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Shades of green energy: Geographies of small hydropower in Yunnan, China and the challenges of over-development

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ABSTRACT

Small hydropower (SHP) has a global reputation as a ‘green’, low-carbon energy source that improves rural livelihoods and contributes to local economic development. In China, SHP has grown rapidly since the early 2000s, particularly in the water-rich provinces in the country’s southwest. However, because SHP plants in China are privately-operated and approved by local governments, there is an incentive to construct large, multiple-cascade systems to generate as much power as possible. In many areas, this has led to over-development of SHP and associated negative environmental and social impacts. In this paper, we identify the factors that shape geographies of SHP over-development, what we refer to as ‘shades’ of green energy. We then analyze the direct and indirect impacts of over-development. We draw on interviews and electricity generation data from six prefectures in Yunnan province, one of the world’s largest hydropower producing regions. We find that prefectures that operate in a semi-autonomous way in electricity management and industrial planning are most prone to over-develop SHP, since they depend on hydropower revenues from electricity generation and local energy-intensive industries. We also find that over-development of SHP causes streamflow reductions and unstable electricity generation, and in some areas, drives an increase in environmentally-destructive mineral processing and reduces irrigation water access. These findings suggest a need for coordinated river basin planning on small watersheds and a reassessment of the role of SHP in local economic development.

1. Introduction

Small hydropower (SHP) is often promoted as a ‘green’ energy source that drives rural electrification and climate change mitigation without the ecological footprint of large hydropower or fossil fuels (UNIDO and ICSHP, 2013; Nautiyal et al., 2011; Huang, 2009; Hicks, 2004). For areas without access to the power grid, SHP can provide relatively stable, low-cost electricity in place of traditional fuels such as firewood and charcoal (Gurung et al., 2012; Mahapatra and Dasappa, 2012; Nautiyal et al., 2011; Byrne et al., 2007). Unlike large dams, many SHP plants are ‘run-of-river’ diversion-type schemes that have negligible reservoir regulation. For many low-income countries, SHP is the only renewable energy source that can be developed economically, since it does not require investment in large-scale electricity infrastructure. For these reasons, SHP construction is booming across large parts of the world (Ferreira et al., 2016; Mishra et al., 2015; Dursun and Gokcol, 2011), making it extremely important for rural energy provision and local economic development globally.

There is no international consensus on the definition of SHP. SHP systems range from micro-turbines that power only a few households or villages, to permanent facilities that produce large amounts of electricity. This lack of agreement causes large variances in national statistics and makes it difficult to compare SHP between countries. The International Center for Small Hydropower, which publishes the *World Small Hydropower Development Report*, refers to SHP as < 10 megawatts (MW) installed capacity. Using this definition, at the end of 2012 there were more than 75 gigawatts (GW) of SHP installed in 148 countries and territories (UNIDO and ICSHP, 2013).

China is the world leader in SHP development, boasting nearly half (~35 GW) of global installed SHP capacity using the definition of < 10 MW. The Chinese government itself defines SHP as < 50 MW; using this definition, China has 73 GW of installed SHP capacity as of end 2014. This latter figure is comparable to the *entire* installed hydropower capacity of Canada or the U.S., which rank third and fourth in the world in nations with the most installed hydropower capacity. Fig. 1 provides an overview of installed SHP and hydropower capacity in selected countries, using both the < 10 MW and < 50 MW definitions. For the remainder of this paper, we use the Chinese definition of SHP as < 50 MW.

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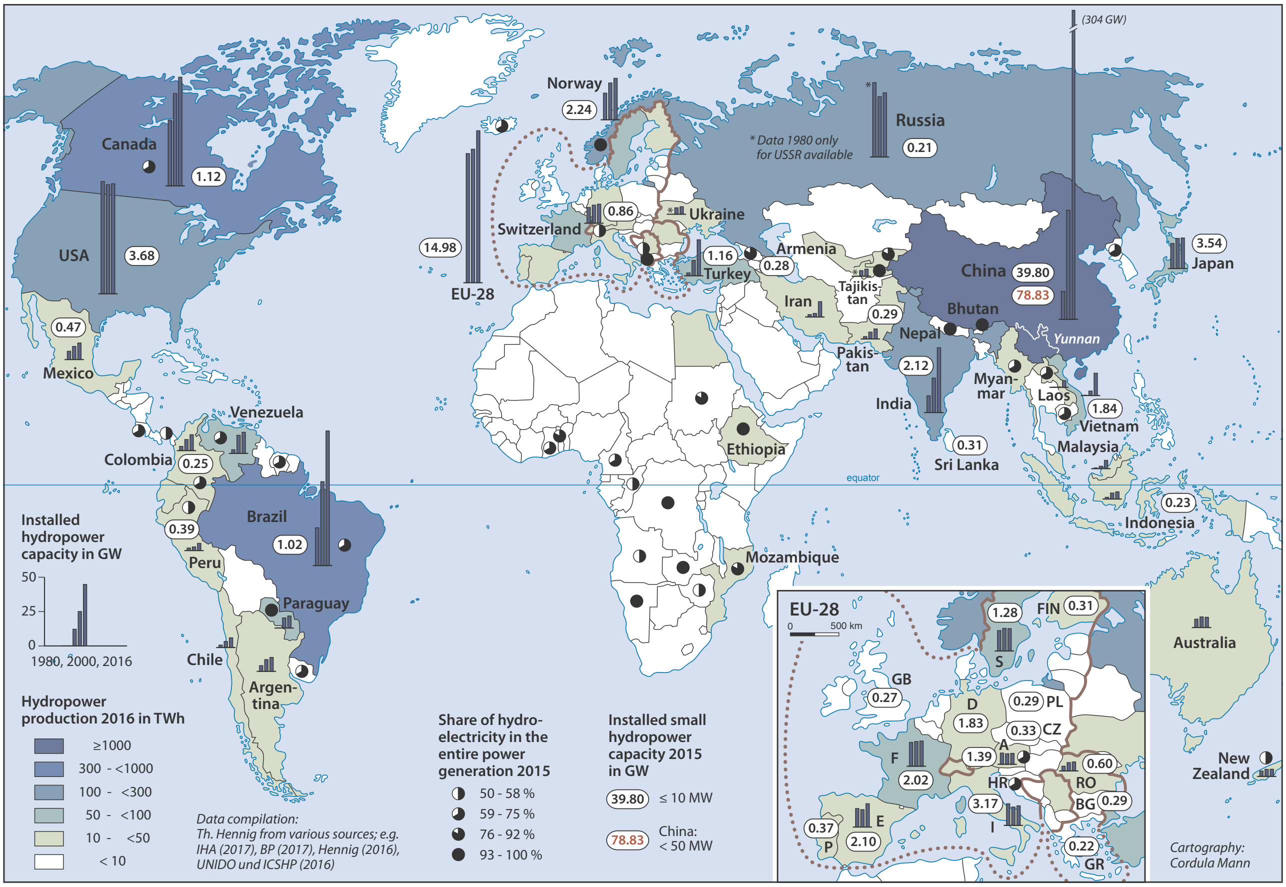

Fig. 1. Overview of global hydropower development in 2014. Includes data for countries with hydropower production > 20 TWh per year, an installed hydropower capacity > 5 GW, or an installed SHP capacity > 500 MW.
Data sources: (BP, 2015; Hennig, 2016a; IHA, 2015).

The Chinese government first deployed decentralized SHP in the 1950s for household rural electrification in mountainous regions, and over time SHP became a primary electricity source for rural towns and industries. Preferential policies made SHP an attractive investment for local governments, who could become self-sufficient in electricity while reducing household firewood collection (Li, 2012; Zhou et al., 2009). In the early 2000s, the Chinese government reformed and privatized energy generation, prompting a boom in private SHP construction that has seen a three-fold increase in installed capacity in ten years (Cheng et al., 2015). Unlike their public predecessors, private SHP plants generate electricity for sale to the grid, which can incentivize investors to build big and ignore environmental regulations. Indeed, recent studies of SHP in China (Hennig, 2016b; Pang et al., 2015; Hennig et al., 2013; Kibler and Tullos, 2013) and India (Premalatha et al., 2014; Abbasi and Abbasi, 2011) highlight that rapid *over*-development of SHP can have adverse environmental impacts, suggesting that SHP may not be 'green' after all.

Here, we define over-development as a rapid, uncoordinated increase in the size, number, and operating hours of SHP in a location where there is either 1) insufficient electricity demand or 2) more suitable energy alternatives to SHP. This results in an oversupply of electricity that cannot be taken up by the grid. Over-development can occur in the context of a watershed or river basin, or in the context of the electricity grid at different administrative levels (e.g. county, prefecture).

Other studies have recognized this over-development trend, but have tended to focus only on specific aspects, such as increase in plant size (Li et al., 2013), cascade development by different companies (Wang et al., 2015), or dispatching issues (Cheng et al., 2015; Yang, 2011). While these studies help identify local contextual factors that lead to over-development, they do not analyze how these factors interact with each other and with national policy, nor why they lead to over-development in some places and not in others. Moreover, while the direct environmental impacts of SHP cascades have received some scholarly attention (Pang et al., 2015; Kibler and Tullos, 2013), the *indirect* impacts that result from energy-intensive industries that use SHP electricity have so far been ignored. In short, focusing only on specific problematic issues and direct environmental impacts misses the multiple geographies of SHP development and their varied effects on the water-energy nexus (Hennig et al., 2016; Keskinen et al., 2016; Biggs et al., 2014). Such analysis is crucial if SHP is to be managed as a 'green' electricity source that contributes to environment and development goals without causing ecological harm.

