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Identification of potential locations for small hydropower plant based on resources time footprint: A case study in Dan River Basin, China

Xiaoxun Huang [a,*], Kiichiro Hayashi [b], Minoru Fujii [c], Ferdinando Villa [d,e], Yuri Yamazaki [f], Hiromu Okazawa [g]

[a] Graduate School of Engineering, Nagoya University, Nagoya, 464-8601, Japan
[b] Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, 464-8601, Japan
[c] Center for Social and Environmental Systems Research, National Institute for Environmental Studies (NIES), Tsukuba, 305-8506, Japan
[d] Basque Centre for Climate Change (BC3), Scientific Campus of the University of the Basque Country, Leioa, 48940, Spain
[e] IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, Bilbao, 48009, Spain
[f] Faculty of Agriculture, Tottori University, Tottori, 680-8550, Japan
[g] Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, 156-8502, Japan

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ABSTRACT

Small hydropower has attracted extensive interest as a clean technology. This study first identified possible sites of small hydropower plants with estimated capacity, and then utilized resources time footprint as a novel way to evaluate the impact of small hydropower plants on the aspects of materials, CO_2, labor, and land. Resources time footprint is a sustainability indicator that uses a uniform time unit (years). It assesses whether the usage of resources exceeds the amount allocated to different people and generations. The smaller the value of resources time footprint, the more environmentally friendly is the process. Preferential locations for small hydropower in Dan River were specified, with a potential capacity ranging from 273 to 1175 kW. Resources time footprint of copper is 8.9–47.3 times as large as that of steel. Resources time footprint of CO_2 emissions is much smaller than that of other aspects, revealing that small hydropower has a great potential to mitigate the greenhouse effect. The overall resources time footprint decreases with an increase in the installed capacity. The methodology proposed in this study can be used to identify the ideal locations for setting up small hydropower plants in other regions as well.

1. Introduction

1.1. International background

In the past several decades, considerable attention has been paid to meeting the growing human energy needs using strategies that preserve the sustainability of the natural environment. Excessive use of fossil fuels has resulted in significant environmental problems, such as greenhouse effects, acid rain, and ozone depletion, which are constraints on the global economy [1]. Many countries are exploring different types of renewable energy sources, in response to the report of the Intergovernmental Panel on Climate Change considering climate change mitigation [2]. Among these renewable energy sources, hydropower is frequently mentioned. Hydropower is the major source of renewable energy in the world generating 16% of the global energy supply and more than half of all renewable electricity [3]. Gernaat et al. [4] estimated the remaining global potential of hydropower as 9.49 PW h per year, of which 39% is located in the Asia Pacific region. Thousands of hydropower installations with large dams have been built to fulfill the demand for low-carbon energy sources, especially in developing countries [5]. In recent years, people are skeptical to build new large dams due to the high socioeconomic costs, greenhouse gas emissions, and detrimental impact on ecosystem services [6].

Small hydropower (SHP) has recently attracted extensive interest as a clean, mature, and cost-effective conversion technology of hydropower with little or no storage facility, which can be flexibly operated and easily maintained [7]. Owing to these advantages, it has become a preferred energy source for generating electricity in rural and mountainous areas [8,9]. SHPs are considered a crucial component of prospective energy strategies worldwide [10]. The definition of SHP is ambiguous, but since nearly 70% of the countries define SHP plants as

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* Corresponding author.
E-mail address: huang.xiaoxun.k5@s.mail.nagoya-u.ac.jp (X. Huang).

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Nomenclature

Abbreviations

BAU	Business as Usual
DEM	Digital Elevation Model
LCA	Life Cycle Assessment
RTF	Resources Time Footprint
PV	Photovoltaic
SHP	Small Hydropower

Symbols

AP	Land area occupied by the SHP plant (km^2)
APH	Annual operating hours
ARC_i	Area of road construction for the *i*th SHP plant (km^2)
AT_i	Area converted by timber use for the *i*th SHP plant (km^2)
CA	Amount of consumption of a resource or emission of pollutant
CD_w	Global in use stock of copper (kg)
CE_i	Cement use for the *i*th SHP plant (kg)
CET_i	CO_2 emissions during transportation for the *i*th SHP plant
CI_{ce}	CO_2 emission intensity of cement production (kg CO_2e/kg)
CI_{co}	CO_2 emission intensity of copper production (kg CO_2e/kg)
CI_{hp}	CO_2 emission intensity of hydropower generation (kg CO_2e/kWh)
CI_s	CO_2 emission intensity of steel production (kg CO_2e/kg)
CI_{tp}	CO_2 emission intensity of coal power plants (kg CO_2e/kWh)
CO_i	Copper use for the *i*th SHP plant (kg)
CR_w	Global copper reserves (kg)
CU	Annual net global carbon dioxide uptake (kg)
EC	Annual electricity consumption (kWh)
H_e	Effective head (m)
IC_i	Installed capacity of the *i*th potential SHP plant (kW)
LRE_i	Land use by renewable energy production for the *i*th SHP plant (km^2)
OA	Amount of resources occupied
P_d	Total population in the provinces of Shaanxi, Henan, and Hubei in China
P_i	Population of beneficiary of the *i*th SHP plant
P_w	World population
PWP_c	Percentage of working-age population in China
Q_i	Flow rate (m^3/s)
$S_{c,i}$	Steel use for construction for the *i*th SHP plant (kg)
$S_{e,i}$	Steel use for equipment for the *i*th SHP plant (kg)
SD_w	Global in use stock of steel (kg)
SR_w	Global steel reserves (iron content in iron ore) (kg)
T	Period of resource occupancy (years)
TA	Total capacity of a resource
TS	Capacity of supply or removal speed of a resource
VC_i	Volume of concrete use for the *i*th SHP plant (m^3)
WH_p	Working hours for hydropower plant construction
WH_r	Working hours for road construction
WO_i	Personnel required for the operation of the *i*th SHP plant
η	Total efficiency

installations with a maximum capacity not exceeding 10 MW, this value is increasingly regarded as the global standard [5,11].

1.2. Proliferation of small hydropower in China

A reduction in the use of fossil fuels and the simultaneous development of clean and renewable energy are indispensable for addressing both energy security and pollution alleviation in China [12,13]. In 2020, coal, oil, and natural gas accounted for 70.5%, hydropower 17.9%, wind 6.3%, and others 5.3% of the total electricity generation in China [14]. To date, 47,000 SHP stations with a total installed capacity $\geq$ 77.9 GW are operational in over 1700 counties in China, making considerable contributions to rural electrification [7,15].

As a conversion technology for hydropower, SHP has numerous merits, some of which are especially relevant for China according to Kong et al. [16]. First, it is clean and green as water quality and volume are not affected, along with the survival and reproduction of fish in the rivers. Second, the technology is very mature, so a new station may be built very fast and can still sustain for a long time with low maintenance and excellent efficiency. Third, it can rapidly supply electricity in isolated areas when the main power grid breaks down after natural disasters. In addition, the comparatively low electricity price of SHP can ease the financial burden in poorer rural Chinese areas [17,18].

