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我国现状能源与水纽带关系定量识别

何国华[1]，姜珊[1]，赵勇[1]，王建华[1]，朱永楠[1]，何凡[1]，韩昕雪琦[2]，李海红[1]

（1. 中国水利水电科学研究院 流域水循环模拟与调控国家重点实验室，北京 100038；
2. 西北农林科技大学 水利与建筑工程学院，陕西 杨陵 712100）

摘要：以省级行政区为研究对象，以2017年为研究时段，分析我国社会水循环过程耗能及电力生产耗水。结果显示：2017年我国社会水循环过程耗电总量为10 828.1亿 kW·h，占当年我国全社会用电总量的17.2%，终端用水是最大的耗能环节；2017年我国电力生产过程耗水量为65.7亿 m^3，占当年全社会耗水总量的2%；火电是我国最耗水的电源，其耗水量占全国电力开发耗水总量的78%。基于计算结果，提出了实现能源-水协同安全的相关建议。

关键词：水资源；能源；纽带关系；协同安全；可持续发展

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能源和水资源是人类生存、经济发展和社会进步的重要物质基础[1]。一般地，能源开采、生产、输送等过程都需要耗水，而水资源的开发、输配、终端使用、回收处理也都需要耗能[2]。根据国际能源理事会的研究结果，目前全球能源开发过程中的用水量已经达到5 830亿 m^3，是仅次于农业的第二大用水户，占全球淡水取用量的15%[3]。预计到2035年，能源生产的取水量将比2014年增加20%[4]。与此同时，全球社会水循环过程消耗的能源则高达28 334亿 kW·h，约占全球一次能源消耗总量的2.5%[5]。从全球尺度看，能源和水资源已经互相成为对方可持续发展的重要制约因素。已有研究表明：将能源和水资源作为单独系统的研究已不足以支撑决策方案的制定，甚至有误导决策的可能[6]。在全球资源需求大幅增加的背景下，只有将能源和水资源作为一个研究整体，增进两者的协同，合理配置，并不断调整人类行为，才能有助于实现区域的绿色发展[7]。

近年来，能源与水纽带关系正逐步成为世界性的热点议题。学术界关于该纽带关系的研究主要集中在以下两个方面：一是能源与水在政策、规划和变化环境下的内在联系；二是量化评估不同地区水循环过程耗能及能源循环过程耗水[8-10]。由于能源、水资源的短缺及两者之间显著的空间分异，我国已经成为全球能源与水纽带关系研究的热点地区，许多学者在黄河流域[11]、北京市[12]等典型地区，以及全国尺度[13-15]开展了能源-水纽带关系的定量研究。目前我国是世界上最大的能源生产国与消耗国，能源生产和消费的比例分别占全球的18%和23%。然而我国化石能源基地主要分布在干旱缺水的中西部地区，能源开发受水资源胁迫程度日益加剧。目前我国也是世界上最大的用水国，用水量约占全球用水总量的9%。根据全国水资源综合规划，2030年我国用水总量将增加到6 960亿 m^3，其中外调水、再生水和淡化海水等高耗能水源供给将大幅增加，这也将导致水利行业与其他行业之间的能源竞争不断加大[16]。根据姜珊等[17]的研究成果，现阶段中国能源与水问题主要面临三方面的挑战：（1）能源与水

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作者简介：何国华（1990—），男，甘肃庆阳人，博士（后），主要从事生态水文及水-能源纽带关系研究。E-mail：hegh@iwhr.com
通信作者：赵勇（1977—），男，安徽宿州人，教授级高级工程师，主要从事水资源管理研究。E-mail：zhaoyong@iwhr.com

的消费需求快速增加。(2)高耗能型的水源和高耗水型的能源的优化选择。(3)能源-水跨部门政策制定的耦合协同。

对能源与水纽带关系进行定量识别是我国经济、社会、生态可持续发展的基础，但目前学术界主要针对该纽带关系的框架概念开展研究，全国范围内的定量研究较少。基于此，以我国省级行政区为最小研究单元，选择 2017 年作为现状水平年，量化分析我国社会水循环全过程的耗电量，电力开发过程的耗水量，并基于研究结果提出我国能源与水协调发展的政策建议，以期为我国经济、资源和环境的可持续发展提供参考。

1　研究方法与数据来源

1.1　社会水循环全过程耗能核算

随着人类活动的增加，社会水循环通量越来越大，这种人类为满足自身需求而人工干预的水循环过程称为社会水循环，主要包括取水过程、制水过程、输配水过程、用水过程、排水过程和污水回用过程。社会水循环耗能是指取水、制水、输配水、用水、排水、污水回用等环节伴随的能源消耗，对社会水循环耗能进行计算的目的是提高水资源和能源的协同管理能力。

1.1.1　取水过程耗能核算

(1)地表取水。地表水取水工程主要分为引水、提水、调水等。引水过程一般是借重力作用把水资源从源地输送到用户的措施，其多依靠自流完成，耗能较小，因此本文对其能源消耗忽略不计。提水工程和调水工程多依靠电泵进行抽取，其耗能计算公式为

$$W_{提}=\frac{mgh}{3.6\times10^6\times\varepsilon} \tag{1}$$

$$W_{调}=Lm^2n^2\frac{(b+2h\sqrt{1+c^2})^{4/3}}{[(b+ch)\times h]^{10/3}} \tag{2}$$

式中：$W_{提}$ 和 $W_{调}$ 分别表示提水工程和调水工程的耗能，kW·h；m 是输水质量，kg；g 是重力加速度，N/kg；h 为水体提升高度，m；ε 为提水泵站效率，柴油泵一般取 15%，机电泵一般为 40%[18]；L 是输水长度，m；n 是渠系粗糙率；b 是渠系底宽，m；h 是水渠水面高度，m；c 为渠系边坡系数。

(2)地下水提水。地下水取水一般指利用水泵等设施从地下含水层抽取水资源，主要消耗电能或化石能源支撑电泵及柴油机克服水的重力做功，其大小取决于地下水埋深、提水量、泵站效率等。地下提水耗能计算公式为

$$W_{地下水}=\frac{mgh}{3.6\times10^6\times\varepsilon\times(1-\theta)} \tag{3}$$

式中：$W_{地下水}$ 表示地下水提水的耗能，kW·h；θ 为提水过程中的水头损失，该损失与泵站类型及提水高度有关，本研究假定 θ 为 5%[19]。

(3)淡化耗水耗能。我国海水淡化工程主要分布在天津、辽宁、河北等沿海地区，现状年海水淡化规模为 4.34 亿 m^3。目前我国海水淡化主要使用反渗透法，平均单位能耗为 6.8 kW·h/m^3[20]。