This article has three purposes. The first is to identify and analyze the local contextual factors that shape geographies of SHP, resulting in what we refer to as 'shades' of green energy. The second is to construct a typology of SHP based on these factors, and identify the specific types that are prone to over-development. The third is to discuss the direct and indirect impacts that over-development of SHP causes, placing special emphasis on the indirect consequences of energy-intensive industries that use SHP electricity. We present this typology and analysis as not only a study of SHP in a specific region of China, but as applicable to SHP development in many parts of China and other developing countries where SHP is being promoted through national policy.

We chose Yunnan province in southwest China as the location of this study for two reasons. First, Yunnan has the highest SHP installed capacity of any province in China, and is the world's largest SHP-producing region. However, it remains highly under-studied, both its hydropower resources and its economic development trajectory. Second, unlike other provinces in China, Yunnan's electricity grid is not yet fully integrated, owing to the geographical and historical remoteness of many regions. Thus, SHP has followed and serves different functions across the province.

To conceptualize this study, we use the concept of the ‘powershed’ first introduced by Magee (2006) and later modified by Hennig et al. (2016). For Magee, the ‘powershed’ brings to the forefront the *spatial* relationships between regions of electricity production and consumption, and the institutional and political-economic context within which these relationships are situated. In particular, he shows how hydroelectricity production in Yunnan – one of China's poorest provinces – underpins the rapid economic growth of Guangdong through long-distance electricity transfer. Here, we broaden Magee's spatial lens to examine the *multiple geographies* of SHP: not just the production and consumption of electricity, but also the industries that use SHP electricity in different locations, the management structure and connectivity of the grid, and local economic and environmental management strategies. This more comprehensive approach allows us to identify the factors that can lead to SHP over-development in different locations – not only in Yunnan, but in other parts of China and the world.

2. Data procurement and case studies

The data used in this paper were collected between 2010 and 2016 in six different prefectures in Yunnan. We chose the prefecture as our unit of analysis since it is the prefecture government which approves SHP stations in Yunnan, and which also conducts river basin planning. In choosing these research sites, we aimed for a range of geographical diversity, from the high mountain peaks of northwest Yunnan, to the heavily farmed valleys of the southeast. We also sought to select prefectures with different socio-economic profiles, such as GDP, average income per household, and degree of economic diversification. All the selected prefectures have high levels of SHP exploitable potential, but differ in exact amount. Table 1 provides demographic, economic, and environmental indicators for each case study prefecture. Hydropower comprises the entire installed power capacity of four of the six case study prefectures.

Both authors surveyed the case study prefectures independent from each other, but followed a similar approach to data collection. Except for Nujiang, which was surveyed by both authors, each author had a different regional focus – Dehong, Baoshan, and Lincang in western Yunnan (author one); and Yuxi and Wenshan in southeast Yunnan (author two). The data were obtained from different provincial government agencies where we interviewed the official(s) in charge of hydropower planning and management. We visited the Bureau of Water Resources and Development and Reform Commission in each prefecture, and interviewed additional officials from Environmental Protection Bureau and China Southern Power Grid (CSPG). We also conducted interviews with the Bureau of Forestry (Dehong and Yuxi), Bureau of Agriculture (Yuxi), and Bureau of Rural Electrification (Dehong and Baoshan). Furthermore, we interviewed officials in some of the above bureaus in one or two counties of each prefecture. Following these initial interviews, we visited approximately 60 SHP plants and interviewed the on-site manager. Both authors also interviewed approximately 40 local villagers living next to SHP plants, and author two conducted a survey of 122 households in Yuxi prefecture. In this way, we sought to triangulate our data and provide a comprehensive view of the different factors that shape SHP implementation and management.

For all interviews with government officials, the authors were accompanied by other researchers or research assistants from Yunnan University (author one) or Yunnan Normal University (author two). All interviews were conducted in Mandarin, with an accompanying researcher translating into English for author one (author two speaks Mandarin). Given our status as foreign researchers in China, we did not voice record any interviews.

We supplemented interviews with data collected from statistical yearbooks (both provincial and prefectural level), documents available online (e.g. Clean Development Mechanism (CDM) project design documents), and from media reports. In addition, author one mapped SHP infrastructure and analyzed its environmental consequences in Dehong and parts of Baoshan, and conducted a fish species inventory in Dehong in cooperation with the Asian International Rivers Center at Yunnan University. Altogether, we compiled a comprehensive database of more than 600 SHP stations.

3. Small hydropower in Yunnan

3.1. Yunnan hydropower context

Yunnan is a mountainous border province in southwest China with a high degree of climactic, ecological, and ethnic diversity. The province receives a relatively high amount of rainfall that is concentrated in the wet season between July-November; however, it is unevenly distributed throughout the province. Yunnan boasts two of the world's major biodiversity hotspots and about half of China's biodiversity, reflected in the

Table 1
Key characteristics of case study prefectures (2014 data).

	Western Yunnan				SoutheasternYunnan	
	Nujiang	Dehong	Lincang	Baoshan	Wenshan	Yuxi
Size (km^2)	14,703	11,526	24,469	19,637	32,239	15,285
Population (m)	0.53	1.25	2.37	2.57	3.41	2.26
Prefectural GDP (m RMB)	10.01	27.40	46.51	50.31	61.85	118.47
GDP per capita (m RMB)	18,540	21,857	18,710	19,648	17,208	50,500
Main industries	Mineral processing (esp. Si), Hydropower, Tourism	Hydropower, Mineral Processing (esp. Si), Trade with MY	Agriculture, Different mineral processing, Hydropower	Mineral processing (esp. Si), Agriculture, Tourism	Mining, Agriculture, Hydropower	Agriculture, Manufacturing, Services
Total installed power capacity	1282 MW	4390 MW[a]	1008 MW[b]	1672 MW	no data	735 MW
InstalledHP capacity	1282 MW	4390 MW[a]	1008 MW[b]	1672 MW	no data	542 MW
Installed SHP capacity	1003 MW	1274 MW	784 MW	693 MW	1201 MW[c]	386 MW[c]

[a] including two hydropower stations in Myanmar, which in Dehong directly feed into YPG (Yunnan Power Grid).
[b] excluding two large dams along the Mekong, which do not directly feed into Lincang's section of YPG.
[c] data from Cheng et al., 2015.

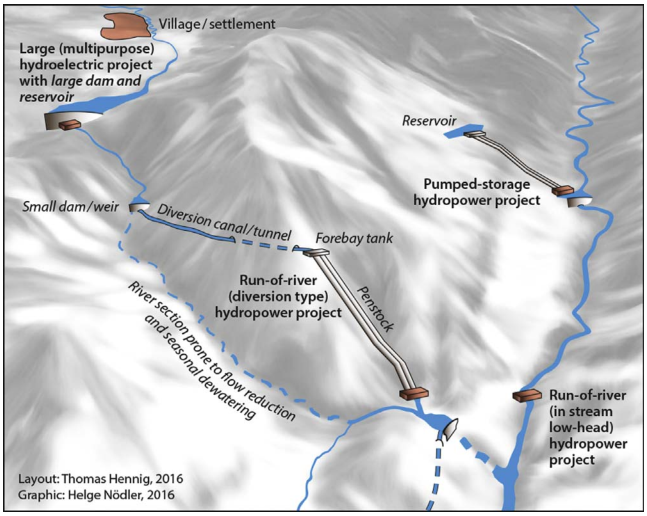

Fig. 2. Types of hydropower projects and their basic structure.

fact that about 6.3% of its territory lies within protected areas on the national or provincial level. Yunnan is also home to over 600 rivers that form six large basins, five of which are transnational. The population is approximately 46 million, with 24 ethnic minority groups making up 34% of the population, one of the highest concentrations of non-Han groups in China. Yunnan shares a 4000 km border with Southeast Asia, and has long been geographically and economically peripheral to the rest of China. Today, however, it is the centerpiece of the Chinese government's infrastructure development plans for Southeast Asia, and has thus experienced high levels of government investment aimed at increasing international trade and connectivity.

As a water-rich province, Yunnan is particularly amenable to hydroelectricity development, second only to Sichuan province in total hydropower exploitable potential. As of end 2016, the entire hydropower (includes both large and small) installed capacity of Yunnan was 62 GW, mainly large cascaded projects in upper Yangtze and Mekong River basin. In 2015, Yunnan produced 262 terawatt hours (TWh) of hydroelectricity (Magee and Hennig, 2017). Since not all of this electricity can be consumed within Yunnan province, much of it (93.5 TWh) is exported to other parts of China, particularly the energy-intensive Pearl River Delta region in Guangdong province (Magee, 2006). This is promoted through the "send Western electricity East" (*xidian dongsong*) and "send Yunnan electricity to Guangdong" (*Yun dian song Yue*) policies. Indeed, the largest of Yunnan's hydropower projects include dedicated point-to-point ultra-high voltage direct current (UHVDC) transmission lines from the plant to Guangdong. The Yunnan government has also developed additional coal-fired power (12.4 GW), wind (7.1 GW), and solar/PV plus biomass (1.2 GW) energies as of end 2015, though none come close to approaching the dominance of hydropower in the province's energy portfolio.

