THE IMPACTS OF CLIMATE CHANGE ON ENERGY-WATER SYSTEMS AND ECONOMIC ANALYSIS

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ABSTRACT

In order to develop a valued decision-support system for climate alteration policy and planning, recognizing the regionally-specific features of the climate change, energy-water nexus, and the history of the current and possible future climate, water and energy supply systems is necessary. This paper presents an integrated climate change, water/energy modeling platform which allows tailored climate alteration and water-energy assessments. This modelling platform is established and described in details based on particular regional circumstances. The modeling platform involves linking three different models, including the climate change model from Coupled Model Intercomparison Project Phase 5 under the most severe scenario (Representative Concentration Pathways, Water Evaluation and Planning system and the Long-Range Energy Alternatives Planning system). This is to understand the impacts of climate variability (changes in temperature and precipitation) on water and electricity consumption in Zayandeh Rud River Basin (Central Iran) for current (1971–2005) and future time period (2006–2040). Climate models have projected that the temperature will increase by 7 °C and precipitation will decrease by 44%, it is also proposed that electricity imports will rise during severe dry scenario in the basin, while power generation will decrease around 8%.

Keywords: Climate change; Integrated modeling; Energy; Water systems; Electricity

INTRODUCTION

About 16% of the world's electricity is produced annually by hydroelectric power plants. Because of low cost greenhouse gases (GHG) emission and high flexibility of hydroelectric power plants exploitation, it is considered as one of the most popular sources of electricity generation (Michie

and Cooper, 2015). Despite its unique features, hydroelectric power generation is considered to be one of the most vulnerable sources of energy production in the face of climate change (Cáceres-Silva, 2000; Li et al., 2018 and Javadinejad^{(12), (14), (15), (16)} et al., 2019). This is due to its direct dependency on the runoff and amount of water level (Vergara et al., 2011). Therefore, due to spatial and temporal changes in runoff as a consequence of climatic changes, generation of hydroelectric power in the current or future plans is uncertain (Cleveland et al., 2017; Yaseen et al., 2020 and Javadinejad⁽¹⁷⁾, 2011). The surveys worldwide indicate that global warming will lead to a water resources crisis in dry regions of the world (DeNooyer et al., 2016). These effects are of particular importance to the Middle Eastern countries, which have already had high water stress condition (Elbatran et al., 2015 and Javadinejad⁽¹⁸⁾ et al., 2018). However, there is a lack in investigation of these important effects in the previous researches; such as Escobar et al., 2011 and Javadinejad^{(1), (2)} et al., 2020 and Abdollahi et al., 2019. Therefore, the main aim of this study is to analyze and discuss these climate change effects on hydroelectric power generation. It is estimated that the annual temperature in the Middle East region will increase by 4.5 °C by the end of the 21st century. Estimates also show that precipitation in the region has been reduced by 25%. These factors can cause substantial challenges in the region. Despite such predictions, unfortunately, efforts to increase adaptability to the consequences of climate change and considering it in the regional planning have not been of high priority in these countries (Javadinejad⁽³⁾ et al., 2020). Urban developments are being proceeded within the historical context, but without considering the consequences of climate change. Zayandeh Rud River Basin in Central Iran (Fig. 1) has a record of extensive hydropower generation historically; however, the question is that in a changing climate, can the basin continue to rely on its hydropower generation capacity (Javadinejad⁽³⁾ et al., 2019). Hydropower supplies 46% of electricity crossways in Iran. This value shows that the basin is highly relied on hydropower energy which also uses clean energy provided. However, because of climate change effects, integration of the water and energy planning in this basin is crucial.

Definitely, hydropower energy production depends on steady source of water flow. However, in the recent years, precipitation has decreased and temperature has increased steadily, in the basin (Sharafati et al., 2020; Mirramazani et al., 2019; Abbas et al., 2020; Al-Ali et al., 2019 and Al-Jaberi et al., 2016). Researchers argue that development programs are particularly at risk in developing countries facing water stress condition. Therefore, considering the potential impacts of climate change on designing dam and power plants which may be vulnerable to climate change is essential. In order to increase preparedness against adverse climate impacts, given the significant

properties of hydroelectric plants, it is necessary to study the consequences of climate change on the production of hydroelectric plants both in developed and developing countries. So far, several studies have been carried out on various aspects of hydroelectric power plant systems at various scales in different parts of the world. Examples include studies of analyzing the amount of hydroelectric power generation (Khalkhali et al., 2018; Maurer et al., 2009 and Javadinejad^{(11), (13)} et al., 2020). A review of these studies shows that in developed countries, more attention has been paid to the effect of climate alteration on hydro-power while there is a lack of studies in developing countries to estimate these effects (Javadinejad et al., 2019). The aim of this paper is to analyze historic climate patterns, future scenarios, and their potential effects on water supplier availability for hydropower production. This paper attempts to discover how energy portfolios can change under different climate scenarios, and discuss the main contemplations in Zayandeh Rud River Basin for water and energy planning in the context of climate alteration.