1.3. Environmental concerns of small hydropower

During regular operation, there is no fossil fuel cost for SHP plants. However, similar to other types of renewable energy, a large initial investment is required in SHP plants in terms of construction materials, electricity generation equipment, and transportation costs that indirectly cause environmental pollution [19]. Global attention has started to focus on the pollution caused by SHP, and a systematic assessment of such pollution is especially required for China considering the rapid expansion of SHP.

Life cycle assessment (LCA) is a methodology for quantifying different kinds of environmental impacts, including global warming potential and acidification potential for a product system throughout its lifespan [20]. Gallagher et al. [21] applied LCA to three run-of-river SHP projects in the UK and identified that capacity should be increased to offset the environmental burdens of an SHP plant. An LCA was conducted in Guizhou Province in China for an SHP plant with an installed capacity of 3.2 MW, indicating that cement, steel, and electricity costs are the dominating factors that contributed the most to the environmental impacts [19]. In another study, Pang et al. [22] evaluated the ecological impacts of the same SHP plant in Guizhou Province based on emergy analysis, which is an eco-thermodynamic method to assess the overall environmental loading and sustainability of systems [23]. Three run-of-river hydropower plants in the Peruvian Andes were analyzed using LCA, and concrete, transmission lines, and reinforcing steel accounted for a large proportion of greenhouse gas emissions [24]. Most LCA studies assume that the infrastructure of SHP plants remains on-site at the end of life, and the construction stage is regarded as the largest contributor to environmental impact [19,21,22,25,26].

Existing LCA studies of SHP plants primarily focus on the flows of material and energy, but they rarely consider the resource stock. Many resources or their supply turnover speed are finite and limited. Many LCA studies of SHP plants found that the enormous quantity of steel utilized contributed to environmental impacts such as greenhouse gas emissions, but they did not consider that steel supply was limited. To evaluate the sustainability of the SHP, analyzing whether the usage of each resource can exceed its capacity is crucial.

1.4. Definition of resources time footprint (RTF)

Fujii et al. [27] proposed the RTF concept to overcome the issues of resource stock and sustainability. RTF is an indicator of sustainability-related to materials, land, labor, and pollution that uses a uniform temporal unit of years. The numerator of each aspect of RTF is resource occupancy arising from products or services, and the denominator is capacity of each resource (Fig. 1). Based on our previous work, The RTF takes into account not only consumption but also the resource availability on Earth, as well as the allocation of each resource among individuals and generations, allowing for a more comprehensive assessment of alternatives and their effect on sustainability. This study utilizes RTF and includes the burden on the labor force caused by the development of renewable energy, which has rarely been included in other studies. In addition, RTF is mostly utilized to compare production processes in our previous work, as well as different practices of forest management [28,29]. Our study is the first to apply it to a site selection study as a spatial assessment. After combining RTF analysis with spatial data, optimal locations for potential SHP plants in the study area were proposed and visualized using GIS analysis.

1.5. Objectives

The objectives of this study were to make an initial attempt to evaluate spatial variation of environmental impact of potential SHP plants through RTF, and to develop a framework for the site selection of future SHP plants, which could provide scientific guidance for decision makers.

2. Materials and methods

2.1. Study area

The Dan River is situated in the Dan River drainage basin (32°30′–34°10′ N, 109°30′–112°00′ E) in the provinces of Shaanxi, Henan, and Hubei in China. The Dan River rises in the Qinling Mountains of Shaanxi, then flows southeast before converging on the Han River at Danjiangkou Reservoir in Hubei [30] (Fig. 2).

The drainage area of the Dan River is 16,812 km^2, and the total length of the main stream is 287 km, of which 243.5 km is in Shaanxi and 44 km is in Henan [31]. The majority of the regions in the Dan River Basin are hilly and have dense vegetation. The average annual temperature is 11–14 °C, and the average annual precipitation is 743.5 mm [31]. At the end of 2018, there were 691 SHP plants in Shaanxi, and the SHP became the most market-oriented part of the province's water conservation industry [32].

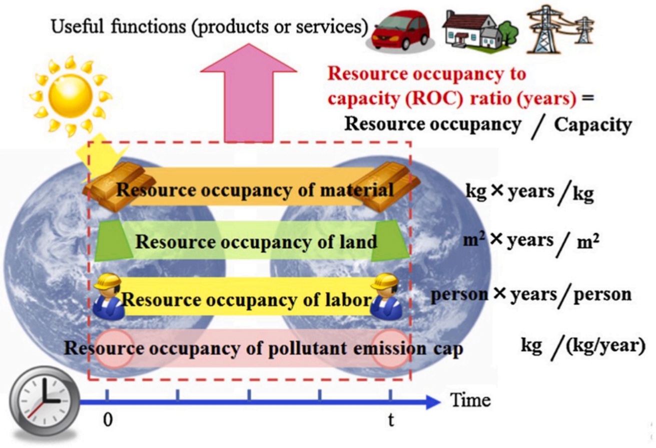

Fig. 1. RTF of different aspects of sustainability [27].

2.2. Research flow

Fig. 3 shows the processes of our study. The flow direction and flow accumulation were estimated from Digital Elevation Model (DEM) using ArcGIS Pro 2.9.2. The monthly water monitoring data for 2019 were downloaded from the Ministry of Water Resources of the People's Republic of China (http://mwr.gov.cn/). We estimated river discharge at each potential point in the study area using a specific discharge rate obtained from the relationship between the calculated flow accumulation (watershed area) and the actual monthly average discharge at the observation sites [33]. Next, SHP generation potential was calculated. After excluding restricted areas, including soil erodible areas, landslide susceptible areas, protected areas, and key biodiversity areas, potential sites for SHP were identified. Road vector data were used to estimate the distance of road construction from the potential SHP plants (Table 1). These spatial data were combined with other inventory data of the SHP plant for RTF calculation in ArcGIS Pro 2.9.2. After calculation, the RTF values of each potential location of the SHP plants were obtained, and preferential locations with smaller RTF values were mapped to the Dan River Basin.

2.3. Small hydropower potential

The SHP generation capacity was calculated using Equation (1) [33,40,41].

$$IC_i = 9.8 \times Q_i \times H_e \times \eta \tag{1}$$

where, IC_i is the SHP generation capacity (kW), Q_i is the flow rate (m^3/s), H_e is the effective head (m), and η is the total efficiency. The H_e was set to 5 m, which is the average value for the run-of-river SHP. The total efficiency η is a value obtained from the efficiency and waterway loss of water turbines and generators and was set to 0.8 [33].

The potential locations for installations of SHP plants with their hypothetical installed capacity (IC_i, $i = 1,2,3,\ldots,11086$) were displayed on the map, and these raster data with 30 m resolution were converted to point data for subsequent RTF analysis.

2.4. Resources time footprint analysis

2.4.1. General equation of RTF

RTF, also referred to as the resource occupancy to capacity ratio by our previous work is a common metric used to measure sustainability. This indicator utilizes the concept of "resource occupancy" of crucial multidimensional aspects connected with sustainability; the definition of resource occupancy is "the potentially reversible use of some type of resource that can be reused for a subsequent purpose within a specific period" [27]; pp.53). The RTF of each aspect is uniformly represented in years, enabling easier assessment of trade-offs among different aspects of sustainability and comparison of alternatives developed to achieve a more sustainable society [27].