In Yunnan, SHP makes up 21.4% of all hydropower installed capacity as of end 2014, and has played a major role in energy provision and local economic development. Yunnan has the most SHP installed capacity of any province in China, with 1595 plants totaling 11.07 GW in 2015 (or 3.9% of China's total number of plants and 15.2% of its total installed capacity) (National Bureau of Statistics, 2016, p. 324). SHP plants are situated on the tributaries and sub-catchments of Yunnan's major rivers, where they are often developed as part of cascade systems. Unlike large hydropower projects, most SHP plants in Yunnan are diversion-type 'run-of-river' (Fig. 2), meaning that they only have enough water storage capacity for a few days of electricity generation. Fig. 3 provides an overview of hydropower generation and installed and potential SHP capacity in each of China's provinces; note that Yunnan has the highest SHP installed capacity in the country.

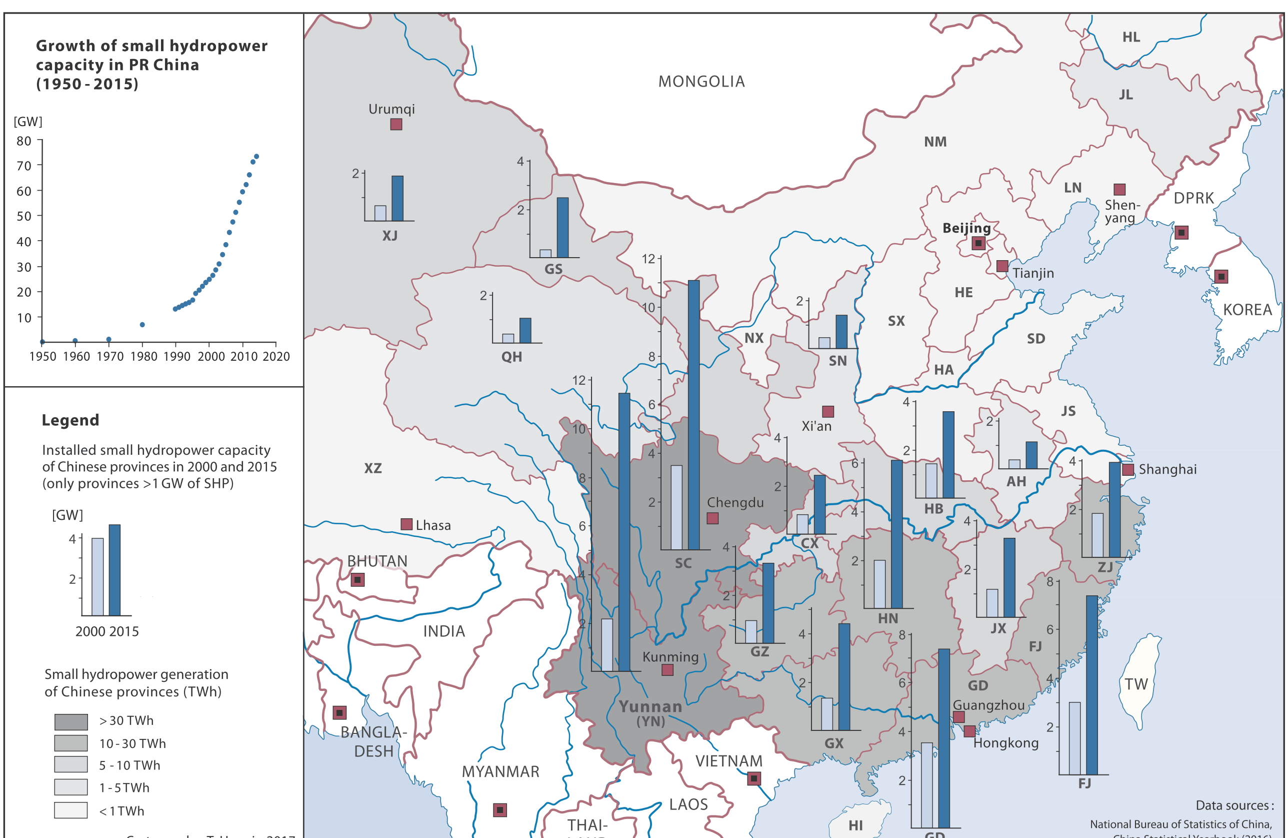

Fig. 3. Hydropower generation and installed SHP capacity (> 1 GW) of Chinese provinces in 2014. Growth in SHP over time refers to plants ≥ 0.5 MW and ≤ 50 MW.

3.2. National drivers of SHP in Yunnan

Though Yunnan today has more SHP installed capacity than any other province, it was relatively late to develop its hydropower potential. The Chinese government first promoted SHP for rural electrification in the 1950s, and gave local governments in Yunnan and other water-rich regions the authority to approve, operate, and re-invest revenues from SHP (Kong et al., 2015; Bhattacharyya and Ohiare, 2012). In Yunnan, local governments constructed thousands of micro-SHP stations in the 1960s and 70s. In the 1980s, following economic reforms, local governments upgraded and linked local grids to provide more reliable electricity for rural enterprises, while the central government extended the state grid to more townships and villages (Peng and Pan, 2006). The definition of SHP was raised to 25 MW in the 1980s and to 50 MW in the late 1990s, which made it easier for local governments to approve and construct larger plants. Local governments in Yunnan continued to construct SHP, as well as large hydropower stations, though Yunnan's poverty and remoteness precluded it from developing as quickly as southeastern China.

In the 2000s, however, Yunnan and southwestern China experienced a boom in SHP construction, with Yunnan's SHP installed capacity increasing five-fold between 2000 and 2015, from 2.2 to 11.1 GW, while China's increased from 24.8 to 73.1 GW (note that we include SHP ≥ 0.5 MW and ≤ 50 MW in these calculations, as the definition of SHP in China had already been changed to ≤ 50 MW before this period). This is due to three main drivers. The first, and arguably the most important, was the privatization of electricity generation as consequence of power sector reforms in 2002. Chinese leaders had already allowed some foreign and privately-owned companies to invest in the large power sector in the late 1990s to meet rapidly rising electricity demand (Wang et al., 2015), and in 2002, this was extended to all generation activities, including SHP. Yunnan, which still had a great deal of unexploited SHP potential, was well placed to channel this increased private investment into new stations and cascade systems, and SHP construction grew rapidly across all prefectures. New stations were nearly all privately-owned, and local governments had to sell off (privatize) much of their older SHP assets. As of 2015, 80.8% of SHP stations in China are operated by private companies (Cheng, 2015).

A second driver of the SHP boom in Yunnan was a set of policies promoting SHP for rural electrification and firewood replacement (Liu et al., 2015). In 1982, the central government established 100 'rural electrification' counties in southwest China, later adding another 500 counties by 1999 (Cheng et al., 2015). These counties received significant funds from the central and provincial governments for SHP construction and the improvement of local grids, and continued to receive funding during the 2000s boom (HRC, 2009). In many counties, including those in Yunnan, these subsidies led to the replacement of micro-SHP (which were not connected to the grid) with larger projects, mainly in the 1–10 MW range. This process has been ongoing: Dehong prefecture achieved full rural electrification in 1997 (the second prefecture in China to do so), while Nujiang prefecture did not do so until 2012.

In addition to this policy, in 2002, central officials launched the 'SHP Replacing Fuel Wood' project (*xiao shuidian dai ranliao xiangmu*), with the goal of reducing firewood use by 149 million m^3 every year, a 65% reduction (Cheng et al., 2015). The central government set aside 127 billion yuan for SHP station and transmission line construction, and subsidized electricity prices in project areas, effectively cutting tariffs in half (Hicks, 2004). The project was eventually extended to 886 counties with a population of 273 million people (Tang et al., 2012).

Third, the availability of Clean Development Mechanism (CDM) funding since the early 2000s has been a major driver of SHP construction in Yunnan. CDM 'offsets' are designed to allow industrialized countries to reduce their CO_2 emissions under the Kyoto Protocol by investing in renewable energy and climate mitigation projects in low-income countries (Erlewein and Nüsser, 2011; Teng and Zhang, 2010; Hepburn, 2007). Based on our analysis of publicly available CDM data (UNEP and DTU, 2016), we found that China has received more CDM funding than any other country, and boasts approximately two-thirds of global registered SHP CDM projects (62.6% of projects and 68.5% of global installed capacity using the < 50 MW definition). Of these, Yunnan itself contains 164 of all worldwide registered 1,047 SHP CDM projects and 15.9% of global SHP CDM installed capacity (18,036 MW). For SHP investors in Yunnan, the CDM provided additional funds that made SHP and even more financially attractive investment because investors could earn back their initial outlay more quickly. The CDM thus primarily benefitted private investors and contributed to the boom in SHP construction in Yunnan.

