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Status, trends and significance of American hydropower in the changing energy landscape

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ABSTRACT

Despite the considerable contribution of hydropower in driving the American economy for over a century, the rationale for hydropower in the U.S. energy mix needs to be reassessed in the context of advanced science and technology. Other alternative-yet-cheaper energy resources have been identified and hazards associated with aging hydro-dams have escalated in recent years. Furthermore, research has shown more negative environmental consequences associated with hydro-dams—and dams in general. To compare the contribution of hydroelectricity to the total energy production in the U.S., and to identify its regional distribution and contemporary patterns, we conducted a systematic analysis of large-scale multi-year data from U.S. federal agencies and tallied the nameplate capacities of major hydro-dams against their existing energy production values. We found that despite continuous efforts at upgrading hydro-facilities, since 2000 the mean contribution of hydroelectricity has remained less than 10% of the total generated energy in the U.S. and has been declining since then. Based on our results, we conclude that reservoir- and dam-based hydroelectricity may not be an efficient energy resource—at least from the American perspective, and perhaps it is timely to consider promoting other non-conventional renewable resources for energy production.

1. Introduction

Hydropower has been an integral component of American electricity production for nearly 130 years and has played a substantial role in the nation's industrial revolution [1]. Differences in regional precipitation and runoff, river morphologies, local settlement patterns and concordant energy needs and alternatives, and the nature of hydropower facilities has varied widely across the conterminous U.S. However, over time as energy demand has outstripped the feasibility to bring additional hydropower capacity online, the contribution of hydropower has declined in the nation's energy mix while, at the same time, annual total and per capita electricity usage in the U.S. has been increasing [2]. The feasibility of satisfying expanding energy needs from alternative renewable energy sources (e.g., wind, solar and biomass fuel) has been increasing with the rapid decline of their costs and improvements in their efficiency. Indeed, the leading U.S. federal labs have reported a consistent annual decline of the levelized cost of energy (LCOE) for land-based- and offshore-windfarms, and utility-scale solar installations in recent years. For instance, the LCOE value of a typical land-based wind project in the U.S. declined from $71/Megawatt hour (MWh) in 2010 to $49/MWh in 2016, and it declined from $225/MWh in 2010 to $173–207/MWh in 2016 for a typical offshore windfarm [3,4].

Hydroelectricity generation from impounded water is still viewed as providing a high level of energy supply services, probably because even in the recent context of other non-traditional sources becoming cheaper, it contributed a substantial 16.4% of the global energy mix in 2016 with an estimated total installed capacity of 1096 GW [5]. From the energy production perspective, three main types of hydro-projects, namely reservoir-based, run-of-river and pumped-storage have been identified; each with its own inherent merits and demerits. Perhaps the most important appeal of a hydroelectric plant is its capacity to load balance instantly as the electricity demand varies on a diurnal basis [6].

Initially, hydropower was promoted as a "carbon-emission free" energy resource and a panacea to mitigate atmospheric pollution; however, recent studies, emerging from tropical to temperate areas—including the U.S., have debunked those assertions by reporting significant emission of greenhouse gases (GHGs) from reservoirs into the atmosphere [7,8]. The current estimated global GHG emission from lentic surface water is 0.8 Pg (petagram) of CO_2 equivalent each year,

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contributed mainly in the form of methane—a highly potent GHG [9,10]. In Brazil, carbon emissions from the proposed reservoir-based hydro-projects may actually exceed those of burning fossil fuels for equal energy production [7]. Whereas in the temperate U.S., summer methane ebullition from hydro-reservoirs was shown to occasionally surpass that of tropical areas—underscoring the significance of temperate reservoirs on GHG emissions [8].

Also, dams across the U.S. are aging. Aging dams impose higher risks of failure causing environmental and human damage, and consequent economic losses. Anticipated changes in precipitation pattern and the corresponding hydrological regimes raise additional uncertainties in the future reliability of hydro-generation in many regions. For example, the risk of compound flooding from storm surges and rainfall has increased lately in major U.S. cities [11]. In 2015, 47 old dams recognized as "high hazard" breached in South Carolina imposing significant damage to local communities [12]. Very few new hydro-dams in the U.S. are being built and even fewer proposed for the near future (i.e., 3–5 years), although some hydro-facilities are proposed to upgrade capacities [13,14]. Changes in precipitation pattern and the corresponding hydrological regimes raise additional uncertainties in the future reliability of hydro-generation in many regions. Modelling indicates a global reduction of up to 74% of the usable capacity of hydropower plants for the next 20–50 years in the absence of pre-emptive system enhancement measures [15]. Some energy experts even assert that the majority of the best dam sites have already been exploited, and what remains available may not be economically or environmentally viable or socially acceptable for new construction [16,17].

Finally, there is a mounting backlash against dams—hydro-dams among them—because of the environmental harm they cause, most notably, by:

(1) Segmenting rivers – for instance, dams have dissected the otherwise intact watersheds, and have restricted the free flow of rivers (e.g., the Kennebec and Susquehanna Rivers in the East Coast, and Columbia River in the West Coast of the U.S.), altering their morphologies in unnatural ways [18]. The average drainage area per dam ranges from as low as 44 km^2 in the high-dam-density areas of the northeastern U.S. to 811 km^2 in the low-density areas of the southwest [14].
(2) Trapping sediments – e.g., hydro-dams on the Susquehanna River (Maryland) were found to trap as much as one-half to two-thirds of the suspended sediment in relatively low-discharge years [19,20]. The impact of low sediment transport to the downstream estuaries, among other systems, is mostly evident on inorganic-sediment-impoverished tidal marshes [21].
(3) Impeding movements of migratory and resident fish - e.g., the migrations of western Atlantic anadromous fish species, such as American shad (*Alosa sapidissima*) and Atlantic salmon (*Salmo salar*), are severely restricted by dams in mid-Atlantic and northeastern rivers [22]. Also, in-stream freshwater fish have lower abundances upstream of dams compared to the downstream populations, mainly due to dam-induced migratory hindrances [23].

These factors have helped foster a growing dam removal movement in the U.S., one in which "*over the past 15 years, dam removal has evolved from a radical idea to an established approach for restoring geomorphic and ecologic function of rivers*" [24]. Within the past 40 years, more than 1000 dams originally built for a variety of purposes have been removed in the U.S., the majority of them within the past decade [25]. Post-dam-removal studies have reported positive biotic and abiotic responses of dam removals [18,24–28]. Migratory fishes are one of the first responders to dam removal and their reappearance in previously restricted river segments is promoting population recoveries. For example, the endangered shortnose sturgeon (*Acipenser brevirostrum*) reached their historic spawning grounds of the Kennebec River after the removal of Edwards Dam which had impeded their access for over 160 years [26].

It is clear that American hydropower is in a state of transition and currently experiences some societal pressures associated with environmental issues. Given these many confounding factors, we analyzed existing data sets on hydropower dams in the conterminous U.S. to better understand the current status of regional differences and overall patterns in the recent past and contemporarily, in order to make future predictions of the state of hydro-generation. This study provides vital information based on calculations of recent data from U.S. federal agencies, which may provide a clearer picture of where the U.S. is headed in terms of hydroelectricity consumption and production and may also aid in informing any existing debates on dams and hydro-energy.

