concentration Pathway | Mean discharges (m³/sec) | Difference with REF (m³/sec) | % Difference with REF |
|------------------------|-------------------|--------------------------------------|--------------------------|----------------------------|----------------------|
| CSC-REMO2009           | REF               | -                                    | 25.84                    | 0                          | 0                    |
|                        | STF               | RCP4.5                               | 27.37                    | 1.53                       | 5.94                 |
|                        | LTF               | RCP4.5                               | 23.72                    | -2.11                      | -8.18                |
|                        | STF               | RCP8.5                               | 22.53                    | -3.31                      | -12.80               |
|                        | LTF               | RCP8.5                               | 18.06                    | -7.78                      | -30.11               |
| KNMI-RACMO22E          | REF               | -                                    | 26.59                    | 0                          | 0                    |
|                        | STF               | RCP4.5                               | 24.92                    | -1.67                      | -6.27                |
|                        | LTF               | RCP4.5                               | 24.05                    | -2.53                      | -9.53                |
|                        | STF               | RCP8.5                               | 26.54                    | -0.04                      | -0.17                |
|                        | LTF               | RCP8.5                               | 23.02                    | -3.57                      | -13.41               |

3.3. Future power generation
The SHP simulation for the reference period demonstrated that the generated energy is 9.91 GWh and 9.94 GWh for the CSC-REMO2009 and KNMI-RACMO22E climate models respectively, Figure 3. The largest amount of generated power equals 10.23 GWh and is observed for the RCM CSC-REMO2009 under the scenario RCP4.5 and under the STF period. This figure is in compliance with the analysis conducted for the future discharges of the Kalamas River, Table 3, since this is the only simulation scenario where increased river discharges were observed in comparison to the REF period. The lowest amount of produced energy is 7.35 GWh which is also presented for the CSC-REMO2009 regional climate model but under the scenario RCP8.5 and under the LTF period (2071-2100). In case of the KNMI-RACMO22E model, the smaller power generation of 9.19 GWh is projected for the STF period for both RCM4.5 and RCM8.5.

Figure 3. Interannual generated energy (in GWh) per climate change model and RCP and per simulation period.
By expressing the future energy generation in percentage differences to the relevant REF periods of each climate model, Table 4, in the case of the climate model CSC-REMO2009 declines of 25.79% and 16.70% of produced energy is foreseen for the climatic scenario RCP8.5 under the LTF and STF periods, respectively. On the other hand, the simulation outputs for the KNMI-RACMO22E regional climate model demonstrate a moderate energy decrease of approximately 7.50% for the STF period for both RCPs. The same model presents negligible diminutions of less than 3% for the LTF period regardless of the climatic scenario.

**Table 4. SHP’s future energy generation under different simulation periods and their differences with the reference period for the utilised RCMs and RCPs.**

| Regional Climate Model | Simulation period | Representative Concentration Pathway | Mean produced energy (GWh) | Difference with REF (GWh) | % Difference with REF |
|------------------------|-------------------|--------------------------------------|-----------------------------|--------------------------|----------------------|
| CSC-REMO2009           | REF               | -                                    | 9.91                        | 0                        | 0                    |
|                        | STF               | RCP4.5                               | 10.23                       | 0.32                     | 3.28                 |
|                        | LTF               | RCP4.5                               | 8.99                        | -0.92                    | -9.25                |
|                        | STF               | RCP8.5                               | 8.25                        | -1.66                    | -16.70               |
|                        | LTF               | RCP8.5                               | 7.35                        | -2.56                    | -25.79               |
| KNMI-RACMO22E          | REF               | -                                    | 9.94                        | 0                        | 0                    |
|                        | STF               | RCP4.5                               | 9.19                        | -0.75                    | -7.57                |
|                        | LTF               | RCP4.5                               | 9.67                        | -0.28                    | -2.86                |
|                        | STF               | RCP8.5                               | 9.19                        | -0.75                    | -7.55                |
|                        | LTF               | RCP8.5                               | 9.66                        | -0.28                    | -2.84                |

The research concludes that the future hydroelectricity generation of the run-of-river small hydropower plant under investigation is going to be affected by climate change; nevertheless, no severe impacts are projected. The outputs are in conjunction with the findings of [20] where at the global level, the overall impact of climate change on existing hydropower generation may be expected to be small, or even slightly positive. In our case study, the CSC-REMO2009 climate model demonstrates important decreased river discharges up to 30.11% only for the worst-case scenario, i.e. RCP8.5 and for the simulation period 2071-2100. In all other cases the decline does not exceed 12.8%, while there is a specific simulation scenario where increased river discharges are foreseen. The “translation” of river discharges to energy generation with the use of the HEC-ResSim hydropower simulation model demonstrates a decrease of 25.79% for the same worst-case scenario, while the maximum decrease in all other simulated scenarios is up to 16.70%. In the case of the KNMI-RACMO22E model, the projected energy decrease does not exceed 7.57% for all the scenarios. It should be mentioned, that in the latter climate model, although the higher reduction of river discharges is presented for the RCP8.5 under the LTF period, i.e. 13.41%, the larger energy generation loss is presented for the RCP4.5 and the STF period. This issue has to do with the timing of water inflows during the year and the projected changes in flow during low-flow periods under climate change, an argument that is also suggested by other scholars [21]. To sum up, the correlation of the future river discharges (Table 3) and future generated hydroelectricity (Table 4) in the case study area illustrates that discharge decrease of ~15% will cause relevant energy declines up to ~10% with the larger impacts to be evident for the RCP8.5 climatic scenario.

**4. Conclusions**

Hydropower production depends on the available water volumes. Climate change projections demonstrate an increased stress on the surface water resources in terms of availability, duration of low and high water levels, and timing of seasonal peaks especially at the end of the 21st century, hence direct impacts in the sector of hydroelectricity are implied. The research following a methodology of coupling future river discharges attributed to specific climatic scenarios with hydropower simulation models illustrates that run-of-river SHPs are also going to be impacted by the climatic variations.
Nevertheless, based on the outputs of the investigated case study, the research suggests that run-off-river SHPs have the ability to generate energy even in cases of declined river discharges and concludes on the slight impacts on power generation under specific water level variations.

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