According to our previous work, the general equation of the RTF (years) is expressed as:

$$\mathrm{RTF} = OA \times \frac{T}{TA} \tag{2}$$

where OA is the amount of resources occupied by an individual or group, T is the period of resource occupancy (years), which is usually set to 100 years in the scenario (close to the lifespan of humans with an assumption of extension due to scientific advancement), and TA is the total capacity of a resource (allocated amount to an individual or a group).

For resources with a finite supply speed, RTF can be expressed as:

$$\mathrm{RTF} = \frac{CA}{TS} \tag{3}$$

where, CA stands for the amount of consumption of a resource or

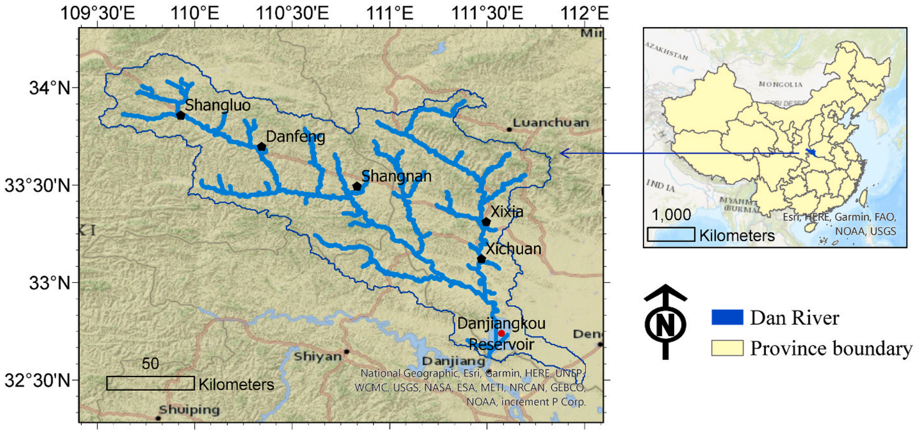

Fig. 2. Drainage basin of the Dan River (province boundary data was downloaded from RESDC [79]).

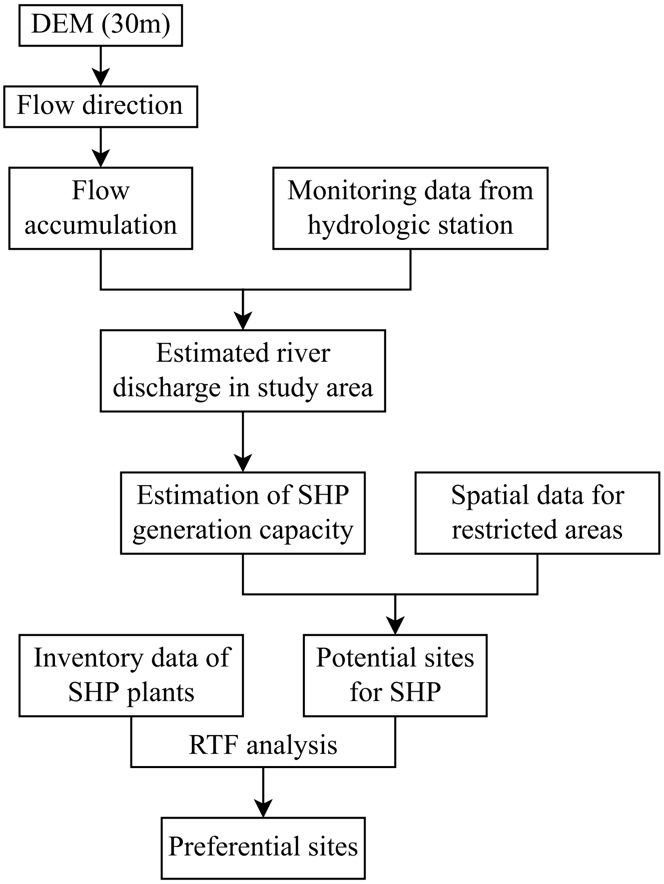

Fig. 3. Research flow of RTF analysis of potential SHP plants.

emission of pollutant per person or per group (kg) and *TS* is the capacity of supply or removal speed of a resource (allocated amount to an individual or a group) (kg). When *CA* represents pollutant, such as CO_2 emissions, the result can also be presented as ΔRTF (the difference of RTF values between a countermeasure and business as usual-BAU scenario), thus the value may be negative. For the case study described in section 2.4, CO_2 emissions during the operation of SHP were calculated as CO_2 emissions from hydropower generation subtracted by CO_2 emissions from the same amount of thermal power generation, hence the value was negative. However, if the purpose is to compare the resource occupation between countries or regions, the result will be absolute values of RTF.

Table 1
Overview of the spatial data.

Data	Type of data	Time	Data source
ASTER Global Digital Elevation Model V003	Raster (30 m grid)	2013	Downloaded from https://search.earthdata.nasa.gov/
Soil erodible areas	Raster (250 m grid)	2021	Computed using ARIES (https://aries.integratedmodelling.org/) [34]
Landslide susceptible areas	Raster (1 km grid)	2017	[35]
Protected areas	Shapefile	2022	UNEP-WCMC and IUCN [36]
Key biodiversity areas	Shapefile	2022	BirdLife International [37]
Road	Shapefile	2018	[38]
Land cover map	Raster (100 m grid)	2019	[39]

Our previous work summarized the interpretation of RTF as follows: When the value of RTF is smaller, fewer resources are used or less pollution is emitted, indicating that the process is more sustainable. If RTF = 0 is the current resource utilization (BAU scenario), ΔRTF<0 suggests that the occupancy of the resource will be negative and the effect on the environment will be positive due to the newly introduced product or service, with larger negative magnitudes indicating larger positive effects. Usually, the absolute value of RTF will not be negative. However, as an exception, in biomass with CO_2 capture and storage (Bio-CCS), CO_2 emission is negative, so the absolute value of RTF of CO_2 can be negative. There were no upper or lower bounds for the RTF value. If the RTF value is greater than an individual's lifespan, the occupancy of this resource may influence other people or the next generation, which is not sustainable. The RTF value calculated in the following case study was ΔRTF (value after construction and operation of the SHP plant minus value of BAU).

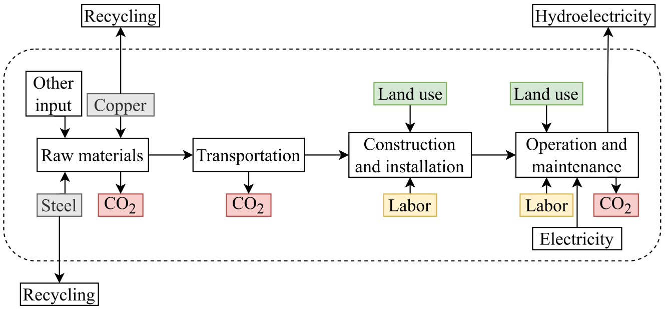

Fig. 4. System boundary for RTF analysis on the power generation by the operation of SHP plant for 100 years.