Two main points can be drawn from this review (Fig. 4). First, though Yunnan contains many large hydropower projects, SHP has played a major role in rural electrification and local economic development, especially since plants are approved by local governments. Second, the size and function of SHP in China and Yunnan has changed over time, and has increased rapidly since the early 2000s. However, small hydropower in Yunnan has not followed one single path; it is highly differentiated geographically, with different characteristics and environmental impacts depending on location – what we mean by 'shades' of green energy. The following sections analyze these local characteristics of SHP development in different parts of Yunnan, and the challenges they each pose for clean energy production and sustainable rural development.

4. Factors shaping SHP development in Yunnan

To analyze the diverse geography of SHP, it is necessary to distinguish between the above national drivers of Yunnan's recent SHP boom, and the local contextual factors that shape its implementation in particular places. From our case studies, we identify *four* local contextual factors in Yunnan: grid management structure, grid connectivity, local industrial development strategy, and local energy portfolio.

4.1. Grid management structure

The first factor shaping SHP implementation is the management structure of the local power grid. Since reforms in 2002, the national electricity grid has been overseen by two different state-owned grid companies: the State Grid Corporation of China, which manages the power grid in most of the country, and the China Southern Power Grid (CSPG), which manages the grid in Guangdong, Hainan, Guangxi, Guizhou, and Yunnan provinces. CSPG is comprised of provincial subsidiary companies that operate the grid in each province, including the Yunnan Power Grid (YPG). These provincial grid companies are further subdivided into prefecture- and county-level branches (which we simply call the 'local grid'). Under this nested structure, the local grid company is responsible for most of the grid infrastructure and electricity dispatch for its administrative area. When required, the local grid company will liaise with the grid company at the next highest administrative level to either 'import' electricity to meet higher demand, or 'export' excess electricity to another region. These imports and exports are tallied in each local grid company's balance sheet. This means, in effect, that local grids 'buy' and 'sell' electricity depending on their ratio of power generation to demand at a given time.

How does this management structure affect SHP development? One of the major costs of SHP construction is the transmission line from the plant to a nearby transformer, which is the responsibility of the investor. Since local grid companies manage their own infrastructure, they can choose to build a new transformer near potential SHP sites to attract investors. Alternatively, if local grid companies do not provide such infrastructure, then there will be less investment in SHP. Thus, there is a close relationship between the decision-making and management structure of the grid operator and the economics of developing an SHP plant.

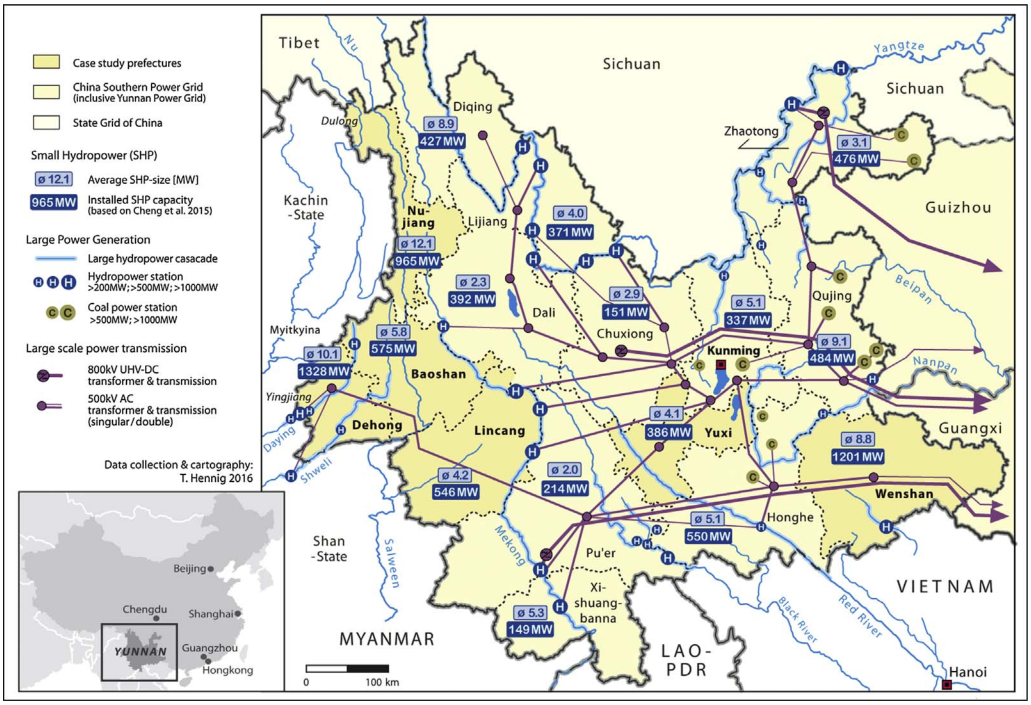

Fig. 4. Small hydropower capacity of Yunnan's prefectures and major transmission lines (includes some larger power projects).

4.2. Grid connectivity

A second, related factor shaping SHP is the connectivity of local grids to provincial and national grids. This requires some historical context in Yunnan. For the first few decades of rural electrification in Yunnan, local grids had no connection to each other; they were completely autonomous and could only generate electricity for local use. In the 1990s and 2000s, the Yunnan government began connecting local grids to the YPG, but in a largely piecemeal fashion. Today, though all local grids in Yunnan (except a tiny grid in the remote Dulong Valley) are part of the YPG, five of the prefectural grids are technically still semi-autonomous, meaning that they have limited connectivity and transmission capacity. This is even the case for prefectures that have a high-kV transmission line, such as Dehong and Wenshan, if they generate more electricity than can be transmitted with existing infrastructure.

The result of this limited connectivity for SHP development is that it causes major network congestion during the wet season, and thus limits the electricity that they can 'export' outside the prefecture. During this period, SHP plants are required by the YPG to reduce electricity output, often to 75% capacity. Thus, connectivity and transmission constraints considerably shape the pathways that SHP development can take.

4.3. Local industrial development strategy

A third local characteristic shaping SHP development is the local government's industrial development strategy. Yunnan has the second lowest per capita GDP of all Chinese provinces (59% of China's average), and all our case study prefectures except Yuxi have a lower per capita GDP than the Yunnan average. These prefectures have little economic activity outside of agriculture, mining and mineral processing, and/or forestry. In these areas, SHP development can make a significant contribution to the local economy. This contribution can take the form of government revenues from SHP taxes, earnings from the 'export' of SHP electricity, and the use of SHP for local industrial development. The type of strategy employed is shaped by local actors (government officials and private investors) and by the connectivity of the local grid to the YPG.

Tax revenues and electricity exports are direct means by which local governments can earn revenue and drive economic development. Some prefectures in Yunnan have signed power agreements with Guangdong province, meaning that electricity for export has a higher priority than local utilization. Dehong, Wenshan, and Baoshan all have these agreements, with Dehong and Wenshan being the only sub-national units in the world in which SHP contributes significantly to long-distance electricity export. In addition, all our case study prefectures export excess electricity to the YPG, which then transmits it elsewhere. However, the ability to export electricity is mediated by transmission infrastructure, which often faces severe bottlenecks during the wet season for those prefectures with semi-autonomous grids.

To combat this limited connectivity and seasonal fluctuations in power generation, many local governments in Yunnan sought to develop energy-intensive industries that could consume excess power, especially in those prefectures with semi-autonomous grids. This was particularly the case in early years following power sector reforms (especially 2002–2005), when local governments cooperated with the local grid company, local banks, and investors to construct SHP for electricity provision to local industries. In western Yunnan, a close relationship developed between SHP and energy-intensive mineral processing, such as silicon, aluminum, and silver. In 2013, Yunnan's energy intensive industries (including processing and manufacturing) consumed 112.3 TWh of electricity, which corresponds to 76.9% of provincial consumption. In our four western Yunnan prefecture case studies, which primarily use SHP-generated electricity, the share of energy intensive industries in local power consumption varies between 85% (Dehong) and 59% (Lincang). This reliance on energy-intensive industries has caused serious environmental consequences, which we examine in Section 6.

4.4. Local energy generation portfolio

Finally, a fourth characteristic shaping SHP in Yunnan is the existence of other types of power generation, or the potential to develop other types. Except for Nujiang prefecture, which is almost completely dependent upon SHP-generated electricity, all prefectures that we studied have both SHP and some medium- and large-scale hydropower plants. The Mekong River in western Yunnan, for example, has a cascade of six large dams of 15.7 GW installed capacity, and another five under construction, with SHP located on its tributaries. The prevalence of large hydropower (and/or exploitable hydropower resources) also creates a need for the grid company to construct high-capacity transmission infrastructure from the local grid to the YPG, thus somewhat relieving congestion issues. Two of the Mekong hydropower plants, for example, have an UHVDC point-to-point transmission line directly to Guangdong, while the other four primarily feed into the YPG. For these reasons, places in Yunnan with high levels of existing or exploitable large hydropower are less enthusiastic about developing SHP, especially in parallel with local energy-intensive industries.