1.1.2　制水过程耗能核算

制水过程是指水厂对水源进行澄清、消毒、除臭、除味、软化等过程。水源在经过水厂的复杂处理，达到城市供水水质标准后进入供水管网。我国各省水厂制水能耗来自 2017 年《城市供水统计年鉴》[21]。

1.1.3　输配水过程耗能核算

输配水过程是指从水源到用水户之间的管网输配环节，输配水过程通常包括供水设备、输水管道、配水管网以及调节构筑物等。不同省份其输配水单位能耗不同，各地区输配水耗能数据来自 2017 年《城市供水统计年鉴》[21]。

1.1.4　用水过程耗能核算

用水过程是整个水循环过程的核心，依据我国水资源公报，我国用水户可以划分成农业、生活、工业和生态等 4 大类。考虑到农业部门用水耗能主要集中在地下水提水环节，用水过程耗能较少，故本研究不对农业用水耗能作单独考虑；由于生态用水过程耗能较少可以忽略，因此本研究只计算生活和工业的用水耗能。

(1)生活用水。生活用水是人类生存和发展的基本需求，其在一定程度上反映人们的生活水平。随着城市化进程的加快，人们生活水平提高，生活用水增加的同时也伴随着相关能源消耗的增加。生活用水耗能主要分为加热耗能和机械耗能，其中加热能耗主要是为满足居民的饮用、烹饪、洗澡时等对高温度水的需求，而机械能耗主要是通过消耗能源产生机械动力，使得用水设施正常运行(例如洗衣机)。生活用水的加热耗能和机械耗能的计算公式为

$$e_{\mathrm{h}}=\frac{[V\rho c(T_{\mathrm{t}}-T_{\mathrm{i}})]/u+E}{Q\times3.6\times10^3} \tag{4}$$

$$e_{\mathrm{m}}=\frac{B\times D\times3.6\times10^3}{Q\times3.6\times10^3} \tag{5}$$

式中：e_{h} 和 e_{m} 分别指生活用水过程中的加热耗能和机械耗能，kW·h/m^3；V 为热水器蓄水的体积，L；ρ

为水的密度，kg/L；c 为水的比热容，kJ/(kg·℃)；T_t 和 T_i 分别为加热器恒温时的温度和空气温度，℃；μ 为加热器的能耗系数；E 为备用热损失，kJ；Q 为加热过程耗水量，m³；B 为某类型洗衣机的额定功率，kW·h/kg；D 为该类型洗衣机的额定洗涤容量，kg。

(2)工业用水。根据 He 等[12]的研究成果，工业用水耗能主要集中在加热耗能环节。工业用水加热一方面直接产生热水或蒸汽，为生产生活提供热能，另一方面则通过动力装置将蒸汽转化为机械能，或进一步将机械能转化为电能。加热耗能的计算公式为

$$e_I=\frac{cm(T_h-T_i)}{3.6\times10^6\times\gamma} \tag{6}$$

式中：e_I 为锅炉加热耗能，kW·h/m³；T_h 为工业用水需要加热到的温度，℃；γ 为锅炉的加热效率，一般为 75%。

1.1.5　排水过程耗能核算

排水过程主要指污水的收集、输送、水质的处理和排放等过程。2017 年我国污水排放量为 756 亿 m³，其中被处理的污水量为 453 亿 m³。2017 年我国各污水处理厂的耗能数据来自《城镇排水统计年鉴》[21]。

1.1.6　再生水处理过程耗能核算

由于污水成分的复杂性以及回用的用途不同，再生水处理工艺差别较大，因此本研究利用全国平均值计算污水回用过程耗能。根据 2017 年《城镇排水统计年鉴》[21]，全国再生水处理单位能耗平均为 0.82 kW·h/m³。

1.2　电力生产过程耗水核算

能源产业是我国的耗水大户，根据我国能源结构，本研究计算了 6 种主要电力能源(火电、核电、水电、生物质能发电、太阳能发电和风力发电)的发电过程的耗水量。由于不同电厂耗水详细数据难以获取，因此电力生产耗水计算主要使用定额法，不同电源的耗水强度见表 1。

1.3　数据来源

本研究中各省引水、提水和调水数据来自《中国水利统计年鉴》[32]，地下水用水数据及各行业用水量来自《中国水资源公报》[33]，不同地区地表水提水扬程数据来自《全国大型灌溉排水泵站更新改造方案》[34]，地下水埋深数据来自《中国地质环境监测地下水位年鉴》[35]，制水耗能数据和输配水耗能数据来自《城市供水统计年鉴》，不同电源发电数据来自于《中国能源统计年鉴》[36]和《中国电力工业统计资料汇编》[37]，不同调水工程的渠系信息来自于各工程实施规划。

表 1　不同电力来源发电耗水定额

分类	电力来源	耗水强度/(L·kW·h⁻¹)	数据来源
火电	直流冷却	0.38～2.31	[23][24]
	循环冷却(塔)	1.10～2.60	
	循环冷却(池塘)	1.02～3.38	
核电	直流冷却	0.65～1.50	[25][26]
	循环冷却(塔)	1.33～3.20	
	循环冷却(池塘)	1.33～2.70	
水电	—	1.80	[27]
生物质发电	—	25.00～35.00	[28]
太阳能发电	光伏发电	0.02	[29]
	光热发电	2.80～3.30	[30]
风电	—	0～0.05	[31]

2　结果与讨论

2.1　社会水循环全过程耗能解析

2017 年我国社会水循环过程耗电总量为 10 828.1亿 kW·h，占当年我国全社会用电总量的 17.2%。根据图 1，用水过程是社会水循环耗能最多的环节，其中工业用水耗能为5 701.1亿 kW·h，生活用水耗能为3 833.1亿 kW·h，分别占整个水循环耗能总量的 52.7%和 35.4%。工业用水和生活用水是 21 世纪以来我国用水增幅上升较快的行业，随着未来工业和人口规模的进一步扩大，我国工业、生活用水量及能源消耗量可能会进一步增加。取水是社会水循环过程中的第二大耗能环节，耗电量为 840.8 亿 kW·h，占水循环耗能总量的 7.8%。供水，输水和排水过程耗能较小，分别占全社会耗能总量的 1.1%、1.4%和 1.1%。从总量来看，再生水处理的耗能要小于地表水和地下水开发；但从单位耗能来看，再生水的耗能(0.82 kW·h/m³)要大于地表水(0.15 kW·h/m³)和地下水(0.32 kW·h/m³)。大量使用再生水可以有效缓解我国水资源压力，但这意味着要付出更多的能源代价。