2.4.2. *System boundary*

Construction and operation are two important stages in SHP plants (Fig. 4). First, resources are excavated and refined into raw materials for the construction of buildings or assemblages of equipment [42]. Because the SHP plant in this study was assumed to be a run-of-river type, large-scale dams were not expected to be constructed. Steel is used for building housing and hydro-equipment, such as turbines, and copper is used for generators [19]. The occupancy period was assumed to be 100 years, and the lifespan of hydro-equipment is usually 30 years [19,43] so materials for hydro-equipment would be replaced three times. We assumed that all the replaced copper and steel could be utilized for other purposes after recycling. The transportation stage consisted of the transport of construction materials and equipment to a potential site by a diesel truck.

The construction stage involves the construction of powerhouse, penstock, and tailrace, and the installation of equipment such as turbines and generators [19]; meanwhile, a new road would be paved from the existing road to the plant site. During this stage, the labor force and land occupancy for plant construction and road pavements were considered. During the operation stage, although there were no direct emissions caused by the hydro-turbine operation, compensation of thermal backup power from the grid was needed for the plant when the turbine stopped running [19]. The relationships between the installed capacity and input for the construction and equipment of an SHP plant were estimated from the inventory table of five SHP plants in Ref. [44]. Input during different stages of the SHP plant can be found in Table A1 in supplemental material. Disposal of SHP plants was not included in this study since the construction would usually remain onsite and demolition of SHP plants were uncommon [19,24–26].

2.4.3. *Beneficiary value of each potential SHP plant*

Since resource occupancy in RTF analysis is usually calculated on a per-capita basis, the benefit of each potential SHP plant is calculated as the number of people who can utilize the electricity generated by the SHP plant to meet the annual electricity demand. The beneficiary value was calculated using the following equation:

$$P_i = IC_i \times \frac{APH}{EC} \tag{4}$$

where, IC_i is the installed capacity of the *i*th potential SHP plant; *APH* is the annual operating hours of the SHP plant, which was set as 3491 h, the average value in China [45]; *EC* is the annual electricity consumption in China, which was 5356 kW h/capita [46].

2.4.4. *RTF of material*

The RTF of materials for each potential SHP plant can be expressed using the following equation:

$$\mathrm{RTF}_{\mathrm{steel}} = \frac{(S_{c,i} + S_{e,i}) \times T/P_i}{SR_w + SD_w/P_w} \tag{5}$$

$$\mathrm{RTF}_{\mathrm{copper}} = \frac{CO_i \times T/P_i}{CR_w + CD_w/P_w} \tag{6}$$

Equations (5) and (6) represent the occupancy of steel and copper per capita during 100 years (kg*year) divided by the present capacity of steel and copper allocated per person (kg). Since steel and copper are usually traded between countries, capacity is allocated per person worldwide (Table 2).

2.4.5. *RTF of CO_2 emissions*

Theoretically, RTF can capture CO_2 and other pollutants. However, this study focused on CO_2 only. The CO_2 emissions were derived from the following stages:1) the production of steel, copper, and cement from primary and secondary sources; 2) transportation of materials from the factories to the potential site of SHP plants via diesel trucks; 3) the

Table 2
Parameters used to calculate RTF.

Parameter	Description	Value	Unit	Reference
AP	Land area occupied by the SHP plant	0.06	km^2	[44]
APH	Annual operating hours of SHP plant in China	3491	hours	[45]
ARC_i	Area of road construction for the *i*th SHP plant	Site-specific		
AT_i	Area converted by timber use for the *i*th SHP plant	$28.98 \times IC_i^{0.83}/5244$	km^2	Forest stock volume data were obtained from National Bureau of Statistics, China [47]
CD_w	Global in use stock of copper in 2020	3.0 E+11	kg	[77]
CE_i	Cement use for the *i*th SHP plant	$2091 \times IC_i^{0.93}$	kg	[44]
CET_i	CO_2 emissions during transportation for the *i*th SHP	Site-specific	kg	See equation A.1 in supplementary material
CI_{ce}	CO_2 emission intensity of cement production in China	0.735	kg CO_2e/kg	[48]
CI_{co}	CO_2 emission intensity of copper production in China	5.88	kg CO_2e/kg copper from primary sources	[49]
		1.59	kg CO_2e/kg copper from secondary sources	
CI_{hp}	CO_2 emission intensity of hydropower generation in China	0.02	kg CO_2e/kWh	[45]
CI_s	CO_2 emission intensity of steel production in China	2.148	kg CO_2e/kg steel from primary sources	[50]
		1.4	kg CO_2e/kg steel from secondary sources	[51]
CI_{tp}	CO_2 emission intensity of coal power plants in China	0.865	kg CO_2e/kWh	[52]
CO_i	Copper use for the *i*th SHP plant	$479 \times IC_i^{0.42}$	kg	[44]
CR_w	Global copper reserves	8.80 E+11	kg	USGS [53]
CU	Annual net global carbon dioxide uptake	2.02 E+13	kg	[54]
IC_i	Installed capacity of the *i*th potential SHP plant	Site-specific		
LRE_i	Land use by renewable energy production for the *i*th SHP plant	Site-specific	km^2	[55,56]
P_d	Total population in the provinces of Shaanxi,	1.96 E+08	person	National Bureau of Statistics, China [57].

(*continued on next page*)

Table 2 (*continued*)

Parameter	Description	Value	Unit	Reference
	Henan, and Hubei in China			
P_i	Population of beneficiary of the *i*th SHP plant	Site-specific	person	
P_w	Total population in the world	7.76 E+09	person	World bank [58]
PWP_c	Percentage of working-age population in China	42%		World bank [58]
$S_{c,i}$	Steel use for construction for the *i*th SHP plant	$446 \times IC_i^{0.71}$	kg	[44]
$S_{e,i}$	Steel use for equipment for the *i*th SHP plant	$89.2 \times IC_i^{0.84}$	kg	[44]
SD_w	Global in use stock of steel in 2020	2.50 E+13	kg	[59]
SR_w	Global steel reserves (iron content in iron ore)	8.50 E+13	kg	USGS [53]
T	Period of resource occupancy	100	years	[27]
VC_i	Volume of concrete use for the *i*th SHP plant	$CE_i/0.36$	m^3	[44]
WH_p	Working hours for hydropower plant construction in China	11.09	Person*hour/ m^3 concrete	Ministry of Water Resources of China [60]
WH_r	Working hours for road construction in China	3.39	Person*hour/ m^2	Ministry of Land and Resources of China [61]
WO_i	Personnel required for the operation of the *i*th SHP plant in China	10 when $IC_i \leq$ 500 kW; 18 when $IC_i >$ 500 kW	Person	Ministry of Water Resources of China [62]

operation of the SHP plant. The CO_2 emissions during the operational stage were calculated as the amount of emitted CO_2 that could be reduced if the hydropower generated was substituted for the same amount of thermal power. During the 100 years, materials for hydro-equipment would be replaced three times. We assumed that the replacement steel and copper were made from secondary (recycled) metals, and those for new installations were from primary sources.