2. Methodology

To assess the current state of hydropower utilization across the U.S. our study analyzed datasets from U.S. federal agencies, namely, U.S. Army Corps of Engineers (USACE), Oak Ridge National Laboratory (ORNL), Energy Information Administration (EIA), Geological Survey (USGS) and National Oceanic and Atmospheric Administration (NOAA).

The USACE maintains and publishes the National Inventory of Dams (NID), a federally authorized database, documenting dams in the U.S. and its territories. Specifically, the NID incorporates dams that have minimum 1.83 m height and over 614×10^3 m^3 storage or have minimum 7.62 m height and their storage exceeds 185×10^3 m^3. The NID also lists dams that do not meet either of these criteria but that pose significant hazard, i.e., they could cause a loss of human life and likely significant property or environmental destruction. The NID contains information about each dams' location, size, purpose, type, last inspection date, and regulations. We accessed the NID at the USACE website (http://nid.usace.army.mil) on Dec 20, 2017. Using the filter option on the dataset, we extracted hydro-dam information for our analysis i.e., dams whose primary or one of the purposes was hydro-electricity production.

Complementing the NID, the National Hydropower Asset Assessment Program of the ORNL maintains the National Hydropower Plant Dataset (NHPD). The NHPD includes geospatial locations and key characteristics of hydropower plants in the U.S. that are currently licensed, exempt from licensing, or awaiting relicensing. Specifically, the NHPD contains information about the maximum capacity from hydraulic turbine-generators, water resource infrastructure, hydrography, and environmental attributes as well as the year when the first generator started its operation. The NHPD was accessed at the ORNL website (http://nhaap.ornl.gov) on Jan 2, 2018.

The U.S. EIA maintains the largest database on commercial energy production in the U.S., which contains information on energy generated from all resources including the conterminous U.S., Alaska, Hawaii and Puerto Rico. The U.S. EIA datasets (EIA form 860 https://www.eia.gov/electricity/data/eia860/ and EIA form 923, https://www.eia.gov/electricity/data/eia923/) were accessed on Dec 17, 2017. We extracted data on total electric power generated by all resources i.e., conventional hydroelectric sources, burning coal, natural gas, petroleum, wood and wood-derived fuels as well as the alternative sources i.e., wind, solar, etc. for national and regional levels (for region delineation- see below). Key information extracted from the U.S. EIA database included:

(1) annual total and hydroelectric energy generation for 1990–2015,
(2) annual nameplate hydroelectric energy generation capacity along with the number of facilities for 1990–2015,
(3) monthly actual hydropower generation from January 2001 to September 2016, and
(4) planned annual nameplate hydroelectricity generation capacity

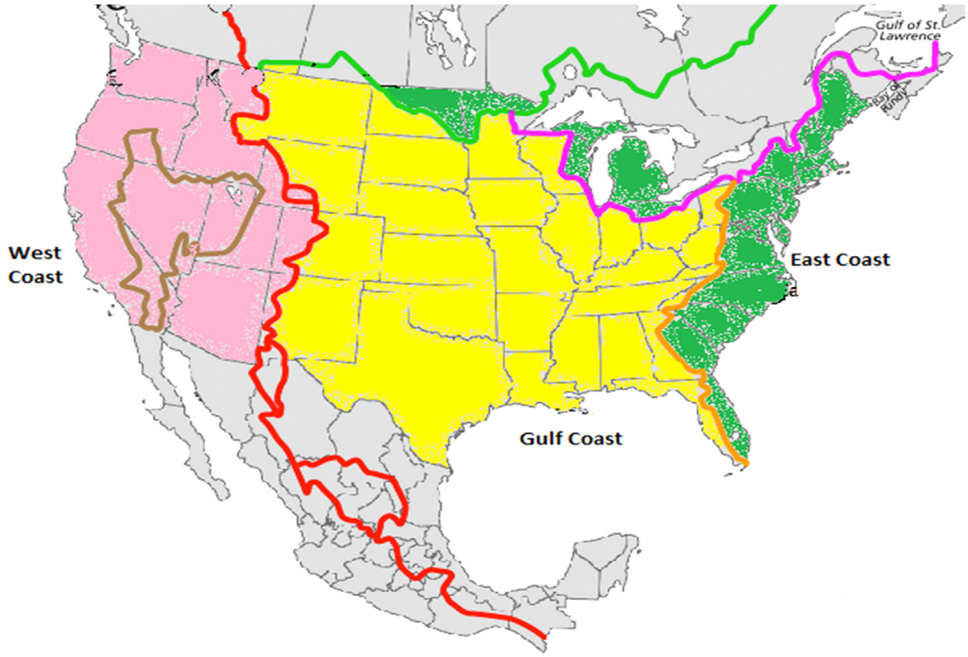

Fig. 1. Map of the conterminous U.S. showing major continental divides and assignment of the states into West, Gulf or East Coast watersheds.

along with the number of generators and facilities proposed from present through 2020.

We also obtained statewide annual and monthly precipitation data from the NOAA website on Jan 5, 2018 (https://www.ncdc.noaa.gov/). Finally, we accessed the watershed database of the United States Geological Survey (USGS; https://nhd.usgs.gov/) and maps thus produced, along with the continental divide maps of North America to delineate regions for our analysis.

Unless stated otherwise, in this study "national" refers to the 48 states of the conterminous U.S. (i.e., excluding Alaska, Hawaii and Puerto Rico) and results refer to the conterminous states unless otherwise stated. At a gross level, we assigned states into East (Atlantic), West (Pacific) and Gulf Coast watersheds based on the location of the estuary where hydropower facilities in those states drain (Fig. 1). The North American continental divides some states into two (or more) watershed regions and, consequently, distributes the facilities within such states into those watersheds (Table 1), e.g., hydro-facilities in Minnesota are distributed among watersheds. We assigned such states to the watershed with the highest number of facilities draining into; for instance, Minnesota was assigned to the Gulf Coast watershed region as it has 22 hydro-dams in the Gulf Coast region and 13 in the East Coast watershed regions (Hudson Bay and St. Lawrence River watershed regions were pooled into East Coast watershed). Michigan was a special case; although geographically being located in the Midwest region of the U.S., it was assigned into the East Coast watershed as all of the hydropower dams in the state drain into the St. Lawrence River—a subbasin of the East Coast watershed. We had 24 states assigned to the Gulf Coast region, 16 states (including Washington, D.C.) to the East Coast, and 8 states to the West Coast regions (Fig. 1).

The NID contains information about 2603 dams with hydroelectricity production as one of the purposes (primary or secondary) in the conterminous U.S. However, only 2155 dams have unique NID IDs, indicating that some dams are a part of larger facilities. There are some cases of dams not being documented in the NID (due to their size being smaller than the defined criterion or being recently built). Magilligan et al. [29], in a recent study concluded, "*The NID significantly underestimates the actual number of dams*" thus the NID might be an incomplete database and may have underrepresented the actual number of dams. Contrary to the NID, NHDP contains information of 2320 hydropower plants. Initially, NHDP was derived from the NID as a subset, but was expanded later with data of facilities that were not present in the NID along with additional information on plant ownership, maximum capacity (MW), number of turbines, and the year when each dam first started its operation. After comparing the two datasets, i.e., the NID and NHDP, we considered the NHDP was more appropriate for our analysis, therefore our analyses followed the NHDP.