2.2　社会水循环过程耗能空间分异

由于水资源本底条件及产业结构的差异，我国 31 省(自治区、直辖市)水循环耗能差异很大(图 2)。江苏是我国用水量最大的省份，其 2017 年用水量占全国用水总量的 9.8%，江苏同时也是社会水循环耗能最高的省区，其 2017 年耗能总量达1 491.3亿 kW·h，占全国耗能总量的 13.8%。西藏则是社会水循环耗能最小的省区，2017 年耗能总量为 21.11 亿 kW·h，仅占全国总量的 0.2%，是江苏的 1/70。从分区来看，由于南北用水规模的差异，南方各省区的水循环

耗能普遍大于北方,2017 年南北水循环耗能总量分别为8 682.4亿和2 145.8亿 kW · h,北方仅是南方的 1/4。总的来看,无论在南方还是北方,终端用水过程都是各地区水循环过程中最耗能的环节。考虑到用水环节中水资源和能源消耗的一致性,在用水终端实行节水措施,可以达到节水和节能的双赢目标。

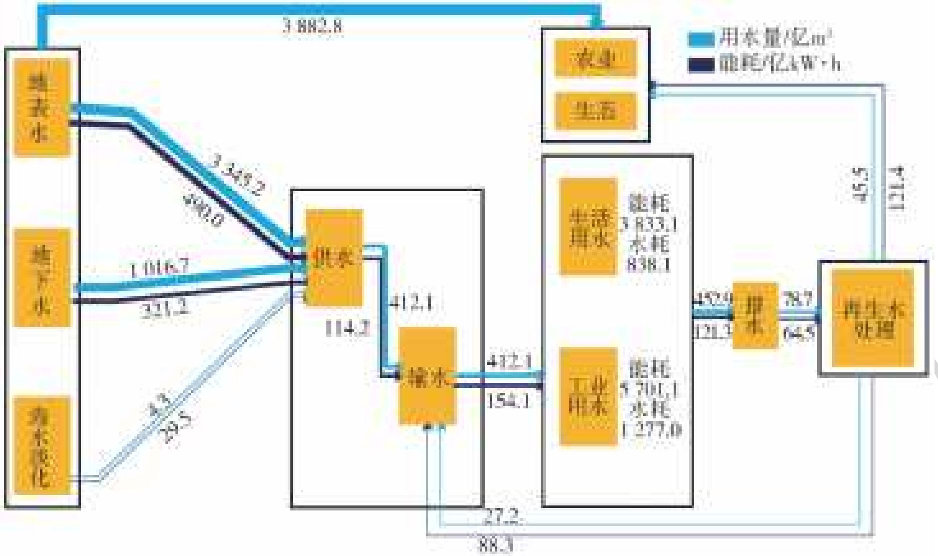

图 1　**2017 年我国 31 省(自治区、直辖市)社会水循环过程耗能**

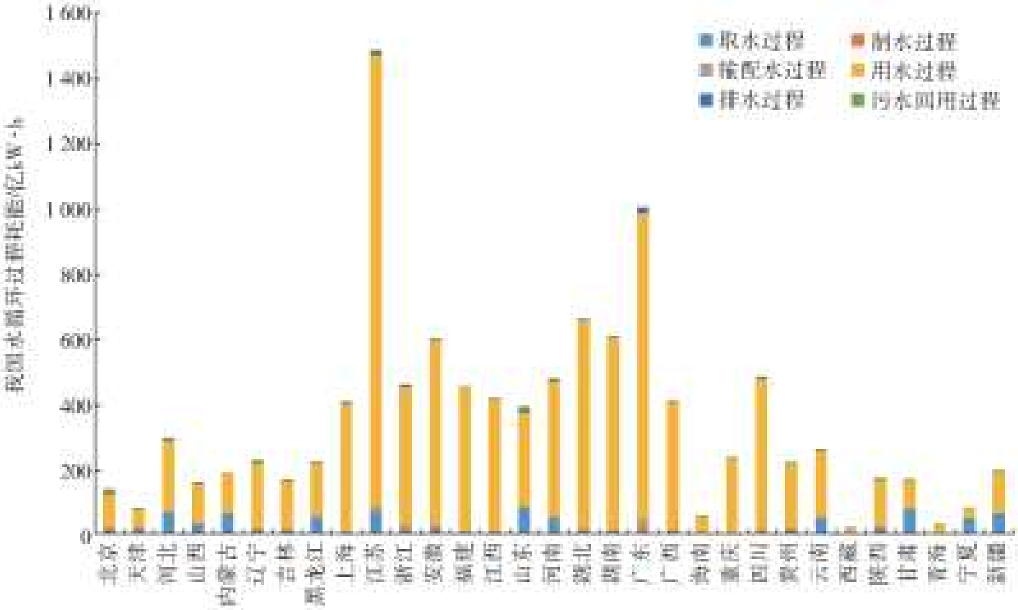

图 2　**2017 年我国 31 省(自治区、直辖市)水循环过程耗能**

2.3　电力生产过程耗水解析

2017 年我国电力生产过程耗水量达 65.7 亿 m³,占当年全社会耗水总量的 2%(图 3)。火电是我国最耗水的电源,其耗水量占全国电力开发耗水总量的 78%。这主要是由于我国的煤炭资源相对丰富,煤储量占中国化石能源储量的 96%,同时火电作为当前主要的电力生产结构,发电量占全国总量的比例高达 76%。核能发电的主要耗水环节为冷却用水。2017 年我国核电耗水量为 6.39 亿 m³,占发电耗水总量的 7.5%。在水力发电过程中,将生产单位能源所需要消耗的水库蒸发量作为为其耗水量,2017 年我国水电耗水总量约为 4.96 亿 m³,考虑到国内现有水电站普遍具有防洪、供水、发电多重目标,本研究计算结果可能高估了水力发电环节的耗水量。由于发电规模较小,我国生物质能、太阳能和风能发电耗水量较低,2017 年耗水总量仅分别为 1.71 亿、0.12 亿和 1.61 亿 m³。对比不同电源的耗水强度可以看出,风电和光伏发电是目前最为节水的电源产品,大力发展风电、太阳能等清洁能源不仅有利于我国生态环境保护、气候变化控制,也有利于缓解我国水资源供需矛盾。

图 3　**2017 年我国 31 省(自治区、直辖市)电力开发耗水量**

2.4　电力生产过程耗水空间分异

电力生产过程中的耗水量受当地发电量、发电技术及电力结构的影响。图 4 显示了 2017 年我国不同省区电力生产过程的耗水情况，其中山东、江苏、内蒙古火力发电耗水量较高，这主要由于该地区火力发电量规模较大，2017 年山东、江苏、内蒙古火力发电量分别为4 378亿、3 823亿和3 726亿 kW·h，分别占全国火力发电总量的10.56%、9.21%和 8.98%。我国核电站主要分布于沿海地区，2017 年广东、福建和浙江核电开发耗水量分别占核电开发耗水总量的 32%、23%和21%。西南地区是我国最主要的水电能源基地，其水电资源量占全国总量的比重高达 66.7%，据研究计算：2017 年四川省水电耗水量为 1.58 亿 m³，占全省电力开发耗水量的 73%；2017 年云南水电耗水量为 1.25 亿 m³，占全省电力开发耗水 82%。水电已成为这两个省份最主要的电力生产耗水部门。我国清洁能源耗水量较少，其中风电耗水主要集中在北方省区，而生物质能发电耗水则主要集中于江苏、浙江、安徽、山东和广东。