5. SHP typology and its key characteristics

Based on the local characteristics above, we construct a five-fold typology of SHP in Yunnan, ranging from small and decentralized plants to larger and grid-integrated. This typology is necessary because it allows us to identify the *combination* of local factors that can drive SHP over-development in specific places, and the specific impacts and challenges for green SHP that result. We emphasize that each type of SHP is not a monolithic bloc, but rather is located on a continuum of SHP development that shares characteristics with other types. This is especially true for Types 2 and 3 (semi-autonomous grid) and Types 4 and 5 (integrated grid). Table 2 provides a summary of the typology in table form, and Fig. 5 in visual form.

In this five-fold typology, Types 2 and 3 are most susceptible to over-development. For Type 2, a combination of limited transmission capacity and a semi-autonomous grid management structure incentivizes local officials to develop SHP plants to power local energy-intensive industries. This was a common strategy in western Yunnan in the early 2000s after electricity generation was privatized and local governments could exploit their hydropower resources without the need for provincial government approval. Sensing opportunity, local officials in these areas simultaneously approved hundreds of new plants, and dozens of decentralized energy-intensive mineral processing smelters. Local officials then presided over yearly negotiations between plant operators and energy-intensive industries over production and demand. However, due to a rapid increase in SHP installed capacity, fluctuating mineral prices on world markets, and inefficient energy-intensive industries, SHP plants in these areas often have their electricity production curtailed. Inefficient energy-intensive industries are particularly problematic because they can cease operation or dramatically reduce output in response to market volatility, which then requires SHP generation to be curtailed.

Type 3 SHP, in contrast, describes areas where local officials develop SHP for both energy-intensive industries and electricity export. This type has a very large SHP installed capacity (typically > 1000 MW), but due to additional larger hydropower projects, SHP has a smaller share in the entire generation portfolio. Like Type 2, the grid management structure of Type 3 SHP is semi-autonomous, which gives local governments the decision-making power to allocate SHP electricity for local industries. Unlike Type 2, however, areas with Type 3 SHP have high-voltage transmission lines that enable them to export electricity to other regions. This combination of local industrial consumption and export incentivized local governments in these areas of western Yunnan to approve rapid SHP construction. As a result, local industries are often unable to consume all the SHP electricity that is generated, and energy exports face transmission bottlenecks in the wet season. Thus, areas with Type 3 SHP can also experience over-development because there is a rapid, uncoordinated increase in SHP where there is insufficient demand and transmission capacity.

Nonetheless, while the broader structural factors in our typology are important, we must also emphasize the role of local actors in SHP decision-making. SHP is the purview of prefecture- and county-level governments who, following fiscal decentralization in the mid-1990s, needed to find ways to generate local revenues. For those areas without large hydropower or other major industrial potential, SHP and its associated industries became a foundation on which to build a local economy. Local officials were incentivized to approve SHP plants due to these specific factors and broader national policy, but they were not forced to do so. Similarly, local actors in Types 4 and 5 operate under a different incentive structure, but still made the decision to develop (or not develop) SHP. Thus, while we can identify the combination of factors that lead to over-development, whether it occurs or not is a result of local agency and decision-making.

6. Challenges for green SHP in Yunnan

As our typology indicates, local characteristics shape SHP development very differently across Yunnan, with some more susceptible to over-development than others, which shows that the geography of SHP resembles ‘shades’ of green energy. Some of these impacts have been already identified by local or provincial governments and have resulted in recent policy reforms. The following section identifies and analyzes the challenges for green SHP development in Yunnan and how they

Table 2
Tabular summary of SHP typology.

SHP TYPOLOGY						
Summary		**Type 1**	**Type 2**	**Type 3**	**Type 4**	**Type 5**
		Rural, small-scale SHP	**SHP for local industry**	**SHP for local industry & export**	**SHP-reliant & grid-integrated**	**Reduced SHP role & grid-integrated**
Characteristics	Grid management structure	Autonomous	Semi-autonomous	Semi-autonomous	Integrated	Integrated
	Grid connectivity	No connectivity (small scale)	110 kV & 220 kV	110 kV–500 kV	110 kV–500 kV	110 kV–500 kV
	Economic development strategy	Rural industry and agriculture	Hydropower generation; energy intensive industries; primary industries	Hydropower generation (including export); energy intensive industries; primary industries	Industrial & service sector industries; (hydro-)power generation; energy intensive industries	Broad economic portfolio (esp. diverse industrial & service sector industries)
	Local energy portfolio	Only SHP	SHP, MHP, minor role of renewables (reliant on SHP)	SHP, MHP, LHP, minor role of renewables (reliant on SHP)	SHP, MHP; other renewables, conventional power (reliant on SHP)	SHP, MHP, LHP; other renewables, conventional power (not reliant on SHP)
Examples		Nujiang ~2000 Dehong ~1980	Nujiang ~2015 Wenshan ~2005	Dehong ~2015 Wenshan ~2015	Yuxi ~2015 Lincang ~2015	Kunming ~2015 Most of E-China
Risk of over-development		Low	High	High	Medium	Low

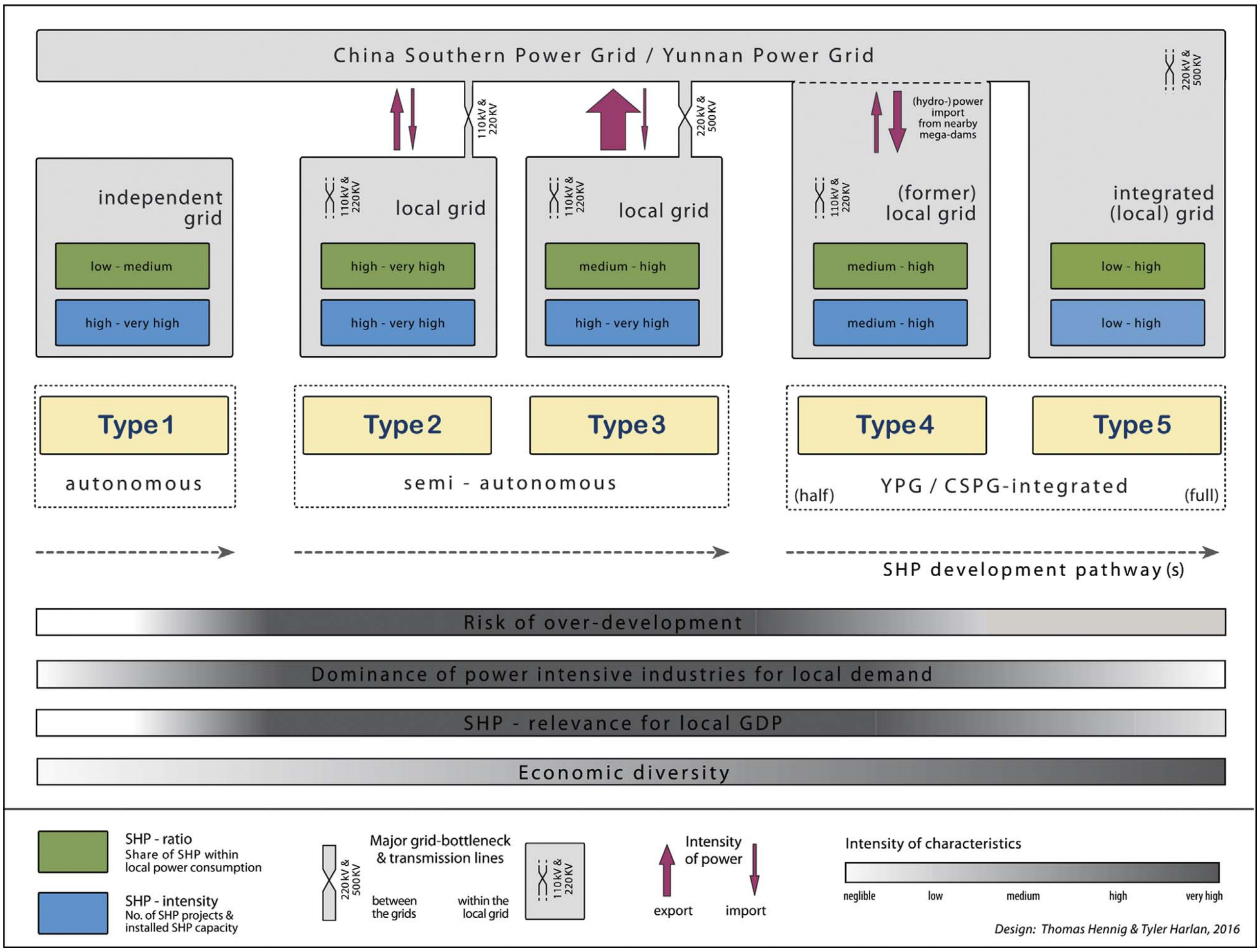

Fig. 5. Visual summary of SHP typology.

apply to different types of SHP. We describe four main challenges: irrigation water access, reduced streamflow, indirect pollution, and unstable electricity generation.

6.1. Reduced irrigation water access

Yunnan's seasonal variation in rainfall, combined with multiple competing water uses, can create significant water stress during the driest months of March to June. In our case study prefectures, water stress manifests in tensions between SHP and farmers, both of whom use water from the same streams and tributaries. This is chiefly a problem for farmers who use irrigation to cultivate sloping land in densely populated basins, while it is less of a problem in forested regions with a low population density. We find that Types 2 and 3 in our typology experience the highest reductions in water access due to SHP over-development and incentives for plant operators to generate as much electricity as possible. This occurs for three main reasons: the design of SHP plants and cascades, the operation of plants during the dry season, and an overall lack of comprehensive watershed planning.