3. Results and discussion

3.1. Hydro-dam construction: past to present

Historical records indicate that the first dam for electricity generation in the U.S. was built in the 1880s [30].Since the 1880s, thousands of dams have been built in the U.S. for hydroelectricity production (Fig. 2). Many dams originally built for purposes other than generating hydroelectricity were later upgraded (or modified) for electricity production; hence, "online year" refers to the time when those dams were first commissioned to generate electricity. Most hydro-dams or hydropower facilities were built in the 1900s-1930s, peaking again in the 1980-1990s (including both built or modified). With its plurality of American hydro-dams, the trend of dam building (or upgrading and modification) in the East Coast was similar to the trend at the national level until 1950s. After the 1950s, the trend of dam building in the West Coast was more akin to the national level than any other regions. Dam building in the Gulf Coast States started to decline shortly after peaking in the 1950s, with a secondary peak earlier in the 1920s (Fig. 2), and along the West Coast, dam construction constantly increased from 1900s to 1990s, peaking in the 1920s, 1960s, and again in the 1980s, and started to decline thence after (Fig. 2). Despite comprising the highest number of states and being the largest geographically, the Gulf Coast region never surpassed other watershed regions in hydropower dam building business in the conterminous U.S.—most probably due to its comparatively lower relief than that of the eastern and western counterparts.

Although there was a sudden dip in the total number of dams constructed in the 1930s,as compared to the previous decades, perhaps because of the Great Depression, the average and total capacity of

Table 1
Number of hydropower facilities and assignment of the states to "watersheds" based on North American continental divides (W= west coast; G= gulf coast; E = East coast; S= St. Lawrence River; H= Hudson Bay).

State	No. of Facilities	Watershed Assignment	Remarks
Alabama	G = 22	Gulf coast	
Arizona	W = 13	West coast	
Arkansas	G = 19	Gulf coast	
California	W = 413	West coast	
Colorado	W = 57; G = 39	West coast	
Connecticut	E = 34	East coast	
Delaware	0	East coast	*Absence of any hydro-facilities; Assigned to the East coast due to its geographical location
Florida	G = 2	Gulf coast	
Georgia	G= 19; E = 19	East coast	* Equal hydro-facilities in the Gulf and East coast; Assigned to the East coast due to its geographical location
Idaho	W = 154	West coast	
Illinois	G = 13	Gulf coast	
Indiana	G = 7	Gulf coast	
Iowa	G = 10	Gulf coast	
Kansas	G = 2	Gulf coast	
Kentucky	G = 15	Gulf coast	
Louisiana	G = 3	Gulf coast	
Maine	E = 107	East coast	
Maryland	G = 1; E = 3	East coast	
Massachusetts	E = 74	East coast	
Michigan	S= 89	East coast	* River St. Lawrence assigned to the East coast watershed
Minnesota	G = 22; H = 8; S = 5	Gulf coast	*Only state that drains into the Hudson Bay
Mississippi	G = 4	Gulf coast	
Missouri	G = 8	Gulf coast	
Montana	W= 15; G = 29	Gulf coast	
Nebraska	G = 11	Gulf coast	
Nevada	W= 13	West coast	
New Hampshire	E = 103	East coast	
New Jersey	E = 4	East coast	
New Mexico	W= 3; G= 5	Gulf coast	
New York	E = 218	East coast	
North Carolina	G= 22; E = 39	East coast	
North Dakota	G= 1	Gulf coast	
Ohio	G= 13	Gulf coast	
Oklahoma	G= 12	Gulf coast	
Oregon	W= 99	West coast	
Pennsylvania	G= 13; E = 15	East coast	
Rhode Island	E = 7	East coast	
South Carolina	E = 36	East coast	
South Dakota	G= 5	Gulf coast	
Tennessee	G= 29	Gulf coast	
Texas	G= 27	Gulf coast	
Utah	W= 74	West coast	
Vermont	E = 83	East coast	
Virginia	G= 6; E = 34	East coast	
Washington	W= 98	West coast	
West Virginia	G= 11; E = 5	Gulf coast	
Wisconsin	S = 34; G= 71	Gulf coast	
Wyoming	W = 7; G= 16	Gulf coast	
Total	**2320**		

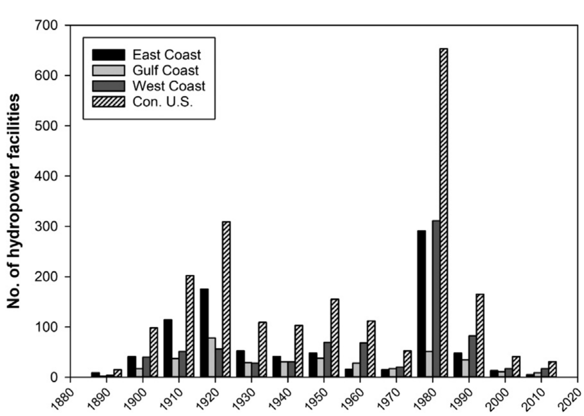

Fig. 2. Number of hydropower facilities constructed (or modified) in each decade. X-axis indicates time in decades. The "Con. U.S." in the legend refers to the conterminous U.S.

Table 2
Mean and Median ages (in years) of hydro-dams in the conterminous U.S. and sub-regions.

Region	Mean dam age ± Standard error (years)	Median dam age (years)
Conterminous U.S.	60.48 ± 0.70	57
East Coast	64.64 ± 1.08	67
Gulf Coast	67.28 ± 1.57	74
West Coast	52.48 ± 1.07	35

newly constructed facilities consistently increased in each decade from the 1890s to 1960s (Fig. 2). Hydropower dams constructed in the decades before the 1930s were smaller in size, and with the progress in technology, newer dams with enhanced capacities were constructed after the 1930s (Fig. 2). Dam construction before the 1970s was dictated to drive the national economy notwithstanding the expense of local environments [13]; however, that scenario changed in the 1970s after the introduction of stricter environmental laws and regulations,

Table 3
Nameplate hydroelectricity generation capacity.

Region	Type[a]	No. of Hydropower Plants	HY MW	PS MW	Total MW
Conterminous U.S.	1	2276	71,639	–	71,639
	2	29	–	19,235	19,235
	3	15	8163	3672	11,835
		N = 2320	T = 102,709		
East Coast	1	907	13,796	–	13,796
	2	14	–	13,074	13,074
	3	5	1033	1129	2162
		N = 926	T = 29,032		
Gulf Coast	1	428	17,727	–	17,727
	2	4	–	2571	2571
	3	2	67	59	126
		N = 434	T = 20,424		
West Coast	1	941	40,117	–	40,117
	2	11	–	3589	3589
	3	8	7063	2484	9547
		N = 957			T = 53,253

[a] Type 1 indicates facility containing capabilities to generate hydropower from hydraulic turbine-generator units only (HY), Type 2 indicates facility containing capabilities to generate hydropower from pumped storage turbine-generator units only (PS), and Type 3 indicates facilities containing capabilities to generate hydropower from both hydraulic and pumped storage turbine-generator units. (Symbols: N = total number of hydropower plants, T = sum total of generated hydropower).