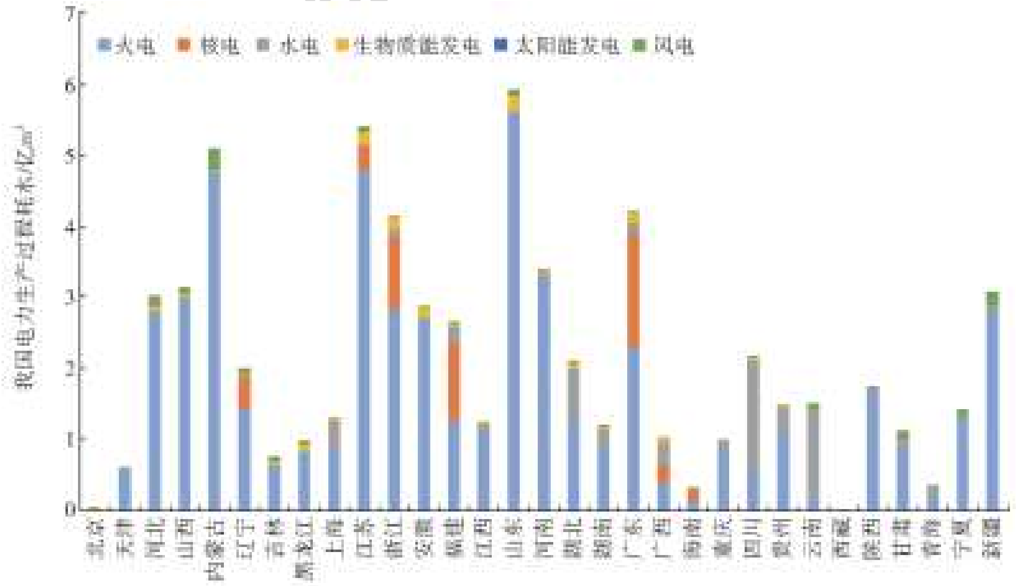

图 4　**2017 年我国 31 省(自治区、直辖市)电力开发耗水量**

3　结论与建议

3.1　结　论

本文分析了 2017 年我国 31 省(自治区、直辖市)的社会水循环耗能和电力开发耗水，得出以下结论。

(1)2017 年我国社会水循环过程耗电总量为10 828.1亿 kW·h，占当年我国全社会耗电总量的

17.2%。终端用水是最大的耗能环节，占社会水循环耗能总量的88.1%。分区来看，江苏和西藏分别是我国社会水循环耗能最大和最小的省区，2017年耗能量分别为1491.3亿和21.11亿kW·h。

(2)2017年我国电力生产过程的耗水量达到65.7亿m^3，占当年全社会耗水总量的2%。火电是我国最耗水的电源，其耗水量占全国电力开发耗水总量的78%。核电和水电开发的耗水量分别为6.39亿和4.96亿m^3，风电、太阳能发电和生物质能发电耗水量相对较小。分区来看，山东和西藏分别是电力开发耗水最大和最小的省区，耗水量分别是5.93亿和0.03亿m^3。

3.2　建　议

由于中国水资源和能源的空间分布上的不均匀，水资源开发耗能及能源开发耗水已经分别对区域能源安全和水安全产生较大影响。为了实现水资源和能源的协同安全，本文基于研究结果提出以下4点建议。

(1)终端用水是社会水循环过程中最大的耗能环节，考虑到此环节用水和用能过程的一致性，在用水端开展高效节水能够有效地提高水、能源利用效率，达到节水和节能的双重目的。

(2)西北化石能源基地是我国未来的主要能源输出区，尽管现阶段西北电力生产过程耗水量较少，但考虑到未来能源开发规模的增加和水资源短缺情形，需要进一步开展西北能源-水纽带关系研究，完善西北化石能源基地的水资源保障。

(3)开发太阳能、风能等清洁能源的耗水强度显著低于火电、核电，在我国大力开发清洁能源不仅有利于减少污染、改善能源结构，也有利于水资源的节约与保护。

(4)要基于不同地区发展特点和资源禀赋条件建立水资源-能源系统管理理念，在水资源开发过程中考虑能源影响，在能源开发过程中考虑水资源制约，实现我国水资源-能源的协同安全。

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Quantitative identification of the relationship between water-energy nexus in China

HE Guohua[1], JIANG Shan[1], ZHAO Yong[1], WANG Jianhua[1],
ZHU Yongnan[1], HE Fan[1], HAN Xinxueqi[2], LI Haihong[1]

(1. State Key Laboratory of Simulation and Regulation of Water Cycle in River basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China; 2. College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, China)

Abstract: The energy consumption of China's social water cycle process and the water consumption of power production is analyzed by taking provincial administrative regions as the research object and year 2017 as the research period. The results showed that: The total power consumption of China's social water cycle process is 1 082.81 billion kW·h, accounting for 17.2% of the total power consumption of China's society in 2017; Terminal water consumption is the biggest energy consumption. In 2017, China's electricity production is consumed 6.57 billion m^3 of water, accounting for 2% of the total social water consumption; and Thermal power is the most water-consuming power source in China, accounting for 78% of the total water consumption in the country's electric power development. Based on the calculated results, relevant suggestions are put forword for realizing energy-water coordinated security.

Key words: water resource; energy; nexus; cooperative security; sustainable development

Energy and water resources are important material bases for human survival, economic development and social progress[1]. Generally, the processes of energy extraction, production and transportation require water consumption, and the development, transmission and distribution, terminal use and recycling of water resources also require energy consumption[2]. According to the research results of the IEA, the global water consumption in the process of energy development has reached 583 billion m^3, which is the second largest user of water after agriculture, accounting for 15% of the global fresh water consumption[3]. It is estimated that by 2035, water withdrawals from energy production will increase by 20% compared with 2014[4]. At the same time, the energy consumed in the water cycle of the global society is as high as 2 833.4 billion kW·h, accounting for about 2.5% of the total energy consumption of the global primary energy[5]. On a global scale, energy and water resources have become important constraints to each other's sustainable development. Previous studies have shown that the study of energy and water resources as a separate system is not enough to support the formulation of decision-making schemes, and it may even mislead the decision-mak-

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Author brief: HE Guohua (1990-), male, Qing yang, Gansu province, postdoctoral, mainly engaged in the research of eco-hydrology and water-energy bond. E-mail: hegh@iwhr.com

Corresponding author: ZHAO Yong (1977-), male, Suzhou, Anhui Province, professor level senior engineer, mainly engaged in water resource management research. E-mail: zhaoyong@iwhr.com ing[6]. In the context of the substantial increase in global resource demand, only by taking energy and water resources as a research body, enhancing the coordination, rational allocation and constantly adjusting human behavior, can the green development of the region be realized[7].