First, the design and placement of an SHP plant's diversion canal, and the length of the cascade itself, can affect the amount of irrigation water available to farmers during the dry season. In diversion-type run-of-river SHP systems, water is diverted from the stream above plant, and flows into the next station (in a cascade) or into the same or larger trunk stream further downriver. Not only does this reduce flow in the watercourse itself, but may also divert water away from existing irrigation canals. In our case study prefectures, we found that some farmers with land located below a plant's diversion intake and above its outflow experienced reduced water access during the dry season because their irrigation canals were often dry.

Second, these diversions can be further exacerbated by the unwillingness of some plant operators to release (i.e. not divert) water during the dry season for farmers to use for irrigation. The degree to which this occurs varies across our case studies. In areas with relatively dense irrigated agriculture, SHP operators are generally required to sign a contract with local villagers to release water several times during the dry season. The contracts do not specify how much water should be released, but only that plant operators must provide water when requested by the local village head. This means that, to abide by the terms of the contract, plant operators must reduce or fully halt electricity generation for several days or weeks. We found that many SHP plants do indeed reduce their electricity output so that farmers can irrigate; however, others continue to divert water even after repeated requests from villagers. This tendency to continue operating is tied to an incentive structure for operators that privileges continuous energy generation over provision of water to farmers.

Third, most of our case study prefectures lack comprehensive watershed planning, producing scenarios in which streams are developed as SHP cascades without adequate attention to competing water uses. In China, large rivers are under the authority of water management agencies set up by the Ministry of Water Resources (MWR), while smaller watersheds are managed by the provincial MWR. However, the smallest streams and tributaries are supervised at the prefecture level by the Development and Reform Commission. Most SHP projects are planned at the prefecture level through a complex assessment of an individual project, which includes an environmental impact assessment, water resources assessment, and a geological survey. However, this assessment only examines the project itself, and does not consider cumulative impacts within the entire watershed. We found that especially following electricity reforms allowing private investment in the early 2000s, local governments in our case study areas fast-tracked SHP projects without necessary comprehensive planning of smaller watersheds. As a result, many watersheds were over-developed with SHP, leading to situations of reduced water access as described above.Example: Farmers and SHP conflicts over dry season water access in Red River basin, Yuxi

The transnational Red River basin is characterized by large hydropower potential on two main streams (the Yuan and Lixiang), while numerous tributaries have been developed for individual and cascaded SHP systems. In the upstream Xinping county of Yuxi prefecture, 25 SHP plants have been constructed on streams flowing east from the Ailao mountain range on an elevation gradient of 800 to 2000 m above sea level. These same streams provide irrigation for hundreds of villages and townships in the basin. A survey of 122 households conducted in eight different villages clusters in December 2015 found that 74% of farmers suffered from reduced water access during the most recent dry season compared to normal conditions, with 42% of these explicitly blaming the local SHP plant. While many respondents said that the plant would eventually release water on request, they complained that it was insufficient. In at least three cases, local officials had to intervene. Due to increased water stress from a variety of factors, farmers in some villages have switched to more drought-tolerant crop varieties.

6.2. Reduced streamflow

SHP systems can also reduce streamflow during the dry season, owing to the same factors that cause reductions to water access. Cascaded SHP systems, in particular, can limit streamflow or de-water entire river sections if the water that flows out of one plant flows directly into the plant (or plants) below. While the effect of moderate de-watering from one SHP plant is almost negligible, the consequences of de-watering over an entire cascade or sub-catchment can be severe (Kibler and Tullos, 2013; Pang et al., 2015). These impacts from flow reduction include reduced aquatic biodiversity (Fu et al., 2008), barriers to fish migration (Shen and Diplas, 2010), channel erosion – due to changes in the natural flow regime (Baker et al., 2011) – and effects on riparian vegetation. To counteract reduced streamflow, the Yunnan provincial government has set a minimum ecological flow requirement of 10%, with an exact requirement specified in the environmental impact assessment for each SHP project. However, this requirement is mostly ignored by plant operators who seek to continue generating electricity during the dry season. Thus, the degree of streamflow reduction largely depends on local government regulatory capacity and objectives.

We find over-developed SHP cascades in all case study prefectures, but particularly those with semi-autonomous grids (Types 2 and 3). This is because, in those areas, local governments sought to use SHP for local industrial development and could make their own management decisions, without sufficient attention to streamflow. Many experts in Yunnan we spoke with suggested that these areas also lacked the capacity to plan small watersheds effectively. Areas with more integrated grids (Types 4 and 5), in contrast, have experienced less reduction in streamflow.

Additionally, many of the SHP-cascaded rivers we surveyed have a multi-ownership structure, which means that a river section is developed by different owners or companies – known as 'demarcating the river' (*paoma quanshui*). This is partly a result of uncoordinated watershed planning described earlier, but also of intense competition between SHP companies to develop the best sites. Such a multi-ownership structure leads to individual plant operators pursuing profit without regard to the effects of their generation activities on the entire watershed. In this setting there is neither an upstream storage project, which would allow a flow regulation, nor is there coordination between the project owners. In some cases, we found that upstream projects caused downstream floods by suddenly releasing water from small storage ponds, or caused flow interruption by filling up these same ponds.Example: Dewatering affects nature reserves in the Mongnai watershed, Ayeyarwady basin, Dehong

Tongbiguan Nature Reserve in Dehong shows characteristics of the northern tropical margins and a unique biological diversity, making it to one of the key biodiversity hotspots in Yunnan (Yin et al., 2007). Tongbiguan has three transnational watersheds that have all been heavily exploited for hydropower. Nine hydropower projects (Σ 260 MW), some in the core zone of Tongbiguan, have caused regular interruptions to streamflow over 26 km of river sections (or 74% of total river length) with an altitudinal gradient ranging from 270 m to 1690 m. This includes seven SHP projects that have dewatered 10.8 km of the Mongnai and Huihe rivers, and one large hydropower plant (Mongnai-Nabang 180 MW) that has dewatered 14.8 km of the Mongnai river, leaving only one 600 m stretch submerged during the dry season (Fig. 6).

Other studies have shown that such complete diversions can have serious effects on the diversity of river ecosystems (Pang et al., 2015; Fu et al., 2008). To test this, we conducted a fish survey at seven sampling spots within the above gradient. Sites were between 200 and 300 m long and chosen to provide coverage of both pool and riffle habitats. Collections were made using a backpack electrofishing unit. The fish survey identified 11 genus, of which 10 were endemic genus and one an alien. We found that all sampled fish were of a small enough size (max. 16 cm) that they could pass through the turbines. However, studies of nearby catchments indicate that fish diversity should be much higher in this region (Endruweit, 2014; Kottelat, 2014; Yang et al., 2016). Thus, these findings lead us to conclude that the impacts of SHP cascades and dewatering on river ecosystem diversity can be quite serious. These watersheds in western Yunnan are the last refuge for endemic and threatened fish species, making their protection crucial for biodiversity conservation.

6.3. Indirect environmental impacts of energy-intensive industries

In addition to electricity sector reforms, preferential government policies, and the availability of CDM funds, one of the main reasons that prefecture governments in Yunnan developed SHP was to generate electricity for industrial development, particularly energy-intensive industries like mineral extraction and processing. All our case study prefectures contain some extraction and processing of minerals, including silver, zinc, copper, tin, and silicon. These industries are most prevalent in prefectures with SHP Types 2 and 3, since these areas have limited grid connectivity to the YPG and need to develop local energy-intensive processes to consume the electricity generated by SHP. Unfortunately, some of these industries use inefficient equipment and processing techniques that result in severe indirect environmental implications, like high greenhouse gas emissions, water and soil pollution, and deforestation. Indeed, a recent study by Wang and Wei (2017) finds that China's silicon producers locate their processing facilities in less economically developed regions because electricity prices are low and environmental regulations are less strictly enforced.