MATERIALS AND METHODS

Study Area

The upper Zayandeh Rud River basin is a part of the Zagros Mountain (one of the largest mountain chains in Iran) which has high rainfall rate. The elevation of the basin varies between 1000 and 3600 m from average sea level. The basins upstream contain all the main water resources reserves.

Based on the Dumarten climate classification method (based on minimum and maximum temperature) most of the basin is a semi-dry to ultra-dry and only a small part of the upstream area is cooler (Rasul et al., 2016). Precipitation in the basin is influenced by the Mediterranean rainfall systems, which come from the north-west. Significant rainfall occurs in the western mountains and the rainfall decreases from west to east side of the basin. Annual precipitation ranges from 407.64 mm on the upper area of the basin (mostly in the west) to 154.95 mm in the center. The rainfall decreases to 105.42 mm on the Gawkhoni swamp (located downstream of the river). Temperature also changes in different elevation. The annual average temperature varies from 6 °C over the west and northwest mountains to 15 °C on the Gawkhoni swamp. In this study, evaporation is estimated by Class A pan. The maximum evaporation (2800 mm) occurs in the Gawkhoni swamp and the lowest (1450 mm) is at upstream, the western and northern parts. Evapo-transpiration ranges from 1200 to 2800 mm is determined through the Penman–Montieth method (Javadinejad ^{(4), (5)} et al., 2019). The highest relative humidity is 63.3% occurs in winter. However, the lowest is 23.6% in summer. Minimum and maximum annual cloudiness per Octa scale are 1.7 in GawKhoni swamp and 2.5 in upper catchment. The lowest wind speed is in November (6.1 m s^{-1}) and the highest

occurs in March (9.6 m s^{-1}). Fig. 1 shows the location of the study area, the basin includes 17 sub-basins and in each sub-basin, there is a meteorological station as well as hydrometric station (Fig. 1). The main dam (Zayandeh Rud regulatory dam) generates hydropower energy in the basin. The dam is built on Zayandehrud River in Iran, in Isfahan province (Javadinejad ^{(6), (7), (8)} et al., 2019). This dam, which was generating power in 1950, was constructed 110 km west of Isfahan. The maximum volume of the reservoir is 1,470 million m^3 (at 2063 m), as well as the area of the dam lake, which is 54 km^2 . The Zayandehrud River Dam target is annual production of 250 GWh of hydroelectric power, seasonal flood control, water management of 100,000 ha of Isfahan plain and water supply needed by industries in Isfahan Province (Javadinejad ⁽⁹⁾ et al., 2018).

Fig. 1. River basin of the study area

The Electricity System in the Study Area

The demand for electricity in the basin is variable throughout the seasons. For instance, the data indicates the highest energy demands in the summer which is around 15% greater than the annual average rate. In fact, the residential and commercial sectors consume high rates of electricity by using air conditioning facilities (especially in hot summers). In order to generate electricity needed in the basin a combination of different power suppliers is required (hydropower and renewables), as well as a constant thermal power generator. Hydropower energy is generated by a regulatory dam in upstream of the Zayandeh Rud River. The hydropower facilities usually generate 46% of the electricity in the basin during spring and summer, however it generates 10-25% of the electricity in autumn and winter seasons. The thermal generation sector, includes natural gas plant, which generates significant electricity in most years. The renewable part, contains solar and wind powers which can generate only a portion volume of electricity (2 to 3%) (Javadinejad ⁽¹⁰⁾ et al., 2016).

Methods and Tools to Simulate Water-Energy Nexus: Water Evaluation and Planning (WEAP) System and the Long-Range Energy Alternatives Planning (LEAP)

In order to simulate hydropower energy in terms of water energy nexus for future time period, two modelling tools (WEAP and LEAP) have been applied in this study. Previous studies did not use the combination model of water balance model and hydropower energy model under the climate change scenarios of CMIP5 for projection the future hydropower balance and capacity under the climate change effects. So, the current study with the novel multi model of WEAP and LEAP filled the gaps. The LEAP software is developed by the Stockholm Environment Institute (SEI) which is used to assist planners to adapt to the water-energy links in the basin. Actually, WEAP can simulate stream flow and water balance of a basin and LEAP can simulate hydropower energy according to the outflow of river in a basin. Therefore, the output of WEAP model which is outflow of basin can insert to LEAP model as an input data.