The RTF of CO_2 emissions for each potential SHP plant can be expressed using the following equation:

$$\mathrm{RTF}_{\mathrm{CO_2}} = \frac{\left[S_{c,i} \times CI_s + \left(S_{e,i} \times CI_s + CO_i \times CI_{co}\right) \times 4 + CE_i \times CI_{ce} + CET_i + \left(CI_{hp} - CI_{tp}\right) \times APH \times IC_i \times T\right]/P_i}{CU/P_w} \tag{7}$$

2.4.6. *RTF of labor*

The labor force needed during the construction of pathways between the potential site of the SHP plant and the existing road, and for the construction and the operation of the plant were calculated.

Table 3
Naturalness and occupancy level of each land cover type in the provinces of Shaanxi, Henan, and Hubei in China.

Land Cover Type	Naturalness[a]	Occupancy level[a]	Total Area (km^2)[b]
Natural Forest	9	0	140,389
Natural grassland	10	0	6812
Artificial forest, shrub	6	0.4	96,838
Artificial grassland	5	0.5	61,714
Cultivated and managed vegetation/agriculture (cropland)	2	0.6	205,344
Urban/built up	1	1.0	32,342

[a] Values were cited from [29].
[b] Data of natural forest areas in Shaanxi, Henan, and Hubei Provinces were obtained from National Forestry and Grassland Administration [63], the Chinese Government [64], and [65], and areas of other land cover types were calculated from land cover map in 2019 downloaded from Copernicus.

The RTF of labor for each potential SHP plant can be expressed by the following equation:

$$\mathrm{RTF}_{\mathrm{labor}} = \frac{\frac{WH_r \times ARC_i + WH_p \times VC_i}{2000} + WO_i \times T}{PWP_c \times P_i} \tag{8}$$

The numerator of this equation refers to the total labor force required for the plant over 100 years (person × year), and the denominator is the total working-age population of the beneficiary (Table 2). Hypothetical annual working hours in China were assumed to be 2000.

2.4.7. *RTF of land*

The timber used during the construction of the SHP plant, electricity consumption and generation during construction and operation, and the area occupied by potential road construction and the plant were involved in the analysis of RTF for land. The RTF of the land occupancy for each potential SHP plant can be expressed by the following equation:

$$\mathrm{RTF}_{\mathrm{land}} = \frac{\left[AT_i \times \frac{1+0.4}{2} \times 40 + LRE_i + (ARC_i + AP) \times 1 \times T\right]/P_i}{\sum_{x=1}^{5} \frac{y \times TA_x}{P_d}} \tag{9}$$

The denominator of this equation represents the corrected occupied land area per capita in the provinces of Shaanxi, Henan, and Hubei where the Dan River is situated. The corrected occupied land area was calculated by multiplying the total area of each land cover type in the three provinces (TA_x) with the corresponding occupancy level y (Table 3). The volume of timber consumed (m^3) was converted to the area of land (AT_i) (km^2) based on the average forest stock volume (m^3/km^2) in the three provinces. After the land was cleared to harvest timber, the land occupancy level was set to 1. It takes an average of 40 years for the land to transform back to the artificial forest, whose occupancy level was set at 0.4. Electricity consumption and generation during construction and operation were converted to the area of land (LRE_i) (km^2) for renewable sources to generate the same amount of electric power. For each potential SHP plant, we assumed that half of the electricity was generated by solar photovoltaic (PV) and the other half was generated by bio-energy from timber. Because naturalness was high in study area, after the land area was used for the road and plant, the occupancy level became “1” from “0”. Therefore, we multiplied the land occupation of road and plant by “1”.

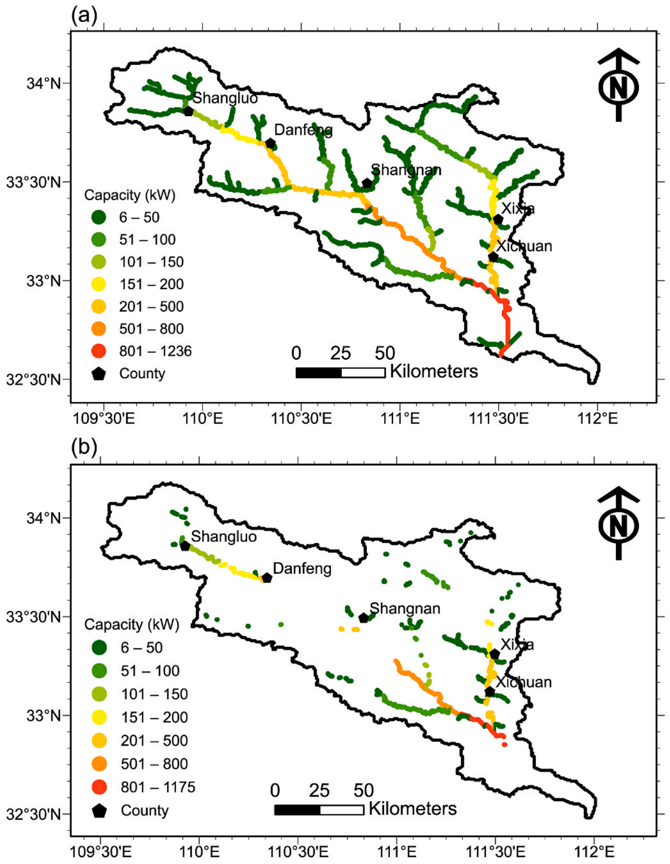

Fig. 5. (a) Potential capacity from the waterway in the Dan River Basin (unit: kW) (b) Potential installed capacity of possible sites of SHP plants in the Dan River Basin after excluding protected areas, key biodiversity areas, landslide-susceptible areas, and soil-erodible areas (unit: kW).

3. Results

3.1. Possible sites of SHP plants in the Dan River Basin

Fig. 5 (a) and (b) were obtained after running the SHP potential model in ArcGIS Pro following the processes in Section 2.3. The potential electricity generation capacity along the Dan River ranged from 6 to 1236 kW of 45,184 points (Fig. 5 (a)). After exclusion of protected areas, key biodiversity areas, landslide-susceptible areas, and soil-erodible areas which were overlapping with the waterway, the remaining part was the possible sites of SHP plants. The potential installed capacity of the SHP plant ranged from 6 to 1175 kW of 11,086 points (Fig. 5 (b)). The main areas excluded from the waterway were the downstream portion of the Dan River, namely the Danjiangkou Reservoir, as well as the downstream of Danfeng and Shangnan County due to the presence of flood plain and landslide susceptibility areas.

3.2. Analysis of RTF for potential sites of SHP plants

The ΔRTF of materials, CO_2 emissions, labor, and land of each potential SHP plant compared to BAU are shown in Fig. 6, and the basic statistics are shown in Table 4.