One example is silicon in western Yunnan. Raw silicon is an important base material for computer chip production and for wafers in photovoltaic cells, and ferrosilicon is used as a crucial alloy for steel and aluminum production and for casting (e.g. in the auto industry). Moreover, like aluminum, silicon processing is highly energy intensive; in 2015 Yunnan's average was 11,694 kW/h per t silicon. Yunnan makes up approximately 31% of China's total silicon production, with nearly all (94%) of this capacity located in western Yunnan, where the industry generated a tax income of 255 million yuan in 2015. In 2014, for example, western Yunnan had a total electricity demand of approximately 13.7 TWh (more than Myanmar or Laos), of which approximately 10.8 TWh was consumed by energy-intensive industries,

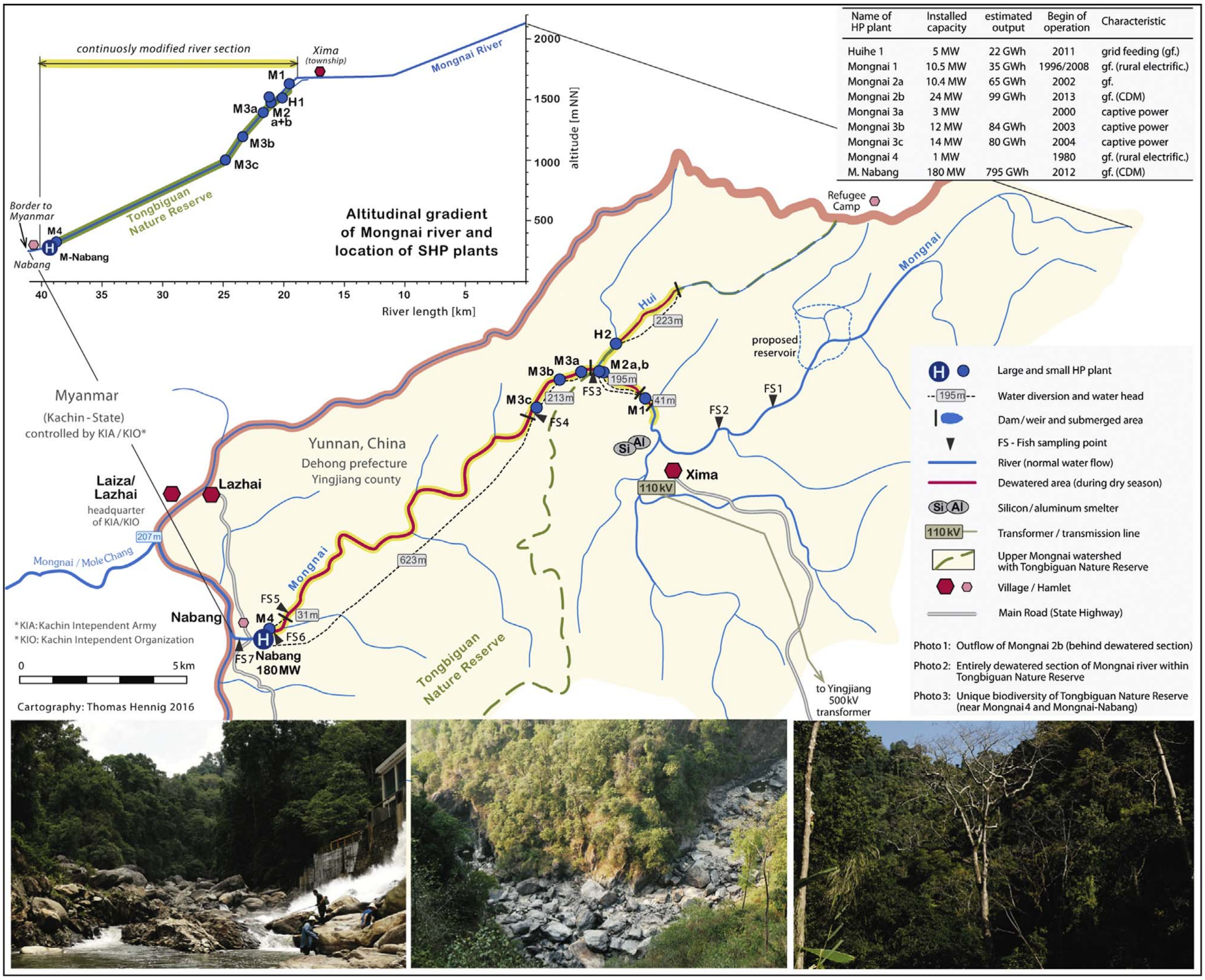

Fig. 6. Cascaded SHP projects in the Mongnai watershed and dewatering of river sections in Tongbiguan Nature Reserve, Dehong.

ranging from 58% to 85% of total consumption in different prefectures in western Yunnan. Moreover, almost three quarters (7.8 TWh) of this electricity used by energy-intensive industries was consumed by silicon smelters. In other words, many SHP plants in western Yunnan produce exclusively for silicon processing. Fig. 7 provides SHP installed capacity and electricity consumption data for Dehong and Nujiang prefectures. Note that the share of energy intensive industries in prefectural power consumption is 85% for Dehong and 84% for Nujiang.

Silicon processing in western Yunnan is achieved by using 68 small smelters with relatively outdated technology. Consequently, the areas in proximity to smelters can experience illegal toxic spill outs, polluting soil and ground and surface water and causing sudden fish deaths in some river sections. In addition, silicon production consumes large amounts of charcoal derived from timber, which exacerbates deforestation. Yunnan's charcoal demand was 281,000 t in 2014, and though this has declined in recent years, it still requires a huge number of logs, either from local forests or imported from Myanmar. In addition to production from forest plantations, both sources drive major (and illegal) deforestation of natural forests. To reduce this indirect cause of deforestation, in 2016 the Yunnan government required that silicon processing phase out charcoal in favor of other reducing agents (such as corn), with its impacts on energy consumption and the water-food-energy nexus still unknown.Example: Unstable and fragmented silicon production and its indirect environmental implications in Dehong

Dehong prefecture, bordering Myanmar, is drained by four transnational watersheds, all of which are tributaries of the Ayeyarwady. In 2013 Dehong produced 13.4 TWh of hydroelectricity, of which 71.2% was exported (mainly to Guangdong). This means that Dehong, with a population of only 1.2 million, itself consumed 3.9 TWh of electricity – more than the entire demand of Laos (pop. 6.8 million) or Cambodia (pop. 15.4 million). Some 84.8% of electricity that remains in the prefecture is consumed by energy intensive industries: of this, 86.4% is used for silicon processing. Silicon production is dependent upon old, small smelters that are operated by private investors and highly susceptible to seasonal fluctuations in SHP generation and constant changes to the market price for silicon. Consequently, monthly power demand for silicon production in Dehong varies between 51 GWh and 390 GWh, and two-thirds of existing smelters are expected to cease operation in the next 2–3 years (3 smelters have already stopped production). The highly variable and competitive nature of silicon production leads older smelters operators to release toxic waste into rivers; the situation is more serious in Dehong than any other prefecture in Yunnan. Moreover, the charcoal demand for Dehong's silicon smelters in 2014 was 120,000 tons, causing illegal deforestation of primary forests (see Supplementary materials 1).

6.4. Unstable electricity generation and grid congestion

Since most SHP plants only have limited water storage capacity, their electricity output varies significantly with rainfall. This means that, during the wet season, these same prefectures generate electricity in excess of local demand that must be exported to the YPG. It also

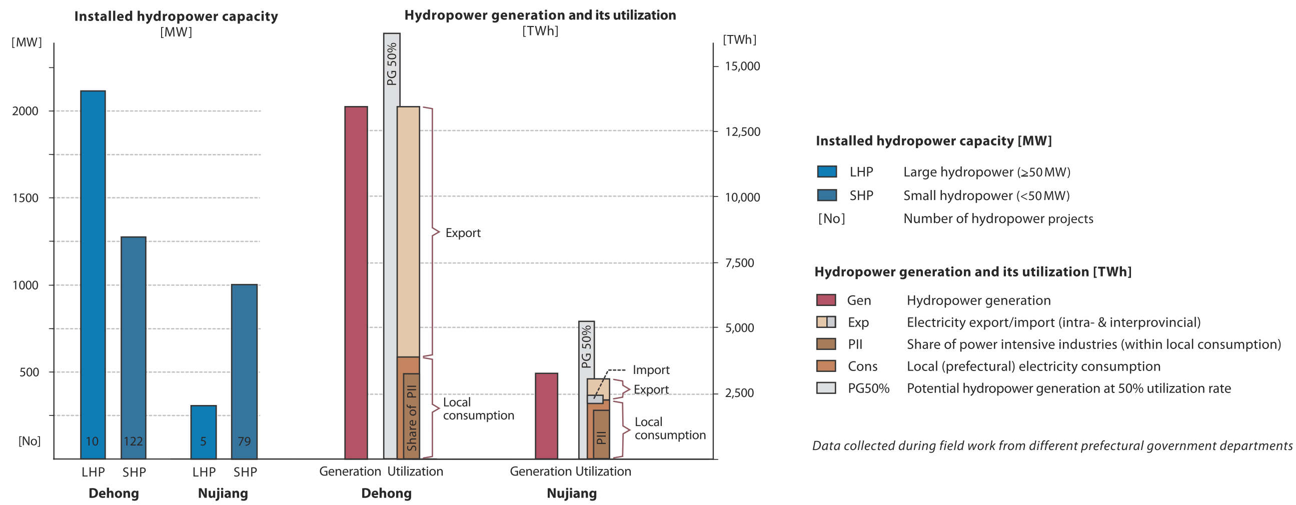

Fig. 7. Comparison of generation and consumption characteristics of Yunnan's Dehong and Nujiang prefectures, two of the world's largest small hydropower sub-regions.

means that, during the dry season, prefectures with a high local electricity demand (especially those with energy-intensive industries) import electricity from the YPG, even if they have a high SHP installed capacity. For Types 2 and 3, the significant seasonal variation in SHP generation and limited transmission capacity causes major electricity bottlenecks during both dry and wet seasons. This requires a coordinated dispatching and management system between power producers and consumers.