In recent years, the relationship between energy and water is becoming a hot topic in the world. The academic research on this link mainly focuses on the following two aspects: The first is the internal connection between energy and water in the policy, planning and changing environment; The second is to quantitatively assess the energy consumption and water consumption of the water cycle in different regions[8-10]. Due to the shortage of energy and water resources and the significant spatial difference between them, China has become a hot spot in the research on the global energy and water nexus. Many scholars have carried out quantitative research on the energy-water nexus in typical areas such as the Yellow River basin[11], Beijing[12] and the national scale[13-15]. At present, China is the largest producer and consumer of energy in the world, with the proportion of energy production and consumption accounting for 18% and 23% of the global total respectively. However, China's fossil energy base is mainly distributed in the arid central and western regions, and energy development is increasingly stressed by water resources. At present, China is also the largest user of water in the world, accounting for about 9% of the global total. According to the national comprehensive plan on water resources, China's total water use will increase to 696 billion m^3 in 2030, among which the supply of energy-intensive water resources such as external water diversion, renewable water and desalinated seawater will increase substantially, which will also lead to increased energy competition between the water conservancy industry and other industries[16]. According to the research results of Jiang Shan et al. [17], at present, China's energy and water problems are mainly faced with three challenges: 1) rapidly increasing consumption demand of energy and water; 2) the optimal selection of energy-intensive water sources and water-intensive energy sources; 3) the coupling and coordination of energy-water cross-sector policy making.

The quantitative identification of the relationship between energy and water is the basis of China's economic, social and ecological sustainable development. But at present, the academic circles mainly carry out research on the framework concept of this bond, and there are few quantitative researches in the whole country. Based on this, this article takes the provincial administrative region for the study of the smallest unit, choose 2017 as the current level year. The electricity consumption in the whole process of water cycle and the water consumption in the process of power development are quantitatively analyzed, and based on the research results, the policy suggestions for the coordinated development of energy and water in China are put forward, so as to provide references for the sustainable development of economy, resources and environment in China.

1 Methods and data

1.1 Calculation of energy consumption of the whole process of social water cycle

With the increase of human activities, the social water circulation flux is increasing. This water circulation process that human beings artificially intervene in order to meet their own needs is called the social water circulation, which mainly includes the water intake process, water production process, water transmission and distribution process, water use process, drainage process and sewage reuse process. Social water cycle energy consumption refers to the energy consumption associated with water intake, water production, water transmission and distribution, water use, drainage and sewage reuse. The purpose of calculating social water cycle energy consumption is to improve the collaborative management ability of water resources and energy.

1.1.1 Calculation of energy consumption during water intake

(1) Surface water intake. Surface water intake project is mainly divided into water diversion, wa-

ter lift, water transfer. The process of water diversion is generally a measure to transport water resources from the source to the user by gravity, which is mostly completed by artesian flow and requires less energy. Therefore, the energy consumption is neglected in this paper. The water lifting project and water transfer project rely on the electric pump for extraction, and the energy consumption calculation formula is shown in formula (1) and (2).

$$W_l = \frac{mgh}{3.6\times 10^6 \times \varepsilon} \tag{1}$$

$$W_t = L\, m^2\, n^2\, \frac{(b+2h\sqrt{1+c^2})^{4/3}}{[(b+ch)\times h]^{10/3}} \tag{2}$$

where: W_l and W_t represents the energy consumption of the water lifting project and the water transfer project respectively, kW・h; m is water quality, kg; g is the acceleration of gravity, N/kg; h is the lifting height of water body, m; ε is the efficiency of the pumping station, diesel pump is generally 15%, and electromechanical pump is generally 40%[18]; L is the length of water delivery, m; n is the roughness rate of canal system; b is the canal system bottom width, m; h is the water surface height of the channel, m; c is the slope coefficient of canal system.

(2) Groundwater extraction. Groundwater intake generally refers to the use of water pumps and other facilities to extract water from the underground aquifer. It mainly consumes electricity or fossil energy to support the electric pumps and diesel engines to do work against the gravity of water, its size depends on the groundwater depth, the amount of delivery water, pump station efficiency. The calculation formula of the energy consumption of groundwater is as follows

$$W_g = \frac{mgh}{3.6\times 10^6 \times \varepsilon \times (1-\theta)} \tag{3}$$

where: W_g represents the energy consumption of groundwater to carry water, kW・h; θ is the head loss in the process of water extraction, which is related to the type of pump station and the height of water extraction, and in this study it is assumed that is 5%[19].

(3) Energy consumption of sea water desalination. Seawater desalination projects in China are mainly distributed in coastal areas such as Tianjin, Liaoning and Hebei, with the current annual desalination scale of 434 million m^3. Currently, reverse osmosis method is mainly used in seawater desalination in China, and the average unit energy consumption is 6.8 kW・h/m^3[20].

1.1.2　Calculation of energy consumption during water production process

The process of water production refers to the process of water plant to clarify, disinfect, deodorize and soften the water source. After the complex treatment of the water plant, the water will enter the water supply network after meeting the water quality standard of the city. The energy consumption of water produced by water plants in various provinces in China comes from the *Statistical Yearbook of Urban Water Supply* in 2017[21].

1.1.3　Calculation of energy consumption during water transmission and distribution process

The process of water transmission and distribution refers to the link of pipe network transmission and distribution from the source to the user. The process of water transmission and distribution usually includes water supply equipment, water pipelines, water distribution networks and regulating structures. The energy consumption per unit of water transmission and distribution in different provinces is different, and the data of water transmission and distribution energy consumption in each region is from the *Statistical Yearbook of Urban Water Supply* in 2017[21].

1.1.4　Calculation of energy consumption during water use process

Water use process is the core of the whole water cycle process. According to China′s water resources bulletin, Chinese water users can be divided into four categories: agricultural, domestic, industry, and ecology. Considering that the energy consumption of the agricultural sector water use is mainly concentrated in the groundwater water carrying process and the energy consumption in the water using process is less, this study does not consider the energy consumption of agricultural water use separately. Since the energy consumption of ecological water use process is negligible, this study only calculates the energy consumption of domestic and industrial water use.