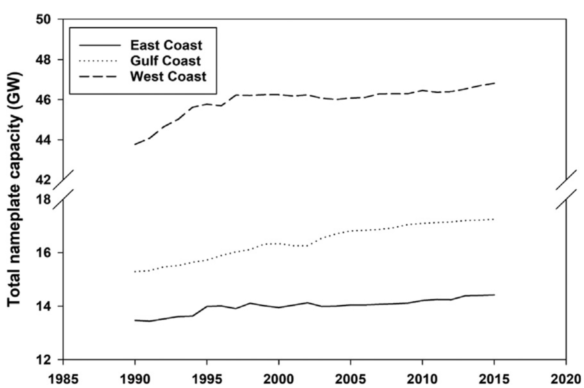

Fig. 3. Total nameplate capacity (in gigawatts; GW) by region from 1990 to 2015.

namely, National Environmental Policy Act (1969), Clean Water Act (1972), and the Endangered Species Act (1973). Further, environmental movements during the 1970s aided in providing tax incentives for investment in other renewable energy that may have lessened the impetus for new dam construction. Despite substantially more dam construction in the 1980s, the average and total capacity of newly constructed facilities did not match the respective values of the 1960s, indicating that technically efficient hydropower dams were built in the 1960s or an indication of exhaustion of most feasible electricity-yielding sites in later decades.

3.2. Hydropower dams features: their age, size and ecological aspects

Hydropower dams are often categorized on the basis of their nameplate capacity (MW) as micro-($\leq$0.1), small (0.1–10), medium (10–100), large (100–500) and very large (> 500). At the national level, small hydropower dams are the most abundant ones, comprising almost 65% of all hydropower facilities (total N = 2320) but generating a mere 3.5% of the total nameplate capacity. Very large hydropower dams are the least numerous (just under 2% of the total facilities) but have the capacity to generate up to 54% of the total hydro-energy. Of the very large facilities (45 total), 53% were constructed in the West Coast watershed. From the ecological perspective, the overall impact-*per*-dam footprint may be greater for smaller dams compared to larger ones. A study assessing the scaled hydropower impacts in the Nu River basin in southwestern China appraised impact per MW of energy production across 14 metrics between small (< 50 MW) and large hydropower projects (> 50 MW) and found that small hydropower dams had highly unfavorable impact per MW for 9 out of the 14 metrics assessed, including the length of the river channel affected and on habitat designated as conservation priorities. Conversely, greater cumulative impacts of large dams were observed on total land inundation, the disruption of the sediment transport and the potential for reservoir-induced seismicity [31].

Based on the NHDP dataset, the mean (± standard error) and median hydro-dam ages for the conterminous U.S. were calculated as 60.48 ± 0.70 and 57 years respectively (Table 2). On the regional scale, the West Coast has the youngest dams (mean = 52.5 ± 1.07 years; median = 35 years) in comparison to the East and the Gulf Coasts (Table 2). Despite the comprehensive information in the NHDP, 275 facilities (11.8%) in the inventory do not have information on their first online year, therefore our analysis of the age of the dams was based on the remainder. Aging dams have increased risks of structural failure; however, even newly built dams have failed. Early in the 1970s, three recently built dams (Buffalo Creek in West Virginia; four years old, Teton in Idaho; four years old, and Toccoa Creek in Georgia; 78 years old) failed, claiming 175 lives and monetary losses amounting over $150 billion, paradoxically, after those dams were deemed “safe” by the dam safety inspectors [32]. The most recent status of dams in the U.S. as assigned by the American Society of Civil Engineers is a “D” and 17% of total dams have been classified as “high hazard potential” [32]. Although regular maintenance can enhance the longevity of dams, this option could be proven thrice more expensive than actually removing them [33]. Nationally, an estimated $45 billion is needed to repair over 2000 potentially hazardous dams [32], and this estimate will only increase the dams become age further. Considering the safety of human life alone, “*dam removal is established as a mainstream policy option to improve dam safety and restore socio-ecological systems*” [34].

Based on type, 2276 (98.1%) facilities generate hydropower from traditional hydraulic turbine-generator units; 29 (1.3%) facilities generate hydropower from pumped storage turbine-generator units, and 15 (0.6%) facilities have mixed hydropower generation capabilities. According to our definition of watersheds based on continental divides, 960 (41.3%) hydro-facilities are located in the West Coast, 434 (18.7%) in the Gulf Coast and 926 (39.9%) in the East Coast watershed regions. California has the highest number of hydro facilities, with 413. Delaware has the lowest number, with zero. The mean number of hydro facilities by state is 48.3.