The ΔRTF of steel ranged from 0.92 to 3.55 for potential SHP plants in the Dan River Basin, and the ΔRTF of copper was between 8.19 and 168.11 including the amount used for the construction and equipment. When the potential installed capacity was larger, the ΔRTF of the material in the study area was smaller. Moreover, the ΔRTF of copper was 8.9–47.3 times higher than that of steel, which means that the occupancy of copper has a larger impact on sustainability. Although the amount of copper used was less than that of steel in SHP plants, the copper availability in society is much smaller than that of steel in the current situation. Because RTF considers the ratio between the occupancy of the resource and the total capacity of the resource, the utilization of copper weighs more in the RTF of the material.

The ΔRTF of CO_2 emissions was negative for all the potential sites for the SHP plant, which means that the absolute value of CO_2 emissions during the operation stage was larger than the CO_2 emissions during transportation and construction. Because CO_2 emissions during the operation stage were calculated as CO_2 emissions from hydropower generation subtracted by CO_2 emissions from the same amount of thermal power generation, the value was negative. The negative value of ΔRTF indicated that compared to BAU scenario, the occupancy of the resource would decrease with the newly introduced product or service. The negative ΔRTF of CO_2 for SHP suggests that if locals utilize electricity generated by SHP instead of traditional thermal power, their occupancy of the allocated amount of CO_2 emissions will decrease.

The ΔRTF of land ranged from −173.65–1781.10 and 68.28–2023.03 with and without conversion of the electricity generation to the land area occupied by solar power and bioenergy to produce the same amount of electricity, respectively revealing that the SHP has the potential to reduce future land occupation incurred by the installation of solar power and bioenergy. Although, for 60% of the potential sites, there was land area occupied by the SHP plant and the pathway, the potential to reduce prospective land use could completely compensate for it.

In terms of the ΔRTF of labor, the values varied between 5.95 and 686.64 (Fig. 6(e)). The ΔRTF of labor was much larger when the potential installed capacity was small, owing to the small number of beneficiaries. Although there were labor inputs during the construction of roads and plants, the ΔRTF of labor was mainly determined by the labor force during the operational period of 100 years.

Fig. 6 (f) shows the overall ΔRTF for four aspects *viz.* materials, CO_2, labor, and land for each potential site of the SHP plant in the Dan River Basin. No weighting factor was included in the calculation. When applying this method to other regions, if some aspects of the RTF are region-specific, the weighting factors can be re-considered in calculating the overall RTF. Among all potential sites, 7151 out of 11,086 had negative overall ΔRTF values, which means the environmental performance of 65% of the potential SHP plants was positive in the study area.

The relationship between the ΔRTF of each aspect and the potential installed capacity of the SHP plant is shown in Fig. 7. With an increase in the potential installed capacity, the ΔRTF of copper, land, and labor decreases considerably between 0 and 50 kW, while the ΔRTF of CO_2 and steel decrease marginally. The capacity of SHP plants to reduce CO_2 emissions and prevent future land use is overwhelming compared to the material and labor inputs during construction and operation.

Although some site-specific factors such as labor force and land use for road construction and transportation of raw materials are included in the analysis of RTF, the trend of the total ΔRTF was determined by the potential installed capacity of SHP plants. When the installed capacity increased within the limits of the SHP, the overall ΔRTF was smaller.

3.3. Preferential sites for potential SHP plant

The top 25% of the 11,086 potential SHP plants in the Dan River as sorted by ascending overall ΔRTF values are shown in Fig. 8. The capacity ranged from 273 to 1175 kW. The top 25% of SHP plants are expected to contribute to sustainability the most among all potential sites in the river basin. The selected potential sites with the lowest ΔRTF would be the most environmentally friendly and would have the highest capacity to contribute to the reduction of CO_2 emissions and prevention

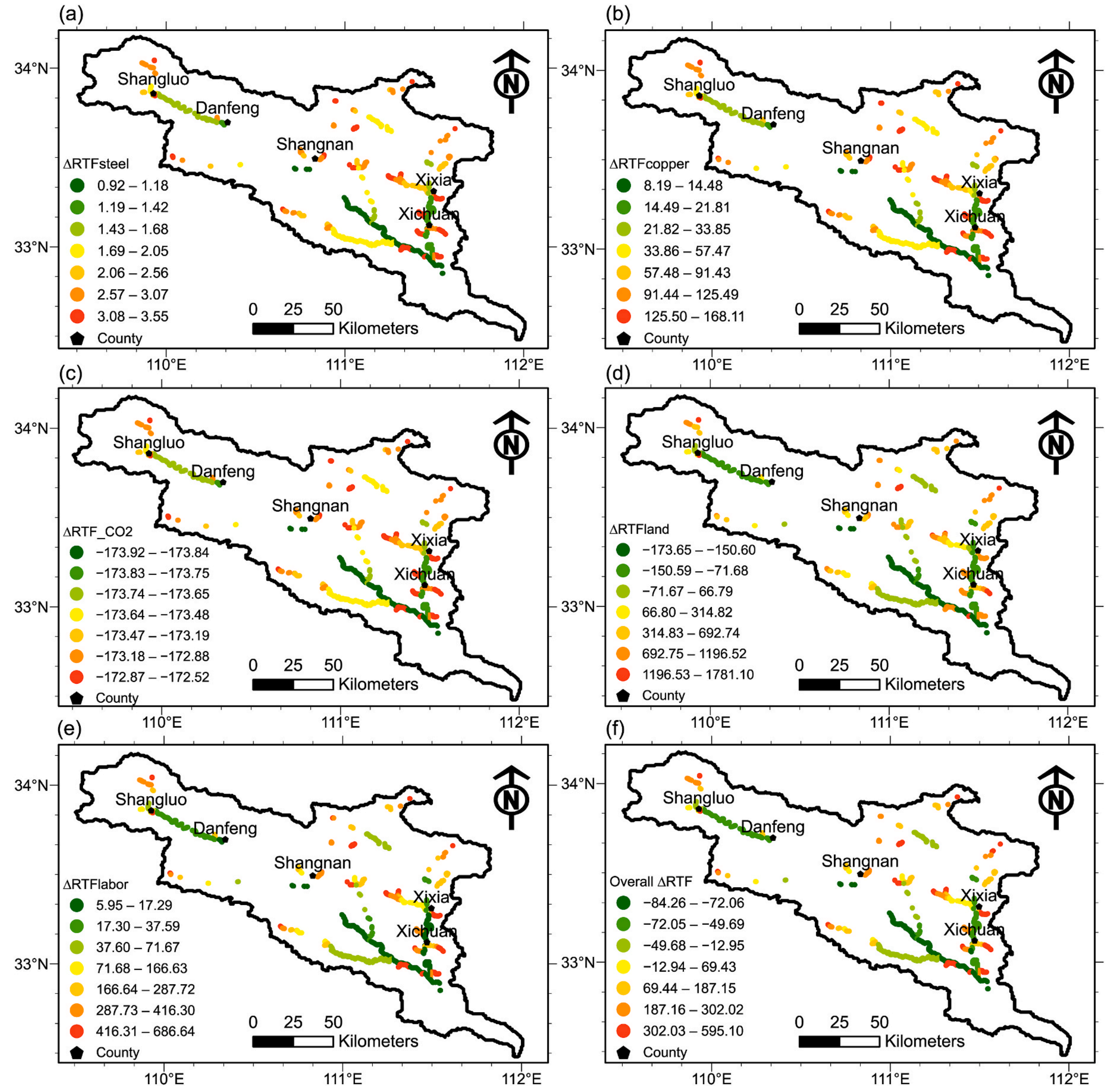

Fig. 6. ΔRTF values of the power generation by the operation of possible SHP plants for 100 years compared to BAU in the Dan River Basin (unit: years): (a) ΔRTF of steel; (b) ΔRTF of copper; (c) ΔRTF of CO_2 emissions; (d) ΔRTF of land; (e) ΔRTF of labor and (f) Overall ΔRTF.