(1) Domestic water use. Domestic water is the basic demand for human survival and development, which reflects people's living standard to some extent. With the acceleration of urbanization and the improvement of people's living standard, the increase of domestic water consumption is accompanied by the increase of related energy consumption. Domestic water consumption is mainly divided into heating energy consumption and mechanical energy consumption. Among them, heating energy consumption is mainly used to meet residents' demand for high-temperature water for drinking, cooking and bathing, while mechanical energy consumption is mainly used to generate mechanical power through energy consumption to make water facilities run normally (such as washing machines). The calculation formulas of heating energy consumption and mechanical energy consumption of domestic water use are shown in formula (4) and (5) respectively

$$e_{\mathrm{h}}=\frac{[V\rho c(T_{\mathrm{t}}-T_{\mathrm{i}})]/u+E}{Q\times 3.6\times 10^{3}} \tag{4}$$

$$e_{\mathrm{m}}=\frac{B\times D\times 3\,600}{Q\times 3.6\times 10^{3}} \tag{5}$$

where: e_{h} and e_{m} respectively refers to the heating and mechanical energy consumption in the process of domestic water consumption, kW · h/m^3; V is the storage volume of the water heater, L; ρ is the density of water, kg/L; c is the specific heat capacity of water, kJ/(kg · ℃); T_{t} and T_{i} are respectively the temperature of the heater under constant temperature and air temperature, ℃; μ is the energy consumption coefficient of the heater; E is standby heat loss, kJ; Q is water consumption in the heating process, m^3; B is the rated power of a type of washing machine, kW · h/kg; D is the rated washing capacity of this type of washing machine, kg.

(2) Industry water use. According to the research results of He et al.[12], the energy consumption of industrial water mainly focuses on the heating energy consumption. On the one hand, industrial water heating directly produces hot water or steam to provide heat energy for production and life. On the other hand, steam is converted into mechanical energy by power plant, or mechanical energy is further converted into electrical energy. The calculation formula of heating energy consumption is as follows

$$e_{\mathrm{I}}=\frac{cm(T_{\mathrm{h}}-T_{\mathrm{i}})}{3.6\times 10^{6}\times\gamma} \tag{6}$$

where: e_{I} is energy consumption for boiler heating, kW · h/m^3; T_{h} is the temperature to which industrial water needs to be heated, ℃; γ is boiler heat efficiency, average of 75%.

1.1.5 Calculation of energy consumption during drainage process

The drainage process mainly refers to the process of sewage collection, transportation, water quality treatment and discharge. In 2017, China's sewage discharge was 75.6 billion m^3, of which 45.3 billion m^3 was treated. The energy consumption data of China's sewage treatment plants in 2017 came from the *Urban Water Drainage Statistical Yearbook* in 2017[22].

1.1.6 Calculation of energy consumption during drainage process regenerated water treatment process

Due to the complexity and different reuse purposes of sewage components, the treatment processes of reclaimed water vary greatly. Therefore, the national average was used to calculate the energy consumption of sewage reuse process. According to the *Urban Water Drainage Statistical Yearbook* in 2017[22], the national average energy consumption per unit of renewable water treatment is 0.82 kW · h/m^3.

1.2 Calculation of water consumption during power production process

The energy industry is a major water user in China. According to the energy structure of China, this study calculated the water consumption of power generation processes of six major power sources (thermal, nuclear, hydro, biomass, solar and wind). Since detailed data of water consumption of different power plants are difficult to obtain, the calculation of water consumption of electricity production mainly uses the quota method.

The water consumption intensity of different power sources is shown in Tab. 1.

Tab. 1 Water consumption quota of different power sources

Category	Power source	Water consumption intensity/(L•kW•h^{-1})	Data sources
Thermal power	Once-through cooling	0.38～2.31	[23][24]
	Circulating cooling (tower)	1.10～2.60	
	Circulation cooling (pond)	1.02～3.38	
Nuclear power	Once-through cooling	0.65～1.50	[25][26]
	Circulating cooling(tower)	1.33～3.20	
	Circulation cooling (pond)	1.33～2.70	
Hydropower	—	1.80	[27]
Biomass power generation	—	25.00～35.00	[28]
Solar power generation	Photovoltaic power	0.02	[29]
	generation solar power	2.80～3.30	[30]
Wind power	—	0～0.05	[31]

1.3 Data sources

In this study the provincial water diversion, handling, and water transfer data from the *China Water Statistics Yearbook*[32], groundwater water data and water use in various industries from the *China Water Resources Bulletin*[33], surface water lifting head data in different regions are obtainedfrom the *Renovation Plan for Large Irrigation and Drainage Pump Stations in China*[34]. Groundwater depth data from *China Geological Environment Monitoring Underground Water Level Yearbook*[35], energy consumption data of water production and water transmission and distribution data from the urban water supply statistical yearbook, power generation data of different power sources come from *China Energy Statistical Yearbook*[36] and *Compilation Statistics of China's Electric Power Industry*[37]. The canal system information of different water diversion projects comes from each project implementation plan.

2 Results and discussion

2.1 Analysis of energy consumption of the whole process of social water cycle

In 2017, the total amount of electricity consumed during the water cycle in China was 1 082.81 billion kW • h, accounting for 17.2% of the total amount of electricity consumed in the whole society. According to Fig. 1, the water-using process is the link that consumes the most water in the social water cycle, in which the energy consumption of industrial water is 570.11 billion kW • h, and that of domestic water is 383.31 billion kW • h, accounting for 52.7% and 35.4% of the total energy consumption of the whole water cycle respectively. Since the 21st century, the industrial water and domestic water are the industries with a rapid increase in China's water consumption. With the further expansion of industry and population in the future, China's industrial and domestic water consumption and energy consumption may further increase. Water intake is the second major energy consumption link in the water cycle, consuming 84.08 billion kW • h of electricity , accounting for

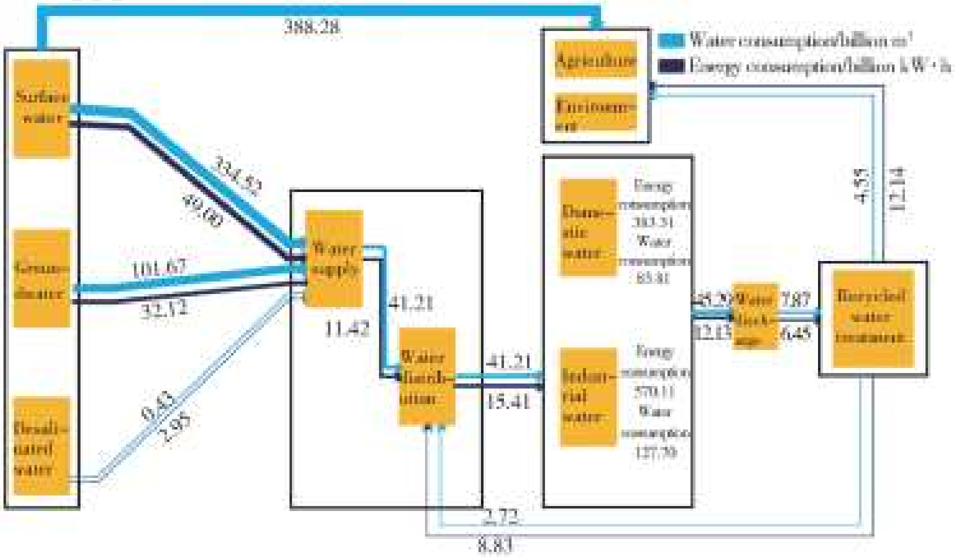

Fig. 1 Energy consumption in social water cycle process 31 provinces(autonomous regions and municipalities)of China in 2017