On a regional basis, we found that the mean distance of hydro-dam

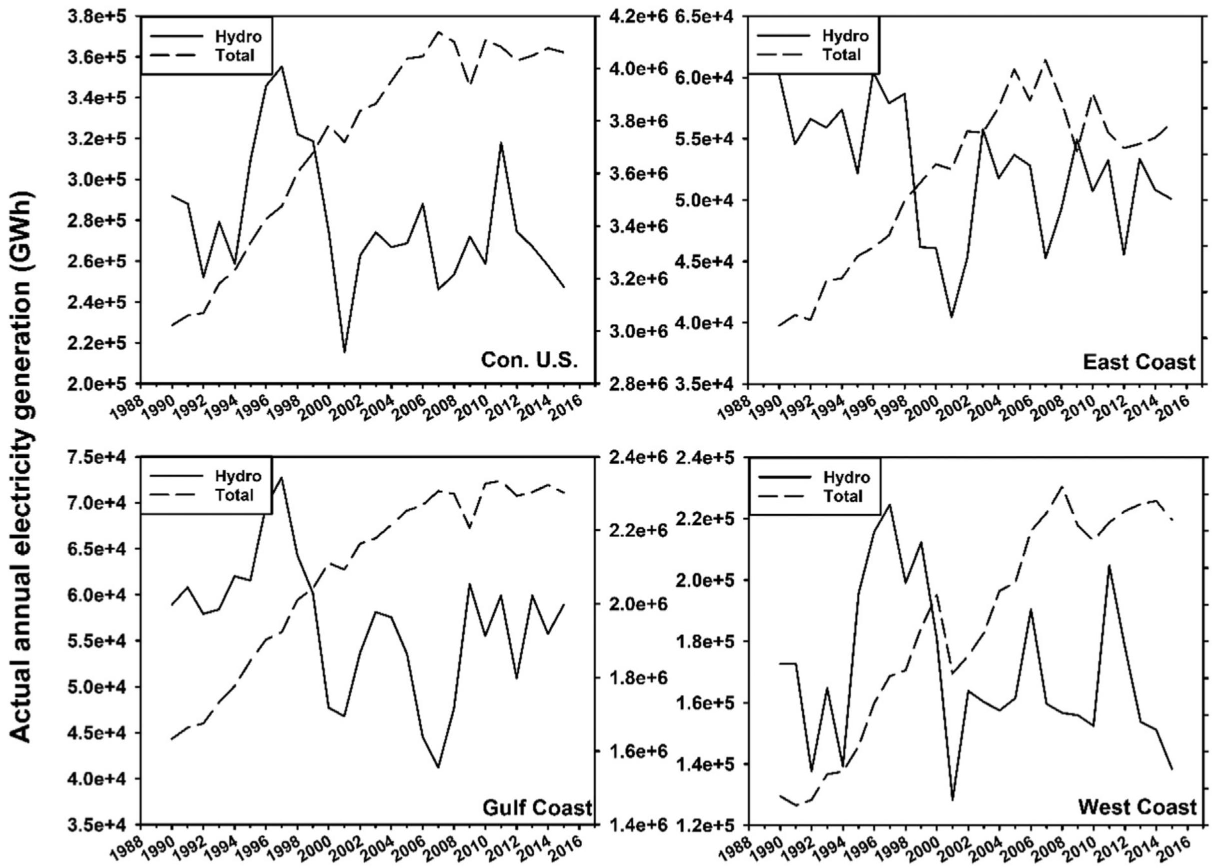

Fig. 4. Actual annual electricity generation (gigawatt-hours; GWh) for the conterminous U.S. and its three watershed regions, 1990–2015. Dashed lines represent total energy (right axis) whereas solid lines represent hydro-energy generation (left axis). The "Con. U.S." label in corner bottom of the first subframe refers to the "conterminous U.S".

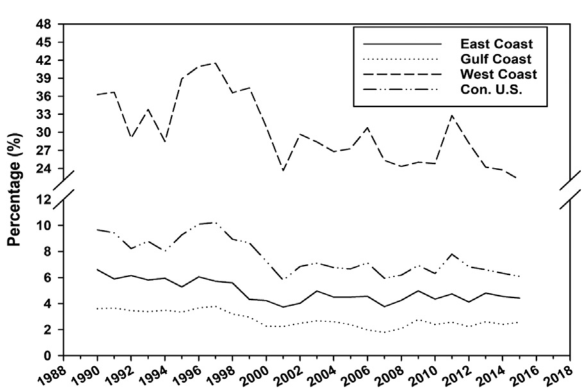

Fig. 5. Relative contribution of the actual hydro-energy production to actual total energy production. The "Con. U.S." label in legend refers to the "conterminous U.S".

facilities from the nearest marine receiving waters (estuaries) is 580 km in the West Coast, 598 km in the East Coast, but 2622 km in the Gulf Coast. However, the presence of some hydropower dams closer to river mouths reduces spawning opportunities for anadromous fish [22]. Hence, from the perspective of energy production, the placement or construction of dams on the physiography of a river may not hold much significance, but it may be highly substantial for migratory fish that are unable to reach their historic spawning grounds [22,23]. A modelling study illustrated the degree of blockage caused by even small dams built closer to the mouth of the river on fish movement and it was found to be highly substantial [35]. In the study, numerous dam-removal combinations for 150 dams in the basin were appraised to enhance river connectedness for salmon in the Willamette River basin (Oregon) and it was found that removing only 12 dams could reconnect and rehabilitate 52% of the drainage basin with a loss of less than 2% of the basin's hydropower [35].

3.3. Hydropower dams distribution: the regional distribution pattern and nameplate capacities

The total nameplate capacity of hydroelectricity generation from 2320 hydropower dams in the conterminous U.S. is 102.7 GW, of which the total capacity from hydraulic turbine-generators is 79.8 GW (78%), compared to 22.9 GW (22%) from pumped storage (Table 3). The total turbine generators in use are ca. 5600 [13]. Hydro-facilities in the East Coast have lower total nameplate capacity than those on the West Coast and the Gulf Coast. For instance, within the past quarter century, the total nameplate capacity (expressed in gigawatts; GW) in the West (mean ± standard error: 45.9 ± 0.1) has remained substantially higher than the East Coast (mean ± standard error: 14.0 ± 0.05) and the Gulf Coast (mean ± standard error: 16.4 ± 0.1), thus indicating a large gap in the nameplate potential of constructed dams between the East and West Coasts (Fig. 3). Indeed, three coastal states of the West Coast (Washington, Oregon, and California) contain over 43% of the installed capacities in the conterminous U.S [13]. The top five states with the highest nameplate capacity (in GW; combined conventional and pumped storage types) are Washington (21.3), California (15.4), Oregon (8.4), New York (5.9) and Tennessee (4.2) with a combined capacity of 55.2 GW i.e., 54% of the total nameplate capacity.

Even the actual hydro-energy production (in GWh) between the East (mean: 52,575) and West Coast (mean 170,300) has differed by a magnitude of 10^1 since 1990 through 2015 (Fig. 4). This disparity

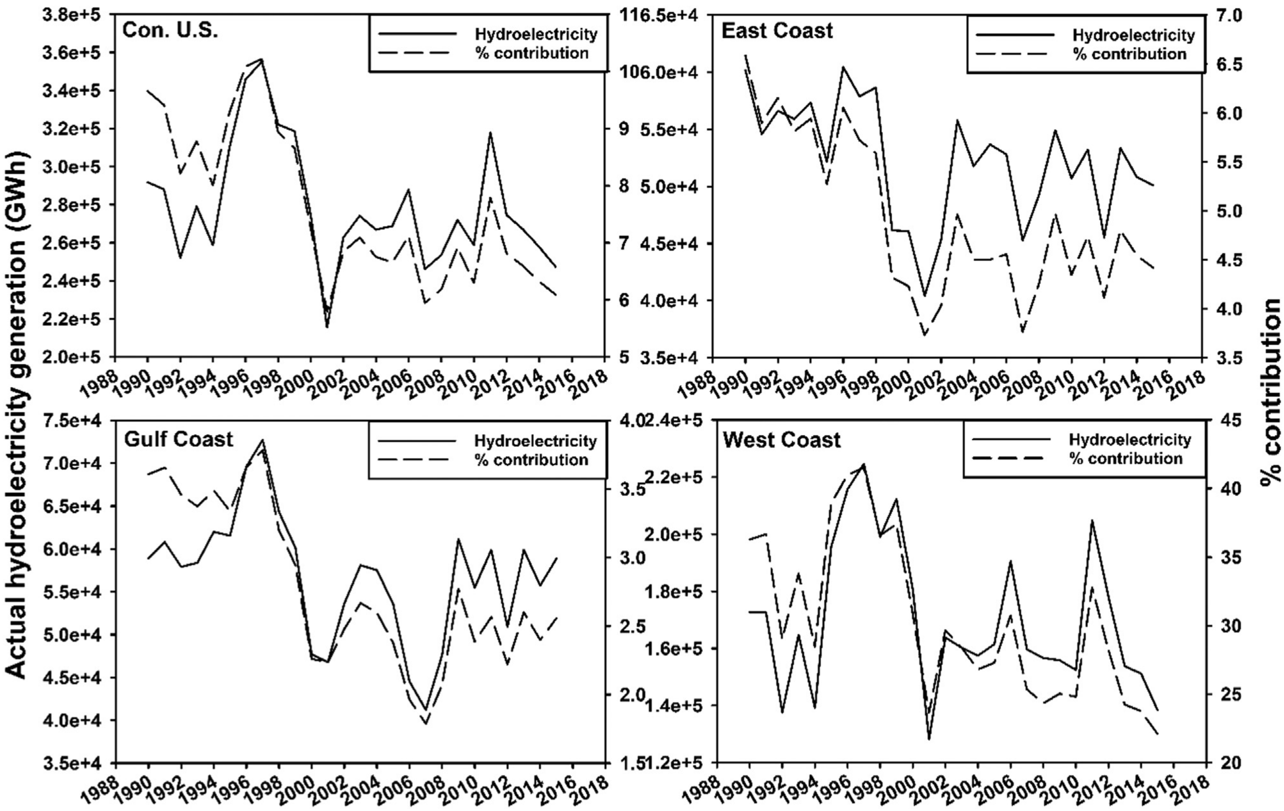

Fig. 6. Actual annual hydro-energy generation (gigawatt-hours; GWh) and relative contribution of hydroelectricity to the total energy mix (%) for the conterminous U.S. (con U.S.) and its three watershed regions, 1990–2015. Dashed lines represent the percent contribution of hydroelectricity (right axis) to the total energy production whereas solid lines represent actual energy production (left axis).