Table 4
Basic statistics of ΔRTF values of the power generation by the operation of potential SHP plants for 100 years compared to BAU.

Aspect	Description	Value of ΔRTF (years)				
		Average	Median	Maximum	Minimum	n
Material	Steel	1.97	1.80	3.55	0.92	11,086
	Copper	55.87	37.22	168.11	8.19	
	Averaged value of steel and copper	28.92	19.51	85.83	4.55	
CO_2	CO_2	−173.46	−173.60	−172.52	−173.92	
Land	land	171.45	−43.92	1781.10	−173.65	
	land_exclude_LRE	413.38	198.01	2023.03	68.28	
	LRE	−241.93				
Labor	labor	132.44	44.62	686.64	5.95	
Overall RTF	Averaged value of four aspects	39.84	−38.32	595.10	−84.26	

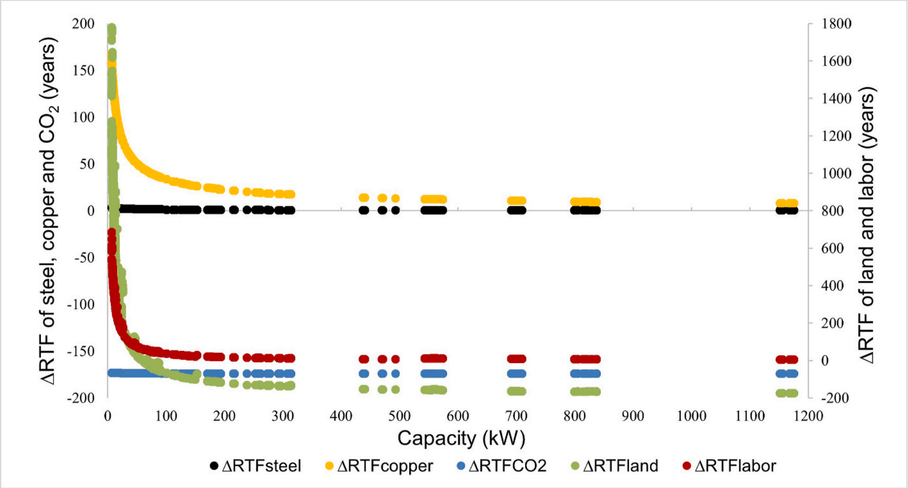

Fig. 7. Relationship between the ΔRTF of each aspect and the potential installed capacity of the SHP plant.

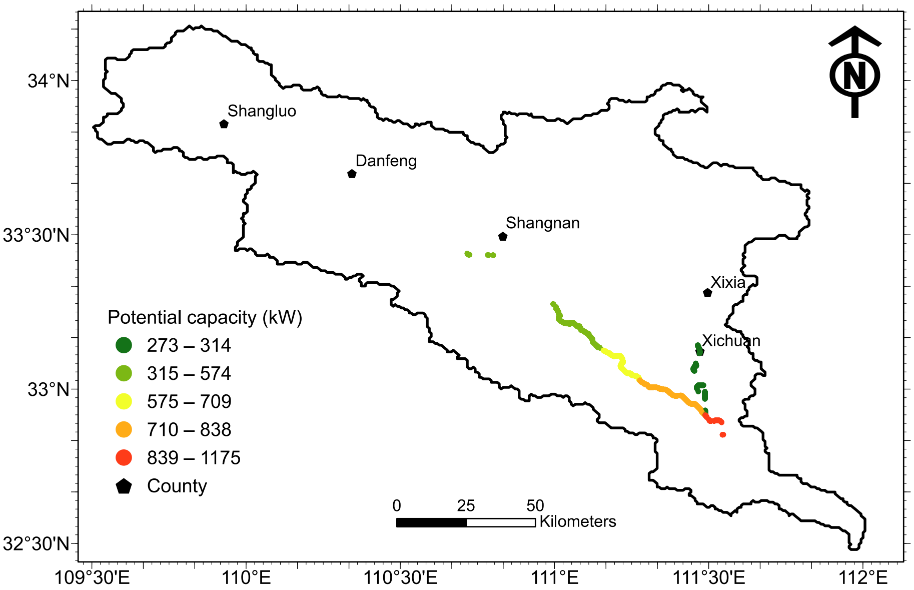

Fig. 8. Preferential sites of SHP plants in the Dan River Basin.

of future land degradation. Therefore, the ideal locations for SHP plants in the study area were the midstream and downstream portions of the main channel of the Dan River.

4. Discussion

4.1. RTF analysis of SHP

SHP which is regarded as a green energy source reduces the requirement for coal-fired thermal power generation. Hence, it could indirectly reduce CO_2 emissions by reducing the workload of the thermal power generators. According to CDM (Clean Development Mechanism), the reduced CO_2 emission is proportionate to the amount of electricity generated by the SHP plant [66]. In this study, the CO_2 emissions were allocated to the beneficiaries in the Dan River Basin, and the ΔRTF value of CO_2 did not change significantly with the installed capacity. CO_2 emissions during operation depend on the installed capacity and annual working hours. Because the ΔRTF of CO_2 was negative, the absolute value of CO_2 emissions during the operation was much larger than the total CO_2 emissions during production and transportation, which indicated that the ΔRTF of CO_2 was determined by the CO_2 reduction potential during the operation stage. If the CO_2 reduction potential during the operation stage cannot compensate for the emissions during construction and transportation (the installed capacity is too small or the operation hours are too short), then the ΔRTF of CO_2 would be positive. Because CO_2 is the primary greenhouse gas emitted from human activities [67], this study only considers CO_2 as a pollutant for RTF calculations. However, the RTF methodology can also be used to assess other pollutants. We did not consider the impact of SHP on aquatic habitat and biota community because the plant assumed in this study was run-of-river SHP scheme without water storage or diversion, and research showed that this scheme was more eco-friendly than the diversion weir and the pondage hydropower plants [68].

Concerning the parameters chosen for RTF analysis, for the raw material use during the construction (steel, copper, cement etc.), we assumed the amount of material uses increased with installed capacity of SHP plants (IC_i). The relationship between material uses and installed capacity was estimated from the inputs of five SHP plants in Ref. [44], since the type and scale of SHP plants were similar to those in our study. For other parameters we basically used Chinese values expect for the denominators of steel, copper, and CO_2. Because metals are finite resources and often traded internationally, the denominator of RTF of material is allocated capacity per capita in the world. As for CO_2, since the effects of global warming are planet-wide, the denominator is CO_2 uptake capacity by nature allocated to each person around the world. In terms of RTF of land, because it is a regional specific issue in our study and the capacity of land is restricted by regional boundaries, results will differ greatly when constructing SHP plants in regions with various land cover types and land areas. Hence, the scope of RTF of land is the provinces of Shaanxi, Henan, and Hubei where the target river basin is situated. Although timber is also traded between countries, it can be produced inexhaustibly through repeated planting and harvesting, so RTF does not regard timber itself as an evaluation target but considers the occupation of finite land which is necessary for timber production. Scope of RTF depends on the research objective, if the topic is global timber production, then the scope will be the entire world.