7.8% of the total energy consumption of the water cycle. The processes of water supply, conveyance and drainage consume less energy, accounting for 1.1%, 1.4% and 1.1% of the total energy consumption of the whole society respectively. In terms of total amount, the energy consumption of reclaimed water treatment is less than that of surface water and groundwater development. However, from the point of view of energy consumption, the energy consumption of single water of reclaimed water (0.82 kW · h/m^3) is higher than that of surface water (0.15 kW · h/m^3) and groundwater (0.32 kW · h/m^3). The extensive use of renewable water can effectively relieve the pressure of water resources in our country, but it means that we have to pay more energy costs.

2.2 The spatial difference of energy consumption in the social water cycle

Due to the differences of water resources background conditions and industrial structure, the energy consumption of water cycle varies greatly in 31 provinces (autonomous regions and municipalities) of China (Fig. 2). Jiangsu is the province with the largest amount of water consumption in China, accounting for 9.8% of China's total water consumption in 2017. Meanwhile, Jiangsu is also the province with the highest energy consumption of water cycle in the society. Its total energy consumption in 2017 reached 149.13 billion kW · h, accounting for 13.8% of the country's total energy consumption. Xizang is the province that consumes the least amount of water in the society. In 2017, its total energy consumption was 2.111 billion kW · h, only accounting for 0.2% of the national total and 1/70 of that of Jiangsu. From the perspective of zoning, due to the difference in water use scale between the north and south, the water cycle energy consumption of the southern provinces is generally higher than that of the north. In 2017, the total water cycle energy consumption of the north and south was 868.24 billion and 214.58 billion kW · h, respectively, with the north only one quarter of that of the south. In general, whether in the south or the north, the terminal water use process is the most energy consuming part of the water cycle in each region. Considering the consistency of the consumption of water resources and energy in the process of water use, the implementation of water-saving measures in the water use terminal can achieve the win-win goal of water saving and energy saving.

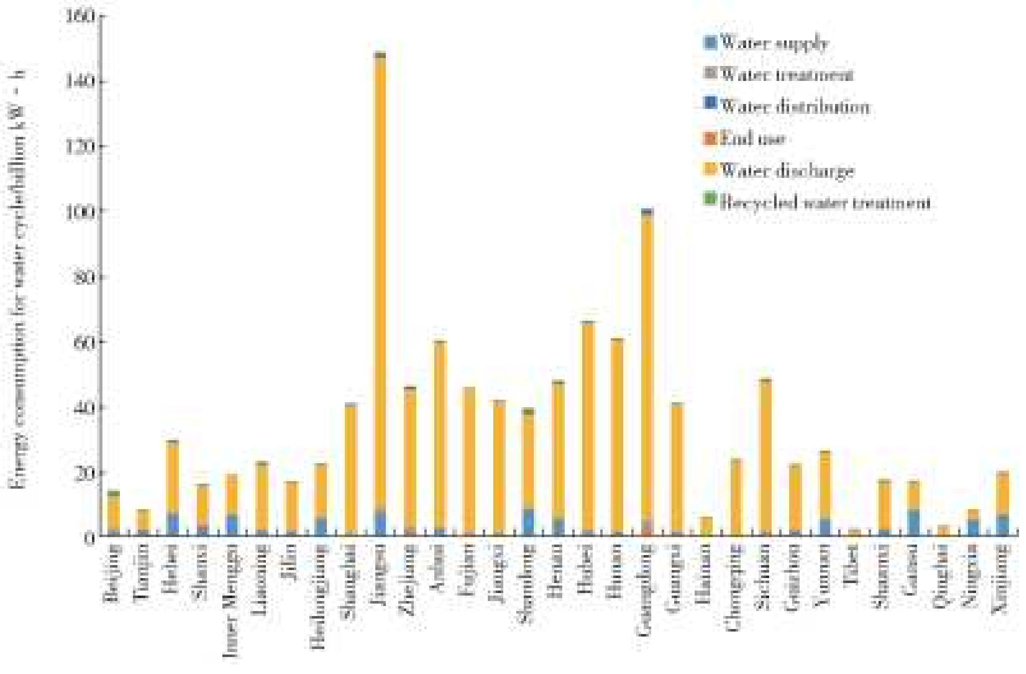

Fig. 2 Energy consumption in water cycle process in different provinces 31 provinces (autonomous regions and municipalities) of China in 2017

2.3 Analysis of water consumption in power production process

In 2017, China's electricity production process consumed 6.57 billion m^3 of water, accounting for

2% of the total water consumption of the whole society(Fig. 3). Thermal power is the most water-consuming power source in China, accounting for 78% of the total water consumption of the national power development. This is mainly due to the relatively rich coal resources in China, with coal reserves accounting for 96% of China's fossil energy reserves. At the same time, thermal power generation, as the main power production structure, accounts for 76% of China's total power generation. The main water consumption of nuclear power generation is cooling water. In 2017, China's water consumption of nuclear power was 639 million m^3, accounting for 7.5% of the total water consumption for power generation. In the process of hydropower generation, the evaporation capacity of the reservoir required for each unit of energy production is taken as its water consumption. In 2017, China's total water consumption of hydropower is about 496 million m^3. Considering the multiple objectives of flood control, water supply and power generation, the calculation results of this study may overestimate the water consumption of hydropower. Due to the small scale of power generation, biomass energy, solar energy and wind energy in China consume less water. In 2017, the total water consumption was only 171 million, 12 million and 161 million m^3 respectively. By comparing the water consumption intensity of different power sources, it can be seen that wind power and photovoltaic power generation are the most water-saving power products at present. The vigorous development of clean energy such as wind power and solar power is not only conducive to the ecological environment protection and climate change control in China, but also conducive to easing the contradiction between the supply and demand of water resources in China.