WEAP is a strong, water planning tool which allows users to understand freshwater organizational disputes and assigns restrictions to the water suppliers, with integrated resource-demand parameters, ecology and water quality factors. WEAP can generate information on water requirement for various consumptions such as energy users. The data can be extracted from runoff which is based on climate variables such as precipitation and temperature. LEAP is a combined modeling tool that can be applied for analyzing energy policy and climate alteration mitigation calculation. The software has a feasible basis that allows local, regional, and global application to use several modeling methodologies such as accounting, simulation and optimization. In one hand,

LEAP can be used in order to analyze energy utilization, production, and supply abstraction in all parts of the basin, and on the other hand, LEAP can analyze GHG emissions and local air contaminants.

Both WEAP and LEAP have principal restrictions. WEAP does not have information about energy necessities for water action, and LEAP does not have information about water accessibility for hydropower and further energy needs. By combining WEAP and LEAP, a better assessment of hydropower irregularity, water demands for further energy and hydropower, and energy needs can be achieved. So, this integrated tool is applied for Zayandeh Rud River Basin to analyze water-energy characteristics at a regional level in this study. After simulation of water-energy status in the basin, a statistical analysis has been done to estimate how economic parameters are affected by changing climate and hydro-electric power.

Modeling the Study Region

The WEAP-LEAP model contains representative nodes for the natural hydrology, storing, groundwater, hydropower services, and local requirement. The climate data, natural hydrology, storage, water demands and population of the Zayandeh Rud River Basin are modeled in WEAP and calibrated and validated by PEST and they are shown by Fig. 2.

Fig. 2. Observed and simulated of flow in Zayandeh Rud River basin with validation process

The electricity sources are simulated in three key stages: a) estimate electricity creation preferences, b) power transmit regulations, and c) electricity requirement. There are three electricity creation options in the basin: hydropower, renewable (for example wind and solar) electricity creation and thermal power (which depends on natural gas). If electricity generated

cannot meet the energy requirement at the end of a given episode, imported electricity can be applied. Power transmit regulations can control the supplies of electricity generated (which can apply for the service of electricity demand in the model). Hydropower plants which supply large loads, have the maximum priority in electricity creation in the model. The next greatest priorities in the creation belong to thermal and renewable plants which can cover some of the local request in the basin. The residual electricity requirement can be met by imported electricity (this is the lowest priority in electricity creation). Electricity requirements for industrial, residential, water utility sectors and commercial are simulated in the model. All of the requirements are computed with considering population, precipitation, temperature, groundwater depth and water deliveries factors. Electricity requirement is significantly related to the temperature in the basin. Because when the temperature increases, using of air conditioners rises in industrial, commercial and residential sectors. The data to calculate electricity requirements are collected from the Ministry of Power (in Iran). There are major electricity-water interfaces in the model which contain water used in hydropower, water used in thermal cooling and the electricity need for pumping groundwater. Water applied in hydropower is dependent on climate circumstances and reservoirs' storage. Water abstractions in upstream Zayandeh Rud reservoir are lower than in the downstream.

Water used in thermal cooling can cool the thermal power plant in the basin. Water temperature can affect plant technology and surface water abstraction. However, low flow conditions lead to lower energy generation. The minor plants in the basin require further water supplies to generate electricity. The values of groundwater abstractions and groundwater depth and electricity requirements have close relationship. If the basin needs more electricity (for example for pumping) in a given period, water flow should be high in that period (in order to use for hydropower or cooling systems).

As mentioned earlier, all energy-water linkages in the model are related to the climate parameters. For example, during dry period, water and electricity requirements usually rise, however, hydropower and thermal power decline, thus the demand for imported electricity will increase. Therefore, in this study the climate model is extracted from the Coupled Model Intercomparing Project Phase 5 (CMIP5) and the climate model is downscaled statistically; the climate parameters (precipitation and temperature) and hydrology parameters (surface and groundwater values) are analyzed to estimate electricity requirement for the future. In addition, the economic parameters which is affected by the future electricity demands is examined through statistical analysis.

RESULTS

Climate Trends

The CMIP5 found that the main water-related concern in the Zayandeh Rud region in a changing climate will be declining rainfall in arid regions. This will put pressures on water supply for human consumption, agriculture and hydroelectricity in water-stressed regions, alongside continuous population growth. Climate-energy-water planning requires understanding of these impacts to elucidate the effects they might have on electricity requirements prospect.