In this study, we made a preliminary comparison between SHP and other energy sources. In the aspect of CO_2, since the coal-fired power plant is the main contributor to CO_2 emissions in China's electricity sector [52], so we calculated the emission reduction potential of SHP compared to coal power. As for land, we compared SHP with other renewable energy technologies but not fossil fuel technologies (coal-fired power plants), because coal itself is not a sustainable resource and it is not the evaluation target of RTF. We compared the land use of SHP with woody biomass (timber) and solar PV which required large tracts of land to show the potential of prevention of land occupation. We choose timber but not energy crops because our study region is a mountainous area with abundant woods, and the expansion of energy crops in China may have negative impacts on food security according to Weng et al. [69]. We choose solar PV because the technology is mature and the cumulative installed capacity in China is the highest around the world [70]. However, the renewable energy technologies to be compared may be changed according to the study area. Since wind, solar, and biomass are widely implemented renewable energy sources in China now, further studies should conduct complete RTF analysis for them to thoroughly compare and choose the optimal one according to local situations.

This study made an initial attempt to apply the RTF to spatial assessment and site selection. Existing literature on RTF usually compares different processes of construction, waste management, and forest management [27,28,29]. This study verified the capability of RTF to rank potential locations for SHP plants. Moreover, potentially sustainable plants could be identified through the ΔRTF (having an overall ΔRTF<0). For future applications, site selection of other renewable energies can also be analyzed using RTF, and a trade-off can be made among different locations as well as different kinds of renewable power plants, serving as scientific information for decision-makers and planners.

4.2. Role of SHP

According to Kong et al. [17], the main sources of energy consumption for the mountain rural people were coal, straw, and firewood as rural alternative energy was underdeveloped or inaccessible. In order to meet the residential energy demand of these social sectors and simultaneously improve the ecological environment, the Chinese government launched a project called "Substituting small hydropower for fuel" in 2003. The electricity produced by SHP plants are supplied directly to the vicinity [71]. From 2009 to 2014, 190 projects had been completed to generate electricity, solving the problem of living fuel for more than 1.3 million rural residents [72]. The residential electricity price of power grid is about 0.54 CNY/kWh (~0.078 USD/kWh), but the average electricity price of SHP is 0.3 CNY/kWh (~0.043 USD/kWh), thus increasing affordability for peasants [73]. The population density in the urban area of Xichuan county in this study is 1594 person/km^2 [74], with the number of beneficiaries of potential SHP plants being only ~180. Therefore, SHP can be considered as a supplementary energy source along with other sources in urban region. In mountainous rural areas, SHP can satisfy the energy demands of the local people.

In the context of global climate change, SHP plants have become a promising alternative to facilitate energy transition to decouple economic development and greenhouse gas emissions. It is estimated that with climate change, the river discharge and SHP potential will increase [75]. Moreover, the study showed that SHP plants could integrate more solar PV to achieve the 100% green electricity goal [76]. However, some regions experienced over-development of SHP in China and even the world due to the lack of rational planning and environmental impact assessment before construction, resulting in a recent decline in the development rate and even the shutdown of existing plants [10,15]. This study contributes to the identification of priority areas for SHP development to ensure the proper utilization of water resources.

4.3. Uncertainty

The monthly average river runoff volume in 2019 was used in the SHP potential model to calculate the river discharge and to estimate the electricity generation potential from the riverway. Nevertheless, over 80% of the annual rainfall is concentrated between May and October, and the remaining between November and April in the Dan River Basin [30]. In addition, annual precipitation increased with the elevation in the study area. Therefore, the operation hours of the SHP plant would be uneven throughout the year, and most SHP plants are confronted by insufficient water discharge. The annual operational time for the potential SHP plant was assumed to be 3491 h (average value in China) in this study [45], but in reality, operational hours fluctuate every year even within the same plant. Since the potential for CO_2 emission reduction and land use prevention depend on installed capacity and annual working hours, the RTF would be larger than the estimated value under short working hours. Therefore, strategies to optimize the operational time and amount of hydropower generated are critical for improving the environmental performance of SHP plants.

Although the RTF evaluates the sustainability of a system over a period of 100 years, future scenarios for parameters in the RTF calculation are not covered by this study. For instance, the exploitable amounts of steel and copper may increase owing to advances in technology and the population will also fluctuate in the future. In addition, the inventory data for the construction and equipment of the SHP plants are based on the current situation, and with technology development, the components and quantity of materials may be different. Moreover, the ratio of solar power generation to biomass as alternative energy sources affects the RTF of land.

Finally, this study did not consider the social and economic factors prevailing under local conditions. Therefore, an on-site investigation is required to verify the social and economic feasibility of each potential location of the SHP plant.

5. Conclusions

SHP plants as a clean way to generate electricity are developing rapidly in the rural areas of China. This study utilized an SHP potential model to identify possible sites of SHP plants in the Dan River Basin and then analyzed the ΔRTF of material, CO_2 emissions, labor, and land for each potential SHP plant compared to BAU in the study area. The potential installed capacity of SHP plants in the Dan River Basin ranged from 6 to 1175 kW. With an increase in the installed capacity, the overall ΔRTF decreased. The potential of SHP plants to reduce CO_2 emissions and avoid future land use was overwhelming compared to the material and labor input during construction and operation. The SHP could be a remarkable alternative for thermal power. The environmental friendliness of SHP plants increased with their installed capacity. Since the operational stage of the SHP plant plays an important role in CO_2 emission reduction and land use prevention, it is crucial to ensure the optimal hydropower generation amount.

Preferential locations for SHP plants with low ΔRTF in the midstream and downstream portions of the Dan River Basin were identified, and the capacity ranged from 273 to 1175 kW. On-site investigations are required to verify the social and economic feasibility of SHP plants.

The methodology developed in this study can be implemented to identify preferential locations for SHP plants with low environmental impacts. It applies to other watersheds in China and beyond and is helpful to the decision-making process during the planning of SHP projects by the local government. To expand this methodology to other regions, additional information should be obtained, such as the specification of SHP equipment, data for CO_2 emission and land use, and standards of the labor force, to modify the parameters for the calculation of RTF to best fit the local situation.

CRediT authorship contribution statement

Xiaoxun Huang: Conceptualization, Formal analysis, Investigation, Writing – original draft. **Kiichiro Hayashi:** Conceptualization, Writing – review & editing, Supervision. **Minoru Fujii:** Methodology, Conceptualization. **Ferdinando Villa:** Writing – review & editing. **Yuri Yamazaki:** Methodology. **Hiromu Okazawa:** Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2023.01.079.

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