between the two regions is mainly due to the size of the water-impounding reservoirs constructed in the West Coast. Many hydropower facilities in the West Coast have been built to capitalize and compensate for the lower precipitation in the region, which is substantiated by the average annual precipitation of 759.8 mm in the West- against 1061.1 mm in the East-Coast regions. The average annual precipitation at the hydropower dams located in the Gulf Coast region is 889.2 mm, whereas it is 901.8 mm for the entire conterminous U.S.

With the escalating energy demand in various sectors, namely, industrial, residential and commercial, the total electric power generation from all generative categories has been increasing [36]. However, despite the rise in overall nameplate capacity of hydroelectricity, since 1993, its actual production has shown inconsistent patterns at the national and regional scales (Fig. 4). Moreover, the relative contribution of hydroelectricity to the total energy production has shown a downward trend for all geographic regions (Figs. 5 and 6). Since the 1990s, the percent contribution of hydroelectricity to total energy output has fluctuated from 10.2 (1997) to 5.8% (2001) in the conterminous U.S. (Fig. 5). The 26-year average of relative contribution of hydro-to-total-energy output has varied substantially between regions: Gulf Coast (2.8%), East Coast (4.9%), and West Coast (30.3%). The 26-year average for the conterminous U.S. is 7.6%.

The capacity factor (CF; i.e., actual production to nameplate capacity of hydropower dams, in percent) varies significantly by years; e.g., across the entire hydropower fleet it was 36% in 2015, 38% in 2016, and 45% in 2017 [37]. Further, variability in hydroelectricity production is correlated with environmental variation, e.g., precipitation, snowmelt, etc. Among the most important factors that determine hydropower generation are precipitation and the total number of facilities. Precipitation, however, can be modulated by water storage behind dams; American dams are capable of storing a large volume of water, equaling usually a significant fraction of a year's mean runoff [38]. Despite this, hydroelectricity generation declined from 1994 and reached its lowest value in 2001 (Fig. 4). We attempted to analyze whether the natural process (i.e., rainfall) or logistics causes (i.e., downgrading of functional hydro-facilities) drove the change. We found that annual hydroelectricity production showed a positive but not significant relationship ($r = 0.269$; $p = 0.184$) with annual precipitation of the conterminous U.S. (Fig. 7A, B). Contrarily, when monthly hydroelectricity production was correlated with mean monthly precipitation for 189 months, a significant correlation ($r = 0.273$; $p = 0.001$) emerged (Fig. 8). This relationship between precipitation and hydro-energy production at two time scales (i.e., inter-annual and monthly) may indicate that hydropower dams are able to be tuned to release the energy in quantities that can be adjusted instantly (e.g., monthly) to electricity demand, and hence the most appealing feature of hydro-resources [6]. On the other hand, despite building large reservoirs capable of holding significant volume of runoff, it is evident that hydroelectricity production depends on atmospheric and environmental factors, which sometimes may be beyond human controls, and under various proposed climate change models, its future may be unpredictable [15].

The capacity factor of conventional hydropower remains on the lower spectrum when compared among other resources. For example, within the first three months of 2018, capacity factors of hydropower were 44.9%, 48.8% and 44.8% respectively. On the other hand, capacity factors of other resources were substantially higher, namely, municipal solid waste (72–76%), biomass including wood (52–55%) and geothermal (76–80%). Additionally, wind power is nearing the capacity factor of conventional hydropower (42–44%) [37].

When the total hydropower generation was compared with the total number of facilities, a significantly positive correlation ($r = 0.509$; $p = 0.007$) was found for the U.S. and for the regional levels (Fig. 9). During the late 1990s, natural gas became more readily available and

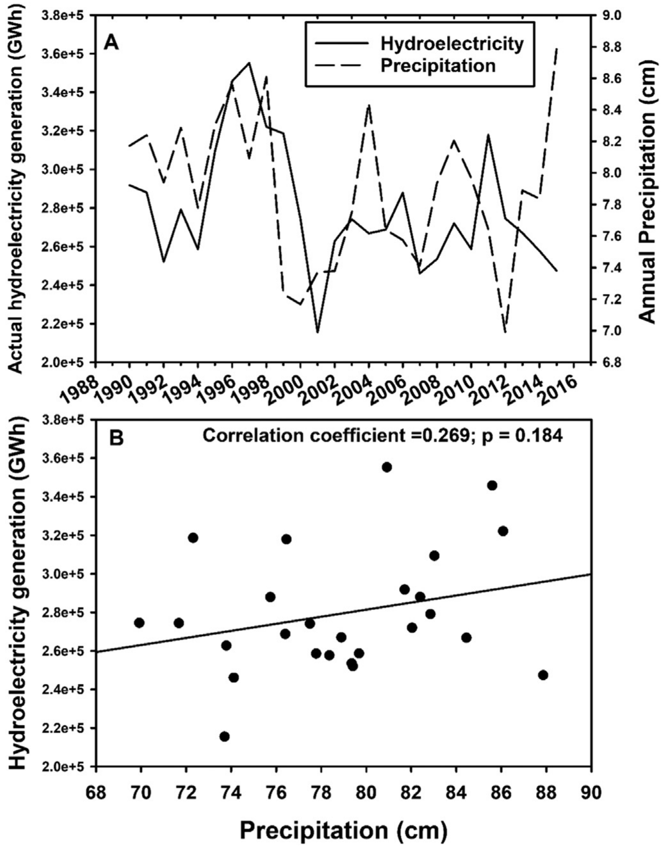

Fig. 7. A- Actual hydro-energy production (gigawatt-hours; GWh) vs. mean annual precipitation (cm) for the conterminous U.S., 1990–2015. Dashed line represents precipitation (right axis); solid line represents actual annual hydro-energy production (left axis). B- Actual annual hydro-energy (GWh) correlated against precipitation (cm) for the conterminous U.S.

cheaper as the producing fields in North Dakota, Oklahoma, Texas, and Pennsylvania went online, so hydropower's price advantage became less appealing to the American consumers [39].

Along the East Coast, New York was found to have the most hydropower stations. However, the majority of power generation capacity in New York is located in one region, in its northwestern part—around Niagara Falls. The southern states, e.g., Georgia, South Carolina, Virginia have fewer hydropower stations than the northern states, e.g., Massachusetts, New Hampshire, Vermont and Maine; however, they have higher combined potential capacity (Fig. 10). Among the Gulf States, although Texas has the most hydropower stations, Alabama has the highest production potential. In the West Coast, California has the most hydropowerstations, yet Washington has the highest potential hydroelectricity (Fig. 10).