Historical Climate by Region

The region has wide range of climates including humid, arid, and semi-arid with the climate varying from cold to very arid zones. The CMIP5 shows that during the last 30 year, Zayandeh Rud precipitation was uneven, at times decreased in east parts, while increased in the west. Mean temperature over 30 years shows an upward trend in the region, as does minimum temperature, while the maximum temperature shows uneven trends. Fig. 3 illustrates the precipitation trends in Isfahan Basin.

Fig. 3. Spatial patterns of mean annual precipitation in Zayandeh Rud basin for historical time period (1971–2005)

As mentioned earlier, temperature and energy production have significant linkages. Fig. 4 shows the relationship between temperature changes and energy demands also displays that by increasing temperature and reducing runoff in the basin, the hydropower generation is reduced and the ability of basin for producing hydro power energy has declined.

Fig. 4. Relationship between energy demand and temperature

Future Climate Trend in Zayandeh Rud Basin

There is a fair amount of uncertainty in climate projections for the basin, especially when it comes to precipitation. For this study, we have drawn on projections of average temperature and rainfall throughout the current century derived from statistical downscaling of general circulation models available at the Koninklijk Nederlands Meteorologisch Instituut. The model is given a resolution of 50 km for emissions scenario of Representative Concentration Pathways, RCP (RCP 8.5 for this study). Fig. 5 shows changes in precipitation for the scenario. This indicates future precipitation can reduce by -3 to -44% for the year of 2006-2100 in the region, as compared to baseline period (1970-2005).

Fig. 5. Spatial patterns of decline in average flow (2006-2100) in Zayandeh Rud basin

This projection presented in in Fig. 6 also indicates a summertime increases in the rainfall regime of 15 to 20%. For the winter season it shows reductions of 30 to 70%. However, temperature increases between 2 to 7 °C for the entire year.

Fig. 6 Monthly precipitation and temperature changes (2006-2100) in Zayandeh Rud basin
Historic flow model and power generation

The observed and simulated flows (WEAP model) are shown in Fig. 2 with the correlation of 0.8. Also, the observed hydropower creation and the simulated one are shown in Fig. 7, the correlation is 0.9.

Fig. 7. Modeled and observed hydropower creation

Historic and Modeled Forecast of Hydropower Energy and Electricity Demand

The model which is designed for evaluating the effects of climate change on electricity and water usage shows that because of climate alteration, the basin is a vulnerable. Table 1 shows that if temperature rises between 2 and 7 °C in the future, electricity requirement will rise by 5.3 and 8.6%. As mentioned before, unlike temperature, electricity requirement has minor relation with precipitation and with 3 to 44% reduction in precipitation, only 3.3% electricity requirement will change. However, electricity requirements depend on groundwater values and if groundwater depth decreases, then the electricity requirements will increase. In addition, this table represents the differences between historical time period (1970-2005) and the future time period (2006-2100) for hydro-power energy requirement and the energy generation. In future time period electricity requirements will increase more than historical time period.

The results of this study indicate that by increasing 7 °C in temperature and decreasing 44% in precipitation, the electricity generation will decline by 4.5%. Therefore, hydropower is sensitive according to the alterations in temperature and precipitation. The results (Table 1) show that thermal creation can be affected by climate alteration. In the scenario for driest condition of RCP (8.5) with limited stream water for cooling, the thermal power generation for future will decrease by about 3.5% (this is deference between 8.6 and 5.3%).

Table 1. Modeled change (%) in electricity demand, generation and imports, compared to the base scenario (%)

Severe dry scenario	Electricity requirements	Electricity creation	Thermal power	Hydropower	Electricity imported
Historical temperature and precipitation (1970-2005)	2	-2	-0.8	-2.9	7
Future (+ 2°C, -3% ppt)	5.3	-6.2	-0.5	-16.2	14.8
Future (+ 7°C, -44% ppt)	8.6	-10.7	-6.2	-25.8	38.9

The results of the effect of climate change on electricity system are displayed in Fig. 8. The electricity requirements are high during the extreme dry periods. However, electricity generation is low during the extreme dry periods. In addition, electricity imports will change significantly during the extreme dry periods and the energy import will rise considerably. Fig. 9 shows reduction in hydropower energy for different sub-basins of the area. The highest energy reduction belongs to sub basin numbered as 4202 and 4203. Because these sub-basins have the highest energy demand and these are far from the dam outlet and from the main river. However, the basin 4215 has the lowest reduction in hydropower energy, since this sub basin is close to the dam outlet and also the energy demand in this basin is low.