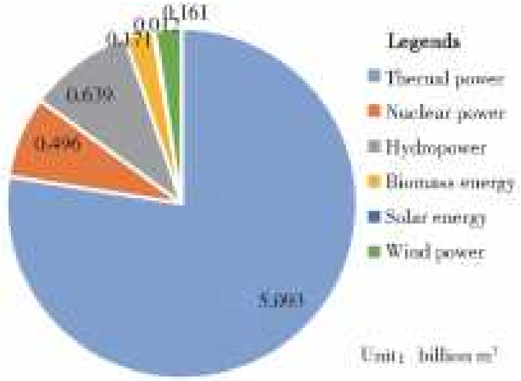

Fig. 3　Water consumption for power development 31 provinces (autonomous regions and municipalities) of China in 2017

2.4　Spatial variation of water consumption in power production process

The water consumption in the process of power production is affected by the local power generation, power generation technology and power structure. Fig. 4 shows the 2017 water consumption of electric power production process in the different provinces in China, among which Shandong, Jiangsu, Inner Mongolia water consumption of coal-fired power is higher. This is mainly due to large scale of thermal power generation in the region. In 2017, Shandong, Jiangsu and Inner Mongolia generated 437.8 billion, 382.3 billion and 372.6 billion kW • h of thermal power generation, accounting for 10.56%, 9.21% and 8.98% of China's total thermal power generation, respectively. China's nuclear power plants are mainly distributed in coastal areas. In 2017, the water consumption of nuclear power development in Guangdong, Fujian and Zhejiang accounted for 32%, 23% and 21% of the total water consumption of nuclear power development respectively. Southwest China is the most important hydropower energy base in China, and its hydropower resources account for 66.7% of the national total. According to the calculation of this study: water consumption of hydropower in Sichuan province in 2017 was 158 million m^3, accounting for 73% of the total water consumption of power development of the province; Water consumption of hydropower in Yunnan in 2017 is 125 million m^3, accounting for 82% of the province's water consumption of power development. Hydropower has become the most important power production and water consumption sector in these two provinces. Clean energy in China consumes less water. Wind power mainly consumes water in northern provinces, while biomass power mainly consumes water in Jiangsu, Zhejiang, Anhui, Shandong and Guangdong.

3　Conclusion and suggestion

3.1　Conclusion

This paper analyzes the social water cycle energy

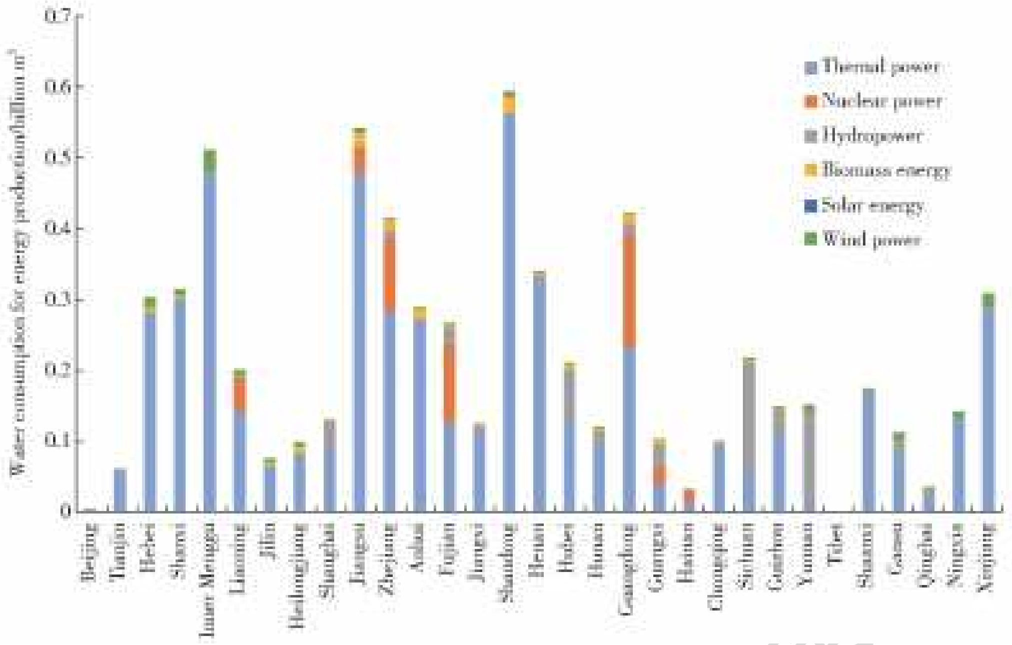

Fig. 4 Water consumption for power development in 31 provinces(autonomous regions and municipalities) of China in 2017

consumption and power development water consumption of the provinces (municipalities and autonomous regions) in 2017 and draws the following conclusions.

(1) In 2017, the total amount of electricity consumed in China′ s social water cycle was 1 082.81 billion kW • h, accounting for 17.2% of the total amount of electricity consumed in China in that year. Terminal water consumption is the biggest energy consumption, accounting for 88.1% of the total water consumption. From the perspective of zoning, Jiangsu and Xizang are the provinces that consume the most and the least water circulation in China, respectively, with energy consumption of 149.13 billion and 2.111 billion kW • h in 2017.

(2) In 2017, China′s water consumption during electricity production was 6.57 billion m^3, accounting for 2% of the total water consumption of the whole society. Thermal power is the most water-consuming power source in China, accounting for 78% of the total water consumption of the national power development. The water consumption of nuclear power and hydropower development is 639 million and 496 million m^3 respectively, while wind, solar and biomass use relatively little water. From the perspective of zoning, Shandong and Xizang are the provinces and regions with the largest and smallest water consumption for power development, respectively, with water consumption of 593 million and 3 million m^3.

3.2 Suggestion

Due to the uneven spatial distribution of water resources and energy resources in China, the energy consumption of water resources exploitation and the water consumption of energy exploitation have exerted great influence on regional energy security and water security respectively. In order to realize the collaborative security of water resources and energy, this paper proposes the following four suggestions based on the research results.

(1) Terminal water consumption is the biggest energy consuming link in the process of social water circulation. Considering the consistency of the process of water and energy utilization in this link, efficient water saving at the water use side can effectively improve the utilization efficiency of water and energy and achieve the dual purpose of water saving and energy saving.

(2) Northwest fossil energy base is the main energy output area in our country in the future, although at this stage the power production process in northwest China consumes less water, considering the increase in the scale of energy development and the situation of water shortage in the future, it is necessary to further study the relationship be-

tween energy and water in northwest China and improve the water resources security of northwest fossil energy base.

（3）The water consumption intensity of developing clean energy such as solar energy and wind energy is significantly lower than that of thermal power and nuclear power. The vigorous development of clean energy in China is not only conducive to reducing pollution and improving energy structure，but also conducive to the conservation and protection of water resources.

（4）The water-energy system management concept should be established based on the development characteristics and resource endowment conditions of different regions，the energy influence should be considered in the process of water resources development，and the water resources restriction should be considered in the process of energy development，so as to realize the coordinated security of water resources and energy in China.

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