3.4. Dam removals and planned hydro-projects

With the escalating demands of energy, dam removal may seem radical, but interests in ecological restoration and the elimination of safety hazards are countervailing forces to hydroenergy expansion. Despite some successful dam removals, conflicts may still arise between pro- and anti-hydropower advocacy groups, but a middle-path may be identified, for example, by compensating the energy production by switching to other energy resources without compromising energy production and ecological integrity of running waters, e.g., "*Shared Rivers Concept*" [40]. Although our analysis only focused on hydropower dams that generate hydroelectricity, many dams and reservoirs serve other purposes as well, therefore it will be difficult to estimate the economic, ecological, recreational and emotional values attached with such structures, if removal vs. *status quo* debates emerge.

Ongoing and planned hydropower construction from 2016 through 2019 totals 900 MW from 62 generators. Almost all of them will be located on the West Coast, except one each in Vermont (3.6 MW), Pennsylvania (5.3 MW), and Virginia (1.8 MW) (Fig. 11). Despite some advocacy by the hydropower industry for expansion and recent federal policy documents promoting hydropower [e.g., 41, 42], the small fraction of the existing hydro-fleet being constructed may indicate near exhaustion of potential economically justifiable sites. The trend toward diminishingly attractive siting opportunities is shown by the fact that in the U.S., most of the installed capacity are located in large projects built between 1930 and 1970, yet the most active decade in number of projects built was the 1980s [6]. Even the U.S. Department of Energy has shown preference towards pumped-hydro storage to conventional dam-based facilities [41]. If hydro-projects are pursued in the future, the upcoming projects may potentially fall into three broad categories [42], each with its own challenges and opportunities. These include (1) sites that are economically viable and socially and environmentally acceptable; (2) sites which are presently not economically viable but are socially and environmentally acceptable; and (3) sites which are socially and environmentally controversial or unacceptable. Careful consideration of costs and benefits will be essential to providing a rationale for possible new dam construction. Tools exist for that purpose now: The Integrative Dam Assessment Modelling tool is designed to integrate biophysical, socio-economic, and geopolitical perspectives into a cost-benefit analysis of a proposed single dam project [43].

Though the expansion of the U.S. hydropower fleet has slowed,

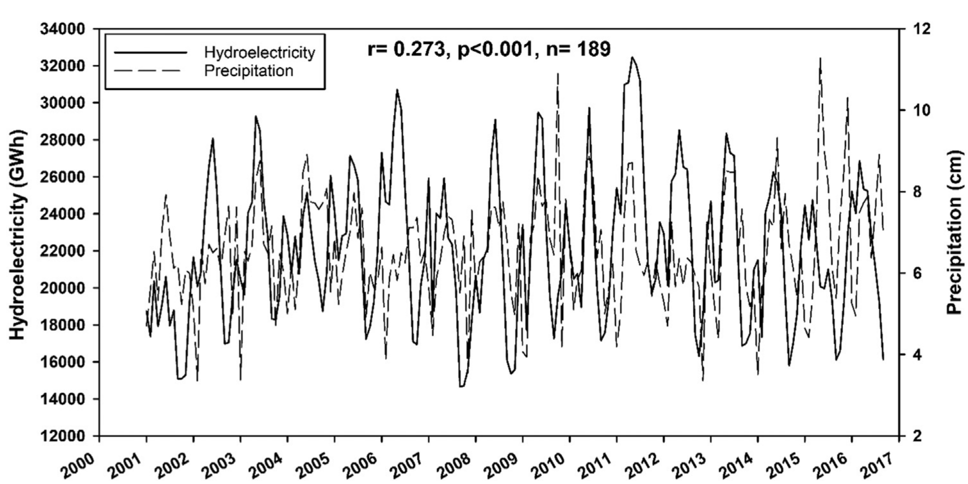

Fig. 8. Mean monthly precipitation plotted against actual hydroelectricity production for the conterminous U.S., 2001–2016.

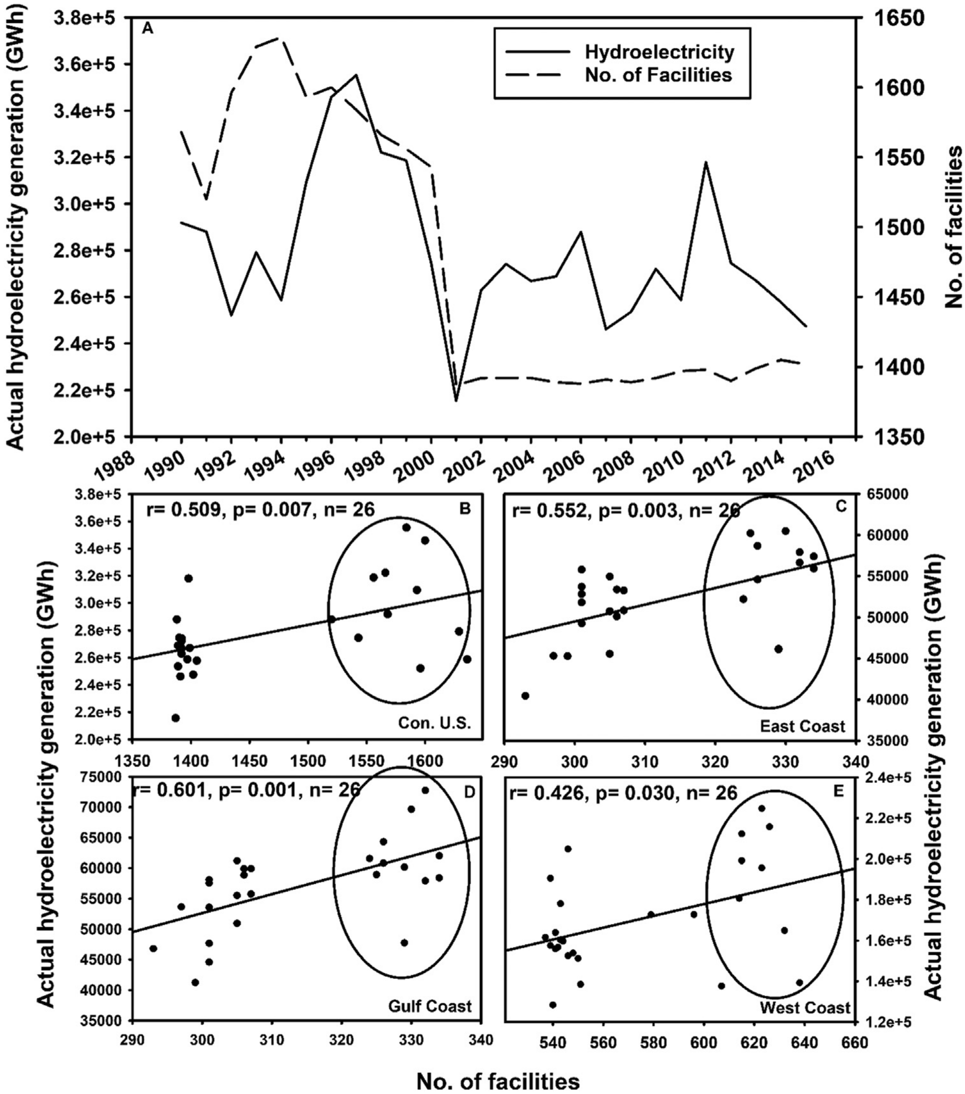

Fig. 9. (A) - Actual hydroelectricity generation (gigawatt-hours; GWh) versus the number of hydro facilities for the conterminous U.S. Dashed line represents the number of hydro-dams (right axis), solid line represents the actual annual hydroelectricity production (left axis). Actual annual hydroelectricity (GWh) correlated against number of facilities for (B) the conterminous U.S.; (C) East Coast; (D) Gulf Coast and (E) West Coast. Circles in B, C, D and E represent the cluster of (higher number of) hydro-dams before 2001.