Fig. 8. Estimated changes in annual electricity generation and energy demands in the base, (+)2 °C & (-)15% precipitation (electricity requirements are shown with gray color. electricity generation is represented by red color. energy import shows with blue color and hydropower energy displays with yellow color)

Fig. 9. Reduction in hydropower energy (2006-2100) that shows by red digits in Zayandeh Rud basin

Table 2 shows the effects of the scenario under driest condition (RCP 8.5) (7 °C rise in temperature and 44% reduction in precipitation) on water/energy use in the basin. Also, water flow from the hydropower services can decrease 27% and water demand for urban and agricultural purposes will increase 3 to 7%. However, water usage for thermal cooling will not change

considerably. Furthermore, hydropower generation will decrease 14%. Therefore, the result shows regional water storage service for preserving water has a significant role during low flow conditions.

Table 2. modeled effect of the dry (with + 7 °C increase in temperature and –44% decrease in precipitation) scenario on the future average annual water and electricity consumption

	Water demand (ha-m)	Electricity generation (MWh)
Hydropower	372739.71	2461331
Alteration from historical period (%)	+ 35.4%	-14.7%
Agriculture	93165.99	64210
Alteration from historical period (%)	+ 6.5%	-6.5%
Industrial, commercial and residential	60251.27	402690
Alteration from historical period (%)	+ 3.5%	-6.6%
Thermal cooling	+ 777.09	6100
Alteration from historical period (%)	0.5%	-0.65%

Economic Effects

As mentioned earlier, the climate change can affect economy. Because when the climate change causes low flow, the energy generation will decrease and the basin needs to import electricity with higher cost. Therefore in Fig. 10, the costs that should use for providing energy are shown for baseline scenario and for the future scenario. As it shown in Fig. 10, in all sub-basin of the Zayandeh Rud River basin, the cost of providing energy in the future is higher than historic period. The cost changes from base line for different uses are also shown in Table 3.

Fig. 10. Comparison the costs (\$) which used for providing energy under historical period (blue color) and future time period (red color)

Table 3. The cost changes from base line for different uses

	Age
Alteration of cost (\$) from historical period for hydropower	36
Alteration of cost (\$) from historical period for agriculture	7
Alteration of cost (\$) from historical period for industrial, commercial and residential	4
Alteration of cost (\$) from historical period for thermal cooling	1

DISCUSSION

Water resource and energy supply models have been developed from year 1970. For example, WATERSIM (Water, Agriculture, Technology, Environment, and Resource Simulation Model), WaterGAP (Watery- Global Assessment and Prognosis), MODSIM (Model for Distribution System Analysis), WEAP concentrated on water use and accessibility and applied in order to improve policies of sustainable water organization. Also, similar energy models such as MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environment), MARKAL (Market Allocation), EFOM (Energy Flow Optimization Model), TIMES (The Integrated MARKAL-EFOM System), BUEM (Bottom-Up Energy Model), OSeMOSYS (Open Source Energy Modeling System) and LEAP can simulate energy supply and requirements. Although the mentioned water and energy models can simulate water and energy supply individually, the connection between water/energy parameters cannot be simulated in those models. Previous studies simulate water as an element of energy model or energy as a supply in water models. For instance, Chandel et al. (2015) examined water pumping system (e.g., photovoltaic). Novosel et al. (2015) calculated the relationship between desalination plant dimensions and water pumping system of photovoltaic. Another example is investigation of consumed water which can be used as supply for energy creation (Owusu and Asumadu-Sarkodie, 2016). In this study, a hydrologic model has combined with an energy model (a thermal power plant). However, there is lack of researches on connection between climate change and water/energy and economic parameters. For example, in the study by Boulanger et al. (2007) only simulating water/energy condition for the current time period was conducted but prediction of climate change for future time period and its effect on water/energy were not considered.

In this study, the effect of climate change on water/energy demands was analyzed and also climate change impacts on economic parameters estimated. The WEAP-LEAP application combined with climate change models used in this study can help support development of low-water, low-carbon scenarios in general.

CONCLUSIONS

In this study, water use in energy planning and energy use in water planning are analyzed for Zayandeh Rud River Basin. Also, the effect of climate change on water/energy usage and generation is estimated. The results show that during the severe dry condition and the driest scenario of RCP 8.5, the water supply and electricity generation are vulnerable. The results of this study indicated that by increasing 7 °C in temperature and decreasing 44% in precipitation, the electricity generation will decline for 9% for future time period. Currently, the basin, except of the flow of the Zayandeh Rud reservoir, can partly meet electricity demands by importing electricity from other sources during severe dry condition. However, this research suggests that for future long time period, the basin should consider alternative adaptation plans to combat the effect of climate change. Thus, future studies are necessary on this aspect.

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