However, Yunnan's dispatching and management system is still a work in progress (Cheng et al., 2015). In Yunnan, each SHP negotiates an annual power generation quota with the local government, a process which involves SHP investors, the grid company (YPG/CSPG), and energy-intensive industries like silicon processing. During the 2000s SHP boom, these annual quotas were relatively high, but have steadily decreased with rising installed SHP capacity and the lack of meaningful improvements to grid connectivity. Indeed, in Dehong prefecture, for example, the average annual generation quota for an SHP plant in 2015 was only 70–90% of the average annual generation quota in 2010. The reason for this lower average annual generation is because installed SHP capacity rapidly increased while local consumption and electricity exports remained stable or decreased. Indeed, many SHP operators complained to us that the YPG purchases even less electricity than the agreed-upon quota. This is due to reduced power demand from local industries, but also due to reduction in industrial output in China and changes to regional and national energy portfolios.Example: Volatile electricity generation and demand causes grid congestion in Nujiang and Dehong

Nujiang and Dehong prefectures experience significant fluctuation in annual and intra-annual electricity generation and demand due to the prevalence of energy-intensive industries. Generation is volatile due to limited transmission capacity to the YPG and the variable electricity needs of local industries in the wet and dry seasons. To assess the degree of volatility, we analyzed the power generation in 2014 of 30 SHP plants –10 in Nujiang, and 20 in Dehong – with a range of between 12 and 40 MW installed capacity. Our analysis only includes electricity that fed into the grid. Results are shown in (Supplementary materials 2) and reveal that the average output compared to theoretical potential was only 48.1% in the two prefectures. In Nujiang, the average output was 44.2%, and individual plants varied between 38 and 61.4%. In Dehong, the average output was 50.1%, and individual plants varied between 31 and 75.5%. The large differences in output variation within Dehong is due mainly to a greater water demand from irrigated agriculture in specific locations and because the theoretical potential of some plants was poorly assessed during their construction phase. The output difference between the two prefectures is mainly the due to Nujiang's gorge topography that limits transmission to one north-south line which is easily congested.

6.5. Recent SHP policy changes

These challenges have not gone unnoticed by the Yunnan provincial government, which has broken from its earlier encouragement of SHP. As discussed previously, in the early 2000s the Yunnan government explicitly promoted SHP as a 'green' technology in Yunnan by giving prefecture governments the ability to approve plants ≤50 MW. In 2012, however, approvals at the prefecture level were restricted to plants ≤25 MW, owing to increasing recognition of the environmental impacts of over-development. In early 2016, the Yunnan government went further still, requiring that, all SHP plants in the province be approved by the provincial government. Moreover, further SHP construction in the Nujiang Basin was entirely outlawed in 2016. According to the government officials and plant owners we interviewed, these twin policies have had the effect of halting any new planning of SHP development in the province (those already approved or in the construction phase can continue).

Why has the Yunnan government enacted such restrictive policies? The stated reason for this change is the environmental and social impacts of SHP; specifically, dewatered streams and water access for irrigation. However, our discussions with officials in Yunnan revealed another underlying motivation: that the YPG is slowly integrating all prefectural grids under its own structure, so that it will have control over nearly all management and dispatching decisions. The YPG has much less desire to purchase SHP electricity due to its inherent instability, and thus does not want any new plants to be constructed.

Another policy change, which has not yet been enacted, will allow electricity producers to sign direct power agreements with large consumers, and provided a fixed transmission tariff to the grid operator (in Yunnan, the YPG). This is a significant change from the current structure established in 2002, in which electricity transmission and distribution is managed by national grids, and tariff structures are set by provincial or prefectural governments. Under this previous policy, SHP operators could not negotiate the sale of electricity directly to an energy-intensive industry, such as a mineral processing facility, and instead had to sell all electricity to the YPG. However, under this new policy (for which Yunnan became a model province in 2015), SHP operators can negotiate the direct sale of electricity to specific industrial users, rather than having to go through the YPG as a middleman. This has raised expectations that SHP operators will be able to obtain higher tariffs and that energy-intensive industries will be able obtain cheaper electricity rates. Further research is required to determine how this new price-setting policy will affect grid congestion and the indirect environmental impacts of SHP in Yunnan.

7. Conclusion and policy implications

7.1. Summary

This paper showed that there is no single trajectory of SHP development – that it ranges from small-scale, decentralized plants for rural electrification to large-scale clusters of cascaded systems. Specifically, we drew attention to the different 'shades' of green SHP – detailed in our four-fold typology – that may exist geographically close to each other, even as they are shaped by different local contexts. We showed that prefectures that operate in a semi-autonomous way in electricity management and industrial planning (Types 2 and 3) are most prone to over-develop SHP, since they depend on hydropower revenues from electricity generation and local energy-intensive industries. We then described the cumulative impacts that over-development can have, both direct impacts on water levels and water access, and the indirect impacts of energy-intensive industries on stream health and stable energy generation. These direct and indirect consequences of over-development can severely reduce the benefits that SHP should provide for electricity provision and rural development, thwarting its reputation as a 'green' energy source.

Our analysis made two key contributions to studies of small hydropower and local energy systems. First, we highlighted to the interplay between national-scale drivers of SHP development and local contextual factors that shape its implementation. The 'boom' in SHP construction that began in the early 2000s was partly a response to the privatization of electricity generation, policies promoting SHP for fuelwood replacement, and the availability of CDM funds. Yet the degree to which SHP was over-developed in specific places is a function of local agency and structural constraints. Second, we emphasized the indirect environmental impacts of SHP over-development due to synergies with energy-intensive industries. Here, SHP plants were not constructed as a replacement for fossil fuels, but specifically as a power source for mining and mineral processing. Thus, we need to be careful about labeling SHP and other energy systems as 'green' without considering the purpose for which they are developed. Renewable energy is indeed a cleaner alternative to fossil fuels, but only if it constructed instead of coal or natural gas, rather than only to generate revenues and power polluting extractive industries.

In addition, while our findings in this paper are limited to Yunnan, we believe the typology of SHP identified here is transferable to many other regions of China and the developing world. In particular, we suggest that the role of local grid, local industrial strategy, and electricity supply and demand are essential to understanding the type of SHP that occurs, and whether an area is prone to over-development and its associated direct and indirect impacts. Moreover, the general themes of our typology are applicable to other types of local energy systems in which decision-making is concentrated at the local scale. As SHP and other localized energy systems continue to expand, it is imperative that scholars examine the broader environmental, social, and political-economic context that shapes energy production and use at different scales.

7.2. Policy and management implications

In addition to the academic contributions above, we also highlight two implications for SHP policy and management in China. These implications are concentrated at the local scale of decision-making, but are also strongly affected by shifts in national policy, technological change, and future infrastructure investments (such as improved grid connectivity). SHP policy and management must therefore be adaptable to new incentives and structural constraints that arise from broader regional and national dynamics.

First, we emphasize the need for a stronger and more comprehensive watershed planning process for hydropower projects on small watersheds. Watershed planning and SHP management are currently the responsibilities of the local government, which tends to evaluate the impacts of individual SHP projects rather the cumulative impacts of cascades. To improve this planning process, individual plants should be analyzed as part of cascaded systems and the overall watershed. Planning should be based on comprehensive scientific studies of watershed hydrology, energy generation potential under different climate scenarios, and cumulative impacts of cascades on river/riverine ecology, hydrological regimes, and irrigation water access. This would mean incentivizing local officials to comprehensively assess new projects and regulate existing projects, such as through evaluation criteria, enforcement provisions, and funds for alternative energy sources and industries. The result of this planning process would be a more gradual, guided process of hydropower development on selected watersheds and river sections, rather than uncoordinated development that is spatially diffuse.

As part of this planning process, we also suggest that SHP cascades should be developed and managed by the same company. This would enable better coordination of streamflow and electricity generation given the water storage constraints of SHP cascades. This approach could also potentially mitigate negative environmental impacts in a large part of the watershed, because modifications to dam construction and operation parameters (such dam height, number, precise location, and output) are easier to implement if they are managed by the same company. Such a coordinated approach would also enable the project developer to minimize conflicts with irrigation users in the watershed.

Second, and more broadly, we recognize a need to re-assess the role of SHP in local economic development and its relationship to industry. In particular, we advocate a much better understanding of the trade-offs between SHP and power-intensive industries, such as identifying and quantifying indirect environmental consequences. As shown in our paper, SHP plants and associated industries in Yunnan generate tax revenues for local governments and play a major role in the local economy. However, over-reliance on SHP as a revenue source has caused indirect environmental impacts and fluctuating electricity demand and production. To counteract this trend, we strongly suggest a more regulated roll-out of energy-intensive industries in areas of high SHP potential. This would prioritize industrial diversity to minimize the effects of market volatility, and would focus on high technical standards and processes for each industrial facility. It would also identify priority areas for SHP development and areas to be set aside for conservation. In addition, the local or national power grid should calculate current and projected electricity demand, as well as existing and future transmission infrastructure, to determine if the electricity generated by new SHP projects can be purchased and consumed. By integrating SHP into broader debates and policies about energy, water management, and development, SHP can deploy as a 'green' power source that contributes to rural electrification and low-carbon growth goals.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2017.10.010.

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