growth is still occurring from projects that do not involve the construction of new dams. These include unit addition and upgrades at existing facilities, non-powered dams and conduit projects to which hydropower generating equipment is added and low impact, new stream-reach developments [6]. Coupled with the context of climate change, hydro-energy is predicted to get more expensive with time. It is difficult to anticipate whether the East or West Coast will endure the most climate change burden; on an average the East Coast has comparatively smaller reservoir size, and particularly, the Northeast has even smaller; however, the West Coast has been experiencing highly irregular climatic patterns [15]. Further, the periodic maintenance cost associated with old dams (national mean age: 60.5 years) and potential hazard-derived liabilities will progressively make hydro-based energy one of the most expensive energy resources. As dams become older, associated risks increase and make them more prone to failure [44]. On the other hand, there has been much recent interest in the international arena towards hydro-energy. Bartle [38] has underscored the potential of many hydropower projects in the world. In 2012, projects encompassing 105 GW were being built, mostly in Asia (84 GW) and South America (14.8 GW). The rest of the world is now moving towards the direction that the U.S. took decades ago. In some instances, despite knowing hydro-energy as a risky bet, major funding agencies (e.g., the World Bank, etc.) have embraced hydro-energy as a remedy for ameliorating energy crises in the African nations [44,45]. Maybe it is appropriate time for the rest of the world to learn from positive and negative impacts of dam-based hydroelectricity in the U.S.

4. Conclusions

The aim of this study was to analyze the current trends and status of hydroelectricity in the conterminous U.S. and its major watersheds and to determine the significance of hydropower in the changing context of national energy landscape. Data collected from several federal agencies show that both annual demand and production of electricity have been steadily increasing in the U.S.; however, the relative contribution of hydropower in the total energy mix has been declining since 1990. The percentage contribution of actual hydro-energy production in the West Coast region is slightly over 30% of the total energy; however, the share of hydro-energy floats around 7% at the national level. Despite recent emergence of other cheaper alternative energy resources, in the U.S. there continues to be interest in some new hydropower dam construction projects.

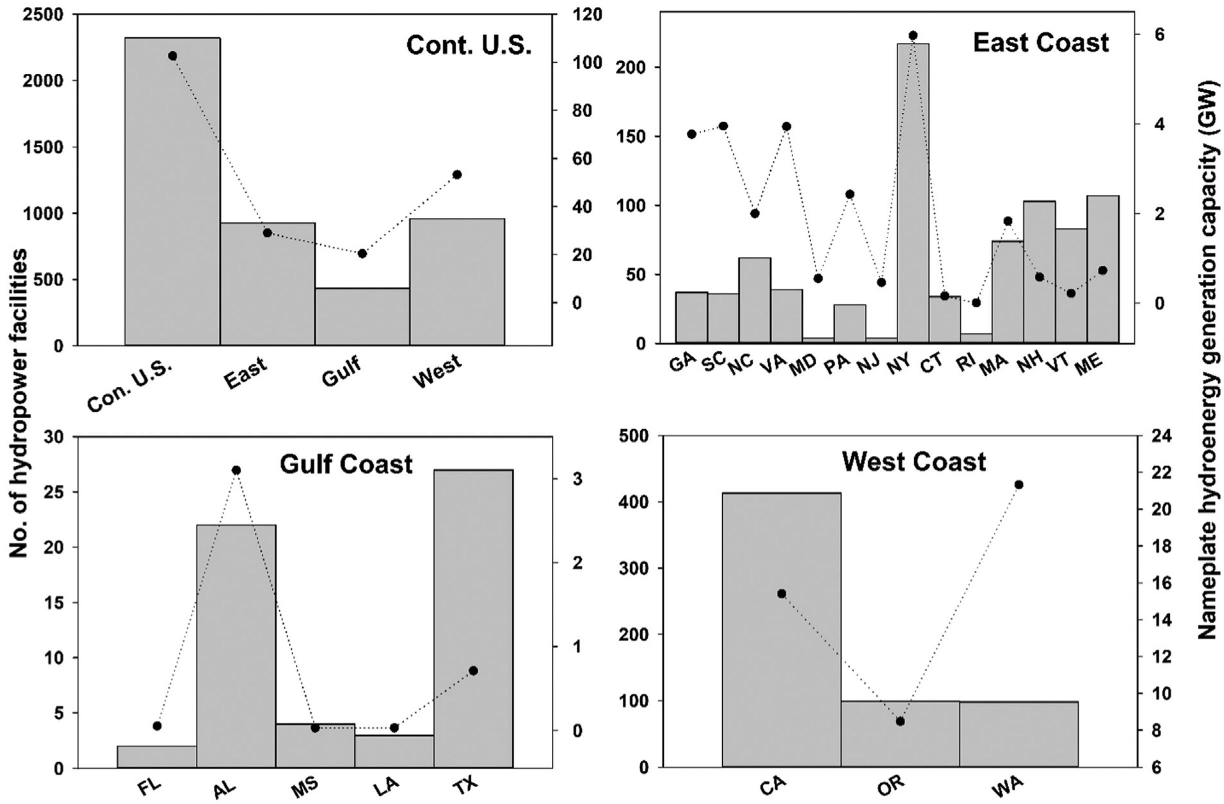

Fig. 10. No. of hydropower facilities plotted against the nameplate hydro-generation capacity (GW) for the conterminous U.S. and watershed regions. Bars represent number of hydro-dams (left axis); dotted lines represent nameplate capacity (right axis).

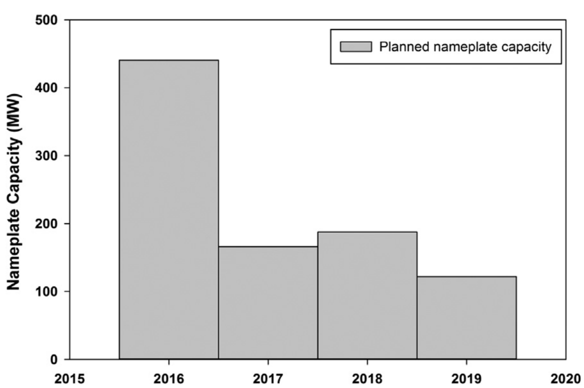

Fig. 11. Planned hydropower nameplate capacity (megawatts; MW) for the conterminous U.S., 2016–